Parametric Effect Investigation on Aerodynamic Interaction Characteristics for Tandem Rotors in Forward Flight

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Abstract: An iterative free-wake computational method is developed for the prediction of aerodynamic interaction characteristics between the twin rotors of a tandem helicopter. Here the mutual interaction effects between twin rotors are included, as well as those between the rotor and wake. A rotor wake model, blade aerodynamic model and rotor trim model are coupled during the process of solution. A new dual-rotor trim approach is presented to fit for the aerodynamic interaction calculations between tandem twin rotors. By the present method, the blade aerodynamic loads and rotor performance for the twin rotors under the interactional condition are calculated, and the comparisons with available experimental data are also made to indicate the capability of the proposed method. Then, the effects of such parameters as the longitudinal separation and axial separation between twin rotors on the aerodynamic interaction characteristics are analyzed. Based on the investigation, the conclusions are obtained to be of benefit to the configuration design of tandem rotors. Furthermore, the performance comparison between the tandem rotors and a single rotor is conducted. It is shown that the strongest interaction does not appear in a hover state, but in a low-speed forward flight state.

Key words: tandem helicopter; twin rotors; aerodynamic interaction; rotor trim model; parametric effect

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0 Introduction

Tandem helicopter has two rotors overlapping each other, making the aft rotor locate below the vortex wake of the front one easily. The front rotor wake may either impact the aft rotor directly or closely pass through the aft one, and severe aerodynamic interaction occurs between twin rotors as well as between the rotor and wake. Compared to a single rotor, the rotor wake interaction of tandem twin-rotors may cause a greater change of flow field and aerodynamic characteristics, helping distinguish its aerodynamic analysis method from that of a single rotor. As a result, such aerodynamic interaction between twin rotors will significantly affect rotor performance. Thanks to the development of the new-generation helicopter with more compact structure and bigger disk loading, the aerodynamic interaction between rotors tends to be stronger. It is essential to conduct the research on twin-rotor aerodynamic interaction of a tandem helicopter.

The researches on aerodynamics of twin rotors for a tandem helicopter were started in 1960's. But the early work almost aimed at the flight performance, stability and control of tandem helicopters and focused on experiments[1-2]. Aerodynamic interference and rotor performance were rarely studied. After that, aerodynamic interaction of overlapping part of two rotors was investigated by researchers through simple momentum and blade-element theory. For example, Ref. [3] derived the calculation formula of performance for tandem rotors in hover, and drew a summary on previous experiments. However, the main disadvantage of momentum theory is that the induced velocity distribution across rotor disk is uniform, which significantly differs from the reality. Since the 1980's, researchers have tried

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to use the vortex theory to study the aerodynamic interference characteristics of tandem rotors. In 1995, Bagai et al. first adopted a free wake method to investigate wake dynamics of tandem rotors[4], but simply analyzed the geometry of rotor wake without involving blade load and rotor performance. Recently, many researches[5-9] on aerodynamic interaction of twin rotors have been carried out in China. However, most of them were for coaxial twin rotors[6-7] and side-by-side (tilt) twin rotors[8-9], and few studies were conducted on parametric effects on rotor performance for a tandem helicopter. In the last five years, some new researches were counducted about tandem helicopter[10-12].

Generally speaking, accurate calculation of rotor performance for a helicopter is challenging, and this is because it has a high correlation with both blade three-dimensional effects and rotor wake. Furthermore, when blade tip Mach number is relatively large, compressibility effects have to be included in the calculation of rotor power. Even in steady forward flight, the variation of blade sectional angle of attack is still unsteady, and mutual interaction between twin rotors will complicate the performance calculation.

Recently, computational fluid dynamics (CFD) technology has made a considerable progress in simulating rotor flow-fields, and some researchers tried to choose CFD methods to investigate flow field interaction of twin rotors[5]. However, CFD methods require so much computer resources, and numerical dissipation problem still remains, especially in capturing vortex wake of twin rotors for a tandem helicopter. Compared with the CFD method, vortex theory (wake analysis) which directly solves governing equation of vortex line may be a more convenient method, as far as the calculation of blade sectional induced velocity and loading distribution is concerned. Thus, this paper tries to develop a coupling iterative computational method of free-wake to calculate the aerodynamic characteristics and parametric effects of twin rotors.

In order to investigate the aerodynamic interactional characteristics of tandem rotors and compare with a single rotor, this paper defines a new additional power factor of twin rotors. Based upon the definition, the variation of aerodynamic interactional characteristics with different twin-rotor structure layout is emphatically studied. Additionally, different from previous researches, a twin-rotor trim analytical model is presented for wake calculation of a tandem configuration in this paper in order to improve the accuracy of calculation.

1 Computational Model

1.1 Free wake model for aerodynamic interaction of tandem rotors

In accordance with the definition of free wake, vortex lines freely move at the local velocity in the flow field. In mathematics, it can be written as the first-order ordinary differential equations (ODE)[4], namely

$$\frac{\mathrm{d}\boldsymbol{r}(\psi,\psi_{\mathrm{W}})}{\mathrm{d}t}=\boldsymbol{V}(\boldsymbol{r}(\psi,\psi_{\mathrm{W}}))=\boldsymbol{V}_0+\boldsymbol{v}_{11}(\boldsymbol{r}(\psi,\psi_{\mathrm{W}})+\boldsymbol{v}_{12}(\boldsymbol{r}(\psi,\psi_{\mathrm{W}})+\boldsymbol{v}_{21}(\boldsymbol{r}(\psi,\psi_{\mathrm{W}})+\boldsymbol{v}_{22}(\boldsymbol{r}(\psi,\psi_{\mathrm{W}})) \tag{1}$$

where $\boldsymbol{r}$ is the position vector of wake point; ψ the blade azimuth angle; ψ_{W} the age angle of wake vortex; and $\boldsymbol{V}_0$ the velocity of free flow. $\boldsymbol{v}_{11}$ and $\boldsymbol{v}_{22}$ are the self-induced velocities of rotor 1 (R1) and rotor 2 (R2), respectively.

To obtain the correct wake structure, the governing equation of vortex line should be numerically discreted and solved. Although Eq. (1) is relatively simple in form, the solution is quite difficult. This is because the local velocity includes free-flow velocity, mutual induced velocity and self-induced velocity of wake vortices. In physics, helicopter rotor wake is unstable. This will result in great difficulties in solving the governing equation of rotor wake. Previous methods mostly adopt explicit time marching method[13]. One major problem of explicit time-marching method is the numerical instability. Afterwards, some researchers attempted to partly overcome this problem by introducing numerical damping. But rotor wake is strained when introducing numerical damping, and the condition of no load-bearing of wake is destroyed and the calculation results could not be reliably used. Compared mith the explicit time-marching method, semi-implicit scheme relaxation method[14] has better numerical stability. In view of this, the relaxation method is also employed here for the tandem twin-rotor configuration.

When Eq. (1) is solved, initial values in the spatial domain and boundary conditions in the time domain need to be given, i. e.

$$\boldsymbol{r}(\psi,\psi_{\mathrm{W}})=\boldsymbol{r}(\psi+2\pi,\psi_{\mathrm{W}}) \tag{2}$$

$$\boldsymbol{r}(\psi,0)=r_{\mathrm{tip}}[(\cos\beta_0\cos\psi\cos\alpha_s+\sin\beta_0\sin\alpha_s)\boldsymbol{i}+\cos\beta_0\sin\psi\boldsymbol{j}+(\sin\beta_0\cos\alpha_s-\cos\beta_0\cos\psi\sin\alpha_s)\boldsymbol{k}] \tag{3}$$

where r_{tip} is the shedding location of tip vortex; β_0 the coning angle of the rotor; and α_s the tip-path-plane tilt angle.

1.2 Blade aerodynamic model for rotor performance analysis

Blade aerodynamic force and blade circulation are closely related, and the distribution of blade circulation is solved by satisfying the impenetrable condition on control points at 3/4 chord-line position, i. e.

$$\sum_{j=1}^{M}A'_{ij}\Gamma_j=\boldsymbol{n}\cdot(\boldsymbol{V}_0+\boldsymbol{v}'_{11}+\boldsymbol{v}'_{12}+\boldsymbol{v}'_{22}) \tag{4}$$

where Γ is the circulation of blade bound vortex; M the total number of control point; A' the influence coefficient of blade bound circulation and wake induction; $\boldsymbol{v}'$ in right end the induced velocity of two rotors on control point; and $\boldsymbol{n}$ the normal vector.

After solving the circulation of each blade segments through the free-wake model, the inflow of rotor disk plane can be determined, and the aerodynamic force of blade section can be further calculated. Blade aerodynamic lift and drag per unit length can be calculated.

$$L=0.5C_{\mathrm{l}}(\alpha)\rho U^2 b \tag{5}$$

$$D=0.5C_{\mathrm{d}}(\alpha)\rho U^2 b \tag{6}$$

where α is the sectional angle of attack, U the total sectional flow velocity. C_{l} and C_{d} are the airfoil lift and drag, respectively; ρ the air density; and b the chord of blade section airfoil.

The aerodynamic environment of rotor airfoil section is more complicated than that of wing, because the Mach number and the section angle of attack at different radial positions are different. Moreover, the Mach number and the section angle of attack at different azimuths are different in a forward flight. In the current analysis, the well-known Beddoes model[15], which can consider flow compressibility and separation effect and calculate thrust coefficients at different Mach numbers, is utilized to determine airfoil lift and drag. Lift coefficient depending on the angle of attack can be expressed as

$$C_{\mathrm{l}}(\alpha)=\frac{2\pi\alpha\cos\alpha\left[\dfrac{(1+\sqrt{f})}{2}\right]^2}{\sqrt{1-Ma^2}} \tag{7}$$

where Ma is the local Mach number of sectional airfoil and f the ratio of separated location to chord length

$$f=\begin{cases}1.0-0.3\exp[((\alpha-\alpha_z)-\alpha_1)/s_1] & \alpha-\alpha_z\leqslant\alpha_{0.7}\\ 0.04+0.66\exp[(\alpha_1-(\alpha-\alpha_z))/s_2] & \alpha-\alpha_z>\alpha_{0.7}\\ f_H(90-(\alpha-\alpha_z))/(90-\alpha_H) & \alpha-\alpha_z>\alpha_H\end{cases} \tag{8}$$

where α_z is the zero-lift angle of attack; $\alpha_{0.7}$ the stall angle of attack at 0.7 chord line; α_H the separation angle at big angle of attack; and S_1, S_2 and f_H are the parameters of airfoil static-stall characteristics.

1.3 Twin-rotor trim model with aerodynamic interaction

Trim analysis was almost not considered in previous research of rotor wake, and the rotor collective pitch and cyclic pitch controls are directly given in the calculation. A major reason is that the consideraton of rotor trim will greatly increase the complexity of wake solution. However, as showed in Ref. [16], it may lead to improper results without considering rotor trim.

For the tandem two rotors with front and aft asymmetry, its trim is different from that of the single rotor and coupling of two rotors is necessary. However, it will add the time of wake solution. To improve the calculation efficiency, this section presents a new trim model for tandem rotors. Usually, the trim process for single rotor is as follows: giving inclination of rotor axis and forward flight velocity, and adjusting the collective pitch $\theta_{0.7}$ and cyclic pitch θ_{1c}, θ_{1s}, then obtaining longitudinal tip-path-plane tilt angle a_1 and lateral tip-path-plane tilt angle b_1 by solving the equation of flap motion. Next, compare the calculated thrust coefficients C_{T}, a_1 and b_1 with the specified values, and obtain convergent solution after iterative calculations. This paper sets rotor thrust coefficient C_T, rotor roll moment M_x and pitch moment M_y as the target values, thus there is no need to obtain longitudinal tip-path-plane tilt angle a_1 and lateral tip-path-plane tilt angle b_1 by iteratively solving implicit equation of flap motion. a_1 and b_1 are directly given to reduce the computing time greatly.

Meanwhile, it is necessary to consider the influence between two tandem rotors and torque trim. Tandem twin-rotor is different from single rotor in trim process, and the control inputs and outputs are of six items instead of three items. Control input and output vectors are defined as

$$\begin{cases} \boldsymbol{x} = (\theta_{0.7}^1, \theta_{1c}^1, \theta_{1s}^1, \theta_{0.7}^2, \theta_{1c}^2, \theta_{1s}^2)^{\mathrm{T}} \\ \boldsymbol{y} = (C_{\mathrm{T}}^{\mathrm{tw}}, C_{\mathrm{Q}}^{\mathrm{tw}}, M_y^1, M_x^1, M_y^2, M_x^2)^{\mathrm{T}} \end{cases} \tag{9}$$

where superscript ″tw″ means twin rotors, and superscripts ″1″ ″2″ refer to the aft rotor and the front one, respectively. $C_{\mathrm{T}}^{\mathrm{tw}}$, $C_{\mathrm{Q}}^{\mathrm{tw}}$ are the sums of the lift and torque moment of two rotors. Expanding vectors into the first-order Taylor series, one has

$$\Delta \boldsymbol{x} = [\boldsymbol{J}]^{-1} \cdot \begin{bmatrix} C_{\mathrm{T}}^{\mathrm{tw}} - C_{\mathrm{T}_{\mathrm{obj}}}^{\mathrm{tw}} \\ C_{\mathrm{Q}}^{\mathrm{tw}} \\ M_y^1 - M_{y_{\mathrm{obj}}}^1 \\ M_x^1 - M_{x_{\mathrm{obj}}}^1 \\ M_y^2 - M_{y_{\mathrm{obj}}}^2 \\ M_x^2 - M_{x_{\mathrm{obj}}}^2 \end{bmatrix} \tag{10}$$

where $\boldsymbol{J}$ is a 6×6 Jacobian matrix of twin rotors.

During trim process, firstly, give the rotor flapping input and pre-suppose output response, then solve equations via step iteration. When $\Delta \boldsymbol{x} \leqslant \mathrm{RMS}$ (RMS is assigned as a small value), convergent trim control is considered to be achieved. In actual calculation, the solution of flapping equations and update of trimming variables is in iterative processes, and is coupled with the rotor wake solution.

1.4 Coupling model of twin rotors for aerodynamic interaction

Fig. 1 gives the flowchart of aerodynamic in-

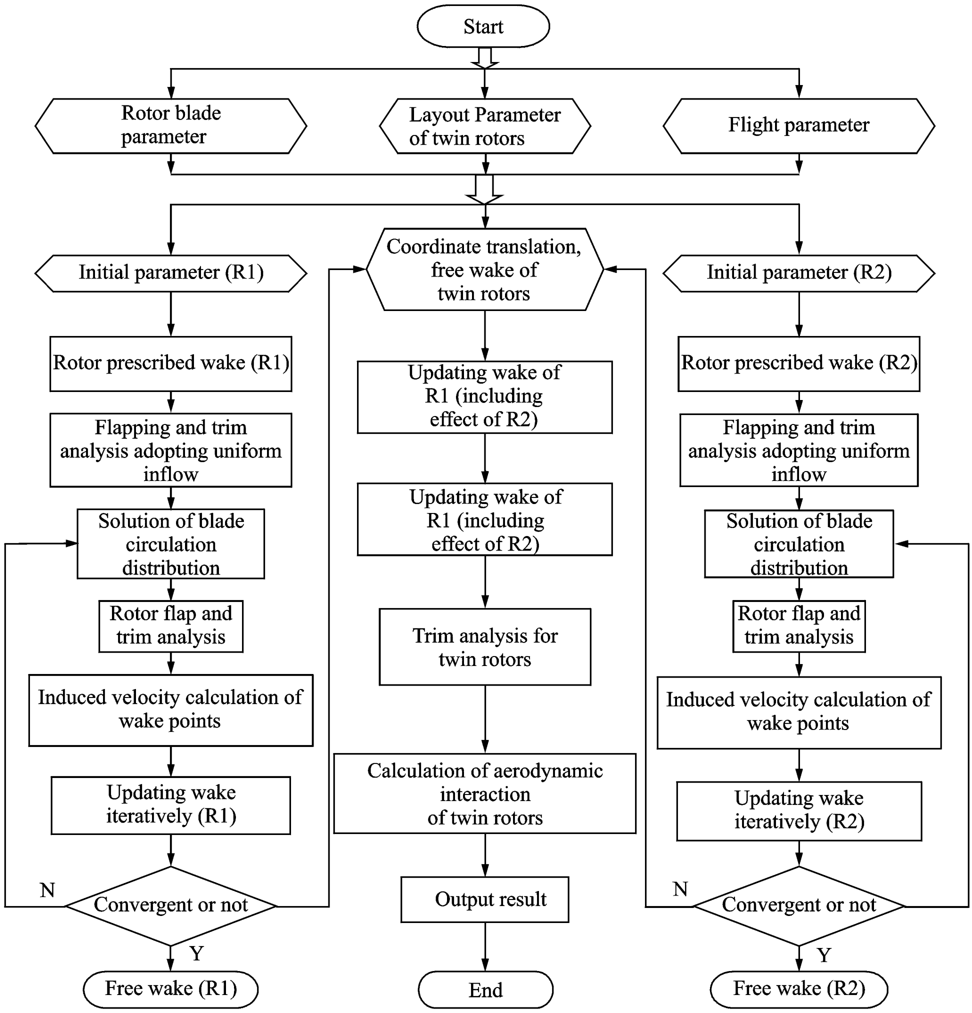


Fig. 1 Flowchart of aerodynamic interaction characteristics for tandem rotors

teraction characteristics combining the wake model of two rotors and aerodynamic model with rotor trim model. Calculations of the wake-point induced velocity and trim analysis need to include mutual effects of two tandem rotors. Because it needs massive computational time when the wake of two rotors is simultaneously iterated in updating the free rotor wake, here the calculation of wake points is for each rotor alone, and the influence of interaction needs to be considered after obtaining the wake of two rotors, then the wake of two rotors is iteratively calculated to get convergent solution. To do so, computational time is relatively less.

2 Method Verification

The model rotor with available experimental data in Ref. [2] is chosen as the numerical example for performance calculation of tandem rotors, and the main parameters are shown in Table 1.

Table 1 Main parameters of model rotor

Parameter	Value
Rotor radius/m	1.143
Chord length/m	0.194
Number of blades	2
Blade twist/(°)	0
Rotation speed/(rad • s^{-1})	79.577
Airfoil	NACA0012
Longitudinal separation	2.06R
Vertical separation/m	0

In Ref. [2], the thrust and torque coefficients of a tandem model with two two-blade rotors and an isolated single rotor were measured in the same state. It was found in the experiment[2] that the measured performance of the tandem rotor is better than that for the single rotor, because the tandem rotors required less power than the single rotor at the same thrust coefficient. Fig. 2 gives the current calculating results of tandem rotors and single rotor in hover as well as the comparisons with experimental data[2]. As shown in Fig. 2, the good correlation between calculated values and experimental data is achieved. It is also noted that although there is no overlapping area for twin rotors, the overall performance in hover is better than that of a single rotor when the longitudinal separation of twin rotors reaches 2.06 R, due to the mutual induced interaction of two rotors.

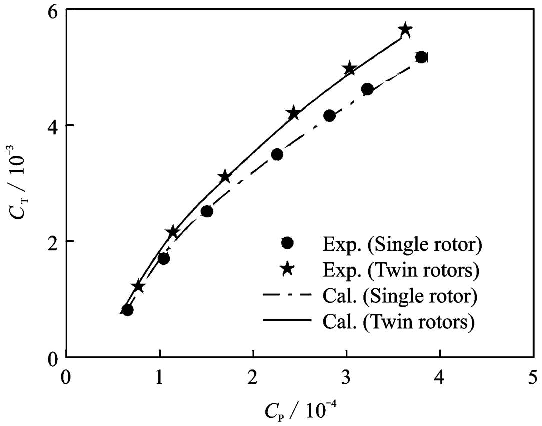


Fig. 2 Comparison of performance between tandem rotors and single rotor (μ=0)

When the longitudinal separation is 0, the layout is the same as that of coaxial twin rotors. To further verify the calculating method in this paper, coaxial twin rotors are also taken as an example, and the distribution of induced velocities is calculated. Fig. 3 shows the distribution of induced velocities at 0.2R vertical station below upper rotor and its comparison with the test data[6]. The calculated results agree with experimental data reasonably.

3 Parameter Effect and Aerodynamic Interaction Calculation

This section chooses the full-scaled twin rotors of tandem helicopter CH-47D as an example, and the main parameters are as follows: three blades, rotor radius of 9.145 m, chord of 0.81 m, blade negative-twist of −8 °, rotation speed of 23.5 rad/s and NACA0012 airfoil.

The typical layout parameter of tandem rotors is (1.3R, 0, −0.2R), as shown in Fig. 4. It has no large longitudinal separation and compact airframe structure but great interaction. The hub center of aft rotor is defined as the origin of coordinate. The x-direction is along longitudinal body, the y-direction along lateral body, and the z-direction along axial one. In Fig. 4, d_L is the longitudinal separation between rotors, d_V the axial separation, and v the forward velocity.

