Design and Analysis of Rotor/Wing Flap for Canard Rotor/Wing Aircraft

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Abstract. In the present study, a kind of blunt trailing edge airfoil with its flap is designed for the purpose of reducing drags of blunt leading and trailing edge airfoils which are used for rotor/wing of CRW. The aerodynamic characteristics of designed flaps and elliptic airfoil which has the same thickness are numerically investigated based on the Reynolds-averaged Navier–Stokes equations and the SST k-\omega two-equation turbulence model. The comparisons of aerodynamic force and moment coefficients show that, the lift characteristic is improved for designed flaps, but the drag will not be reduced if the flap has great bending trailing edge, and small bending trailing edge design is suitable for this kind of flap, and it will reduce the drag and improve the longitudinal stability characteristics.

1. Introduction

The Canard Rotor Wing (CRW) aircraft is a high-speed vertical takeoff and landing concept. It combines the low disk loading hover efficiency and low-speed flight characteristics of a helicopter with the high-subsonic cruise speed of a jet powered fixed-wing aircraft. For takeoff and landing, the wing rotates as a reaction-driven rotor. At conversion speed, the canard and lifting horizontal tail reduce the rotor thrust to zero, allowing the rotor to be stopped in a benign condition. After the rotor/wing is stopped, the vehicle continues flying as a three surface aircraft and the jet is used for the required propulsive force [1].

This concept was demonstrated under the X-50A “Dragonfly” program conducted by Boeing Company and Defense Advanced Research Projects Agency (DARPA) in 2003-2005. Although the X-50A program was cancelled in 2006 after the crashes of two prototypes, this concept is still a potential high-speed rotorcraft, and more investigations have been made by China and Korea recently [2-5].

Blunt leading and trailing edge airfoils make up the sections of the rotor/wing of CRW, because the trailing edge of the retreating blade in rotary-wing flight becomes the leading edge in fixed-wing flight. For X-50A prototype, the rotor/wing had an elliptical airfoil section with maximum thickness-to-chord (t/c) ratio varying from 24\% at the root to 16\% at the tip [6]. This incurs a profile drag penalty in both rotary and fixed-wing modes. The use of drag reduction techniques continues to be investigated, which range from circulation control to reversible airfoils, and the use of deployable flaps [7-9].

In the present study, a kind of blunt trailing edge airfoil with its flap is designed, and a Computational Fluid Dynamics (CFD) based study is also undertaken to evaluate the aerodynamic performance of the designed airfoil with flap in high speed condition, relative to elliptic airfoils which has the same thickness.

2. Design of rotor/wing airfoil and flap
For the purpose of containing flap, and maintaining blunt shape as leading edge, this kind of rotor/wing airfoil is constructed by arcs and spline curves as show in figure 1, and the profile of this airfoil is symmetrical relative to both X and Y axis.

The process of the designing of this airfoil is summarized below:

Firstly, the dimension and position of the arcs at the leading and trailing edge are determined, according to the setting radius of curvature;

Secondly, the reference point P1 of spline curve is determined, according to the setting rotary angle of flap from fold to deploy. This point is on the trailing edge arc, and we can draw a straight line from the center of this arc to point P1. The angle between this line and X axis is $\theta$, and the setting rotary angle of flap from fold to deploy is $2\theta$.

Thirdly, the reference point P3 of spline curve is determined, according to the setting thickness of this airfoil.

Fourthly, the spline curve is determined according to the position of reference point P2. The tangent of this curve at point P3 is horizontal, and the tangent of this curve at point P1 is vertical to the straight line which has been described in the secondly step.

Finally, the spline curve is mirrored relative to both X and Y axis, and this kind of rotor/wing airfoil including four spline curves and two arcs is constructed after that.

Figure 1. Design of the Rotor/Wing Airfoil

Following the design of the blunt trailing edge airfoil which has been described above, the flap can be designed according to the process below and the key construction points are shown in figure 2.

Firstly, the flap cracking point P4 is determined according to the setting length of the flap.

Secondly, the airfoil curve between P1´ and P4 is rotated around the center of the trailing edge arc anticlockwise, the rotary angle is $2\theta$ and this curve is upper surface of the flap. P1´is the symmetrical point of point P1 and it will coincide with P1 after rotation. The point P4 becomes P4´after rotation.

Thirdly, the spline curve which is the lower surface of flap is determined by point P4´ and positions of reference point P5 and P6. Point P6 is on the lower curve of this airfoil ahead of point P1´, and the tangents of these two curves at point P6 are coincident.

Finally, the curve between point P4 and P6 is setting as the cover of the groove appeared after the flap is deployed, and this cover can void the vortex flow in the groove, which is helpful for reducing the aerodynamic drag.

Figure 2. Design of the Rotor/Wing Flap

According to the designs of this kind of rotor/wing airfoil and flap, series of airfoils and flaps can be constructed by setting different radius of arcs, flap rotary angles, positions of point P4 and P5, and so on. The influences of such design parameters on the aerodynamic performance of the rotor/wing airfoil with flap will be analyzed in following section.[10]
3. Analysis of rotor/wing flap based on CFD

3.1. Numerical Method

3.1.1. Governing Equations. The two-dimensional, time-dependent, Reynolds-averaged Navier-Stokes equations for an ideal gas may be written in an integral form for an arbitrary control volume $\Omega$ with the boundary $\partial \Omega [10]$

$$
\frac{\partial}{\partial t} \int_{\Omega} QdV + \int_{\partial \Omega} F(Q) \cdot ndS = \int_{\partial \Omega} G(Q) \cdot ndS
$$

Where $Q$ is the vector of the conservative flow variables; $F(Q)$ and $G(Q)$ are the inviscid and viscous flux vectors in the standard conservation form, respectively; and $n$ is the unit normal vector out from the control volume boundary. The flow variables were nondimensionalized by the free stream quantities, and the length was normalized by the airfoil chord length.

3.1.2. Turbulence model. For turbulence closure, the SST $k$-$\omega$ two-equation turbulence model was employed. The transport equations for the SST $k$-$\omega$ model are [11]:

$$
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - Y_k + S_k
$$

$$
\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_i} (\rho \omega u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + G_\omega - Y_\omega + D_\omega + S_\omega
$$

In these equations, $G_k$ represents the generation of turbulence kinetic energy due to mean velocity gradients. $G_\omega$ represents the generation of $\omega$. $Y_k$ and $Y_\omega$ represent the dissipation of $k$ and $\omega$ due to turbulence. $D_\omega$ represents the cross-diffusion term. $S_k$ and $S_\omega$ are source terms.

In the present study, all calculations are performed by assuming that the flow is fully turbulent.

3.1.3. Other Computational Details. A characteristic boundary condition was imposed at the far-field boundary, and the no-slip isothermal boundary condition was applied at the solid surface. In the present study, all calculations were performed by assuming that the flow was fully turbulent. To simulate the viscous shear layer accurately and to avoid the numerical difficulties involved in using highly stretched triangular cells, hybrid unstructured meshes were adopted in the present study. The hybrid meshes consisted of quadrilateral cells inside the boundary layer and isotropic triangular cells for the rest of the computational domain, as shown in figure 3. More than 161 points are set around the airfoil, and the non-dimensional minimum spacing normal to the solid wall is $10e-6c$ to capture the viscous effect near the wall, where $c$ is the reference chord length of the airfoil. The mesh contains about 57 thousands points to simulate the aerodynamics of the airfoil.

![Figure 3. Hybrid mesh around a 16% thickness elliptic airfoil](image-url)
Because the flow field around an elliptic airfoil is inherently unsteady due to the presence of a pair of vortices at the blunt trailing edge, calculation is performed in a time-accurate manner and the steady-state result is obtained by averaging the periodic time-varying solution.

3.2. Results and Discussion
Five rotor/wing airfoil with flaps are designed for analysis, and they are labelled from E01 to E05. Shapes of these airfoil with flaps are presented in figure 4, and table 1 shows parameters of them.

![Figure 4: Shapes of rotor/wing airfoil with flap for analysis](image)

Calculations are firstly described for several meshes to investigate the mesh dependency of E01. The basic mesh is the same as elliptic airfoil, while a coarse mesh contains about 20 thousands points and two fine meshes with 80 and 100 thousands points are respectively generated to calculate the foil’s aerodynamics. Figure 5 and figure 6 show the lift and drag calculated by the meshes with 57, 80 and 100 thousands points are nearly the same, while the results of the coarse mesh present low accuracy. It indicates that the mesh with 57 thousands points is reasonable for the simulations in this study.

**Table 1. Parameters of rotor/wing airfoil with flap for analysis**

| Parameters                                      | E01  | E02  | E03  | E04  | E05  |
|-------------------------------------------------|------|------|------|------|------|
| Thickness of airfoil(\% of airfoil chord length) | 16%  | 16%  | 16%  | 16%  | 16%  |
| Radius of arc(\% of airfoil chord length)       | 3%   | 3%   | 3%   | 2.5% | 2.5% |
| Flap rotary angle(degree)                       | 120  | 140  | 140  | 140  | 150  |
| Extending length of flap(\% of airfoil chord length) | 8.6% | 10.1%| 12.2%| 10.8%| 11.0%|

![Figure 5: Lift coefficients of E01 with different meshes](image)

![Figure 6: Drag coefficients of E01 with different meshes](image)
The aerodynamic forces and moment of a 16%-thick elliptic airfoil are compared with those of rotor/wing airfoil with flaps from E01 to E05 at the same flow condition. Calculations were made for high speed condition at a free stream Mach number of 0.4 and a Reynolds number of $1.9 \times 10^6$. For the purpose of comparing the effects of deployed flaps, the reference length for calculating dimensionless coefficient is the chord length of airfoils with flaps folded, equal to the chord length of elliptic airfoil.

In figure 7, the lift coefficients are compared between the elliptic airfoil and designed rotor/wing airfoil with flaps. It shows that the lift coefficients of all designed flaps are greater than elliptic airfoil in the same angle of attack before stall, and the maximum lift coefficients are also greater than elliptic airfoil except E05. The lift-curve slops of all designed flaps are greater than elliptic airfoil, but the stall angles are all about 8 degree, which are smaller than elliptic airfoil. It can be seen that, the E01 has the least rotary angle and largest bending trailing edge, and the lift coefficient of it is greatest among these designed flaps. The analysis of figure 7 and the differences between designed flaps shows that bending trailing edge, long extending length of flap and small radius of leading edge are beneficial for the improvement of lift performance.

Figure 7. Comparison of lift coefficients
Figure 8. Comparison of drag coefficients

In figure 8, the drag coefficients are compared between the elliptic airfoil and designed rotor/wing airfoil with flaps. It shows that the drag coefficient of E01 is enormously greater than other flaps and elliptic airfoil, and the drag performances of these flaps except E05 are not evidently better than elliptic airfoil, although those flaps have sharp trailing edges.

Figure 9 shows the comparison of streamline patterns between elliptic airfoil and E01 flap with nearly same lift coefficient. It is shown that, the flow separating area at the trailing edge of E01 is bigger than...
elliptic airfoil, and this will produce more pressure drag. Concluding from these comparisons, larger bending trailing edge is beneficial for the improvement of lift performance, but is adverse for the reducing of drag.

In figure 10, the lift-to-drag ratios are compared between the elliptic airfoil and designed rotor/wing airfoil with flaps. It shows that the lift-to-drag ratio of E05 flap is greater than elliptic airfoil at the same lift coefficient before stall, and the lift-to-drag ratios of other flaps except E01 are close to the elliptic airfoil.

In figure 11, the moment coefficients are compared between the elliptic airfoil and designed rotor/wing airfoil with flaps. It shows that, the moment coefficient of the elliptic airfoil continuously increased up to stall as the lift coefficient increased, whereas those of designed flaps decreased down until approaching stall. It is shown that, more lift is generated at the rear section of designed airfoil with flaps than elliptic airfoil. In addition, the moment coefficient of E05 shows a more gradual changes than that of elliptic airfoil, this is beneficial for longitudinal stability characteristics.

4. Conclusions
For the purpose of reducing drags of blunt leading and trailing edge airfoils which are used for rotor/wing of CRW, a kind of blunt trailing edge airfoil with its flap is designed. For evaluating the effect of drag reduction and the influences of design parameters, five different rotor/wing airfoil with flaps are constructed, and the aerodynamic performances of them are compared to elliptic airfoil which has the same thickness based on CFD.

The results show that, the lift characteristic is improved for designed flaps, but the drag will not be reduced if the flap has great bending trailing edge. It has been proved from the comparison that, small bending trailing edge design is suitable for this kind of flap, and it will improve the drag and longitudinal stability characteristics.

The results also show that, the lift characteristic of flap with small bending trailing edge (for example E05) is not improved compared to elliptic airfoil, and this is a problem need to be studied.

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