Calculation and analysis of interaction flowfield over tiltrotor aircraft in conversion mode

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Abstract. Aiming at solving the complicated aerodynamic interaction problem of conversion mode, the preconditioning method is applied. Combined with the unstructured hybrid technique and the overlapping grid interpolation technique, a numerical simulation method for tiltrotor aircraft in conversion mode is established. On this basis, the validity of the numerical method is verified. Then, with the numerical simulation of isolated rotor, isolated fuselage and tiltrotor aircraft, the laws of the aerodynamic interaction of rotor/fuselage/wing/tail are analyzed with tilting process. The calculation results show that the rule of the influence of the rotor wake on the aerodynamic performance of the wing is different between the inner side and the outer side of the wing. Compared with the isolated rotor, the thrust coefficient of the rotor of the aircraft increases slightly by 0 ~ 5% during the tilting process due to wing and the fuselage.

1. Introduction

Tiltrotor aircraft is a new type of aircraft which combines the functions of vertical take-off and landing and high-speed cruise. It has a wide range of applications in military and civilian applications. At present, the Bell-Boeing V-22 Osprey [1] has been used by the U.S. military, and the AW609 [2] has also been put into full commercial operation. However, it still has serious complex unsteady aerodynamic interaction problems, and the unsteady aerodynamic interaction of its conversion mode is one of the key and difficult points in the research. Conversion mode is the intermediate mode between helicopter mode and fixed wing aircraft mode, which is of great significance for fast, safe and stable takeoff, cruise and landing of tilt rotor aircraft. It can be seen that the prediction of the effect of downwash induced by rotor on the wing and fuselage in the conversion mode is difficult. Therefore, it is of great theoretical and practical significance to study the unsteady aerodynamic interaction of the tiltrotor aircraft.

Due to the remarkable unsteady characteristics of the conversion model, it presents a great challenge to the experiment and numerical simulation. There are few published literatures on this field. Compared with the experimental research [3-5], the numerical simulation research of the tiltrotor aircraft has the advantages with low cost and little shape limitation. Johnson [6-8] in NASA research center calculated the aerodynamic characteristics of tiltrotor with CAMRAD helicopter analysis software based on vortex theory[9], but did not study the aerodynamic interaction of tiltrotor aircraft rotor between wing and fuselage; Yong Su Jung [10] in South Korea carried out the aerodynamic interaction of rotor and tail on conversion mode with CFD method. The result shows that the increase of the sideslip angle causes the amplification of the amplitude of the yaw moment and the roll moment,
but the engine nacelle in the conversion mode is only simulated at 80° and 90°. A. Jimenez[13] in the University of Glasgow, UK, used the CFD method of momentum source to simulate the conversion of ERICA, analyzed the aerodynamic interaction of rotor, wing and fuselage, but the engine nacelle only simulated at 30°, and the accuracy of flow field detail feature capture was not guaranteed. In China, Li Chunhua[12] and others used the free wake method to calculate the conversion mode of the isolated tiltrotor. In reference [13-14], the V-22 conversion mode was simulated by the CFD method based on momentum source[15], but the viscosity is not considered by Euler equation and the details of the flow field are not captured by momentum source method. Li Peng and Zhao Qijun[16] used CFD method to calculate the conversion mode of the isolated tilt rotor, but did not study the aerodynamic interaction of the rotor, wing and fuselage of the tiltrotor aircraft. It can be seen that, there are few published literatures on the study of the conversion mode of the tiltrotor aircraft, and the research methods have gradually shifted from the early experimental research and vortex theory research to CFD numerical simulation research. The research object is mostly a single rotor, and few research of experiment and numerical simulation on the whole tiltrotor aircraft.

In this paper, aiming at solving the tiltrotor aircraft's complicated flow problems, the unsteady preconditioning method and the Spalart Allmaras equation turbulence model[17-18] are used. Combined with the unstructured hybrid grid generation technique and the overlapping grid interpolation technique, which are suitable for the complex configuration and large displacement of tiltrotor aircraft, a numerical simulation method for tiltrotor aircraft is established. With local time step, multigrid technology and large-scale parallel computing technology to accelerate the solution of the subsonic flow field, the interaction flow field between the airframe and the rotor in the conversion mode of the tiltrotor aircraft is analyzed, which has certain guiding significance for the aerodynamic design of the high-performance tiltrotor aircraft in the future.