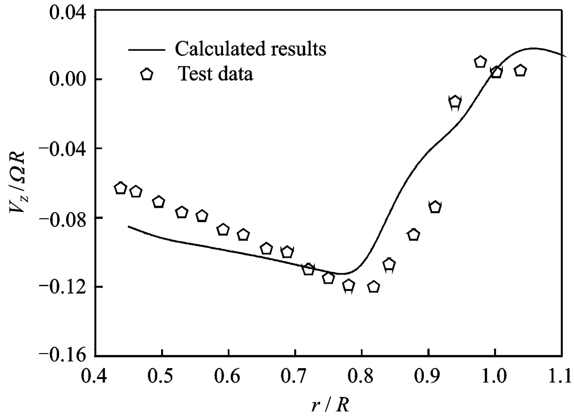


Fig. 3 Induced velocity distribution at 0.2R below rotor

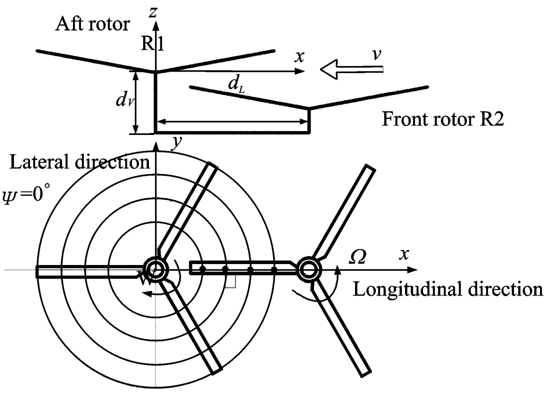


Fig. 4 Coordinate for tandem twin rotors

4 Trim Analysis and Aerodynamic Loads Calculation for Tandem Rotors

Fig. 5 gives the variation of blade section loads with azimuth angle at the radial station of 0.85R in a forward flight ($\mu=0.3$) for tandem twin rotors and a conventional single rotor. Longitudinal coordinate denotes non-dimensional blade section load M^2C_l. In Fig. 5, blade loads vary with azimuth angle greatly. Besides, due to the mutual interaction between the twin rotors of a tandem helicopter, loads distribution of the front rotor and aft rotor is different from that of a conventional single rotor.

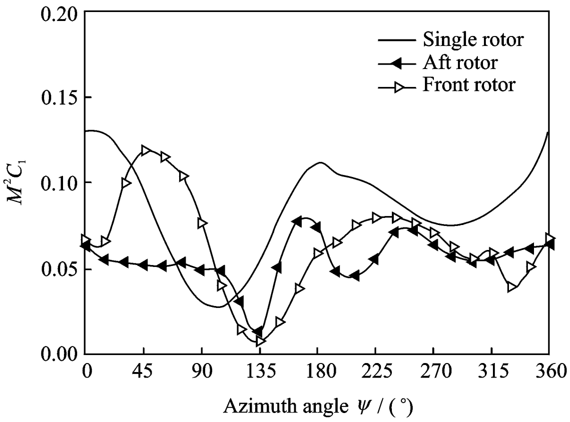


Fig. 5 Variation of blade load with azimuth angle for tandem rotors (0.85R, $\mu=0.3$)

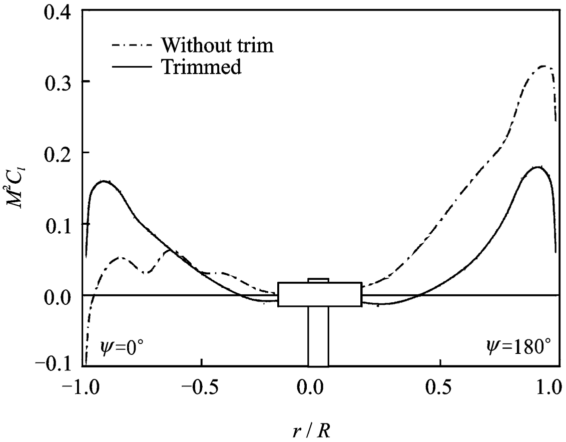
To illustrate the impact of trim on rotor aerodynamic loads, Fig. 6 gives a typical calculated result of longitudinal load distribution without and with trim of tandem rotors. From Fig. 6, the blade load without trim is larger at the 180° azimuth angle, thus generating a nose-up pitching moment easily. Blade load distributions at 0° and 180° azimuth angles are nearly symmetric after trim. It is also noted that in Fig. 6(b), in spite of the inclusion of trim, the load distribution fluctuates significantly at 0° azimuth angle (overlapping area) of front rotor. This is because blade of front rotor at 0° azimuth angle is under the wake of aft rotor, and the trimming has a large effect on the calculated results.

4.1 Calculation of performance for twin rotors

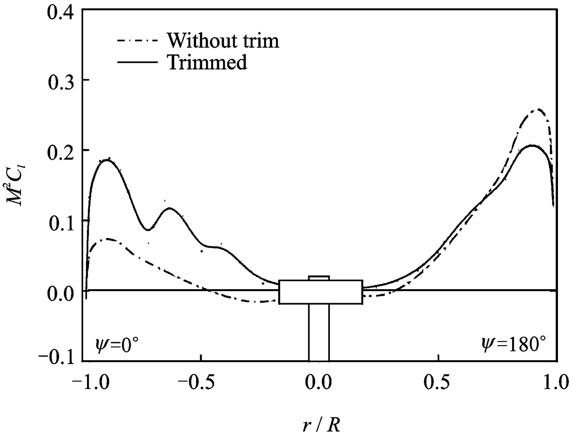
Fig. 7 gives performance curves of front and aft rotors at advance ratio (μ) of 0.1 for tandem rotors with comparison of single rotor. It is shown that the performance of front rotor is similar to that of a single rotor in a forward flight ($\mu=0.1$), but the aft rotor performance is worse than that of front rotor or single rotor, which is consistent with the calculation result in Ref. [5], with the adoption of a CFD method.

4.2 Effects of layout parameters for tandem rotors

To compare with the single rotor, and to investigate the effect of layout parameters for tandem rotors, an additional power factor is defined



(a) Aft rotor



(b) Front rotor

Fig. 6 Comparisons of blade load distribution of tandem rotors with and without trim ($\mu=0.1$)

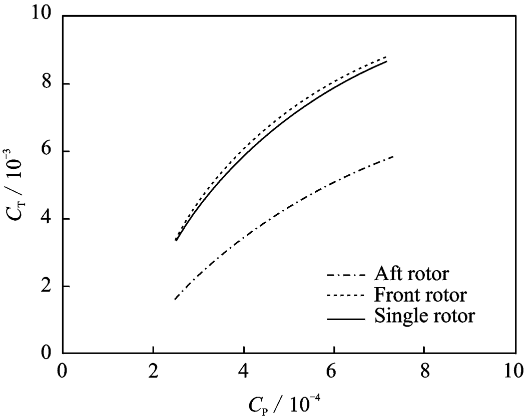


Fig. 7 Performance comparison between tandem rotors and single rotor ($\mu=0.1$)

as follows

$$\delta P = \frac{P_{\text{twin}} - 2P_{\text{isolated}}}{2P_{\text{isolated}}} \tag{11}$$

where subscripts "twin" and "isolated" denote the tandem twin rotors and the isolated rotor, respectively.

Fig. 8 gives a variation of additional power factor with longitudinal separation for the forward flight of tandem rotors. When the longitudinal separation is 1.3R, the additional power of tandem rotors is just about 25.7% ($C_T=0.006$) of two separate rotors, along with the increase of the longitudinal separation increasing. The additional power factor decreases first and subsequently increases. The additional power drops to the minimum when the longitudinal separation between two rotors is 1.8R.

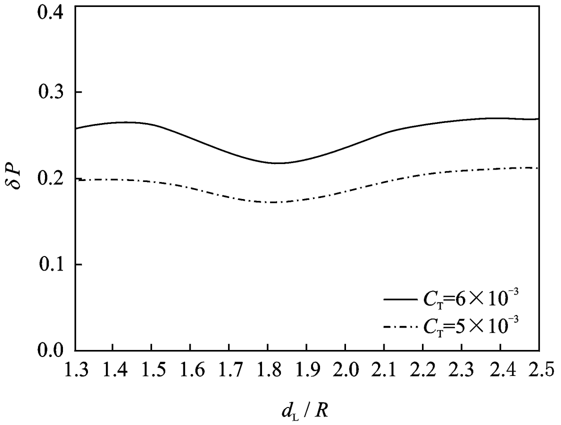


Fig. 8 Variation of additional power factor with longitudinal separation for tandem rotors ($\mu=0.1$, $d_V/R=0.2$)

Fig. 9 is a variation of additional power with axial separation for tandem rotors. Axial separation sort of influences the additional power of rotors in a forward flight, and additional power decreases as the axial separation of rotors increases. Fig. 9 also shows that the increase of thrust coefficient will result in the increase of additional power.

Fig. 10 presents a variation of additional power factor with advanced ratio under the condition of the same thrust coefficient for tandem rotors. Obviously, when thrust coefficient keeps constant, additional power required for tandem rotors increases first and then decreases with the increment of advance ratio. Namely at low speed, as advanced ratio increases, mutual interaction between two rotors becomes stronger, and reaches the maximum at the advanced ratio of 0.1.

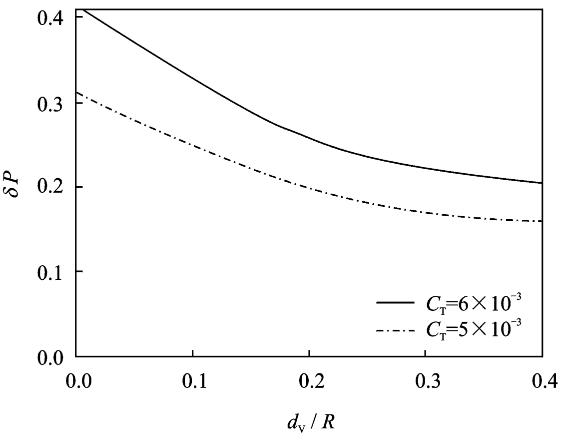


Fig. 9 Variation of additional power factor with axial separation for tandem rotors(μ=0. 1, d_L/R=1. 3)

From middle forward speed to larger speed, mutual interaction between two rotors becomes weaker. For a larger thrust coefficient, the additional power factor of tandem rotors increases.

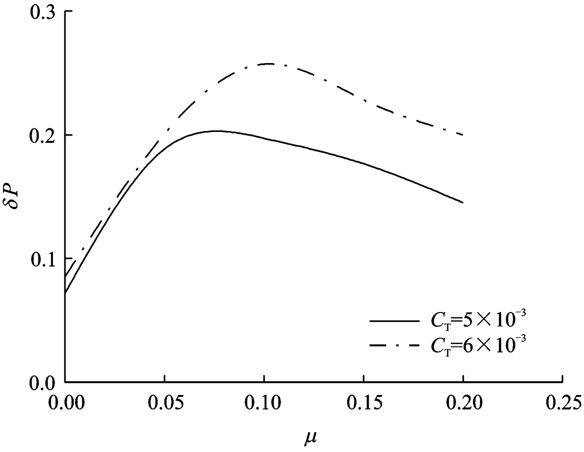


Fig. 10 Variation of additional power factor with advance ratio for tandem rotors

5 Conclusions

The aerodynamic interactional characteristics of tandem twin-rotors for the hover and typical forward flight (μ=0. 1) states are calculated and analyzed, and the parametric effects of different tandem configurations are investigated. Several conclusions can be drawn as follows:

(1) The front rotor performance of tandem rotors is similar to that of the isolated one, while the aft rotor performance is worse than that of the front one or an isolated rotor due to the wake interaction of front rotor.

(2) Compared with two isolated rotors, the tandem twin-rotors need 25. 7% more power at the longitudinal separation of 1. 3R for current numerical case. The additional power will decrease first and increase later when the longitudinal separation increases, and it reaches the minimum at about 1. 8R longitudinal separation.

(3) The variation of axial separation affects the rotor power in a forward flight, and the power will decrease as the axial separation increases.

(4) The additional power needed by tandem twin rotors will increase first and decrease later as the advance ratio increases. The most serious interaction between twin rotors does not appear in hover but in a low-speed forward flight. The interaction will increase when the rotor thrust coefficient increases.

(5) The trim method proposed in this paper is suitable for the calculation of aerodynamic interaction on tandem rotors.

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