2. Simulation calculation methodology

2.1. N-S Equation

The flow field solver used in this paper is the self-developed MFlow software[19-20]. The unsteady compressible Navier-Stokes equations for the original variables are as follows:

\[ \frac{\partial}{\partial t} \mathbf{Q} + \nabla \cdot \mathbf{F} = 0 \]

(1)

Here, \( \Omega \) and \( \partial \Omega \) are the domain and boundary of the control volume, \( \mathbf{F}_i \) is the inviscid flux, \( \mathbf{F}_v \) is the viscous flux. The flux defined in reference [21]. \( \mathbf{Q} \) and \( \mathbf{M} \) are primitive and conservative variables respectively, \( \mathbf{M} \) is the transformation matrix for \( \mathbf{Q} \) and \( \mathbf{W} \). The forms of \( \mathbf{Q} \), \( \mathbf{M} \) and \( \mathbf{W} \) are follow as:

\[
\mathbf{M} = \frac{\partial \mathbf{W}}{\partial \mathbf{Q}} = \begin{bmatrix}
\rho_p & 0 & 0 & 0 & \rho_r \\
\rho_p u & \rho & 0 & 0 & \rho_r u \\
\rho_p v & 0 & \rho & 0 & \rho_r v \\
\rho_p w & 0 & 0 & \rho & \rho_r w \\
\rho_p H - 1 & pu & pv & pw & \rho r + \rho C_p
\end{bmatrix}
\]

(2)

\[
\mathbf{Q} = \begin{bmatrix} u \ v \ w \ T \end{bmatrix}^T
\]

\[
\mathbf{W} = \begin{bmatrix} \rho \ p u \ p v \ p w \ p E \end{bmatrix}^T
\]

(3)

Where, \( u \), \( v \), and \( w \) represent the components of velocity in the \( x \), \( y \), and \( z \) directions. \( Cp \), \( p \), \( T \), \( H \) and \( E \) denote constant pressure specific heat, density, temperature, total energy per unit mass of gas, and total enthalpy. \( \rho_p \) and \( \rho_r \) are the partial derivative of density versus pressure and temperature.

2.2. Unsteady Preconditioning Equation
Weiss-Smith\cite{22-23} preconditioning matrix replaces the parameters $\rho_p$ of the transformation matrix in (1) with the parameter $\Theta$. Due to the strong unsteady flow field of the tiltrotor aircraft in conversion mode, a two-time step method is introduced to solve the problem. Unsteady preconditioning equations are of the form:

$$\frac{\partial}{\partial t} \int \Omega d\Omega + \frac{\partial}{\partial t} \int \Omega d\Omega + \frac{1}{\rho L} \int (F_e - F_i) dS = 0$$ \hspace{1cm} (4)

Where, $t$ and $\tau$ represent the real time and pseudo time respectively. $\Gamma$ is Weiss-Smith preconditioning matrix, the form is as follows:

$$\Gamma = \begin{bmatrix} \Theta & 0 & 0 & 0 & \rho_r \\ \Theta u & \rho & 0 & 0 & \rho_r u \\ \Theta v & 0 & \rho & 0 & \rho_r v \\ \Theta w & 0 & 0 & \rho & \rho_r w \\ \Theta H - 1 & \rho u & \rho v & \rho w & \rho_r H + \rho c_p \end{bmatrix}$$ \hspace{1cm} (5)

$$\Theta = \left( \frac{1}{U_p^2} - \frac{\rho c_p}{\rho c_p} \right)$$ \hspace{1cm} (6)

In equation(6), $U_p$, $U_r$, $k$ and $c$ are the preconditioning speed, rotor tip speed, preconditioning parameter and local sound velocity. The preconditioning parameter is constant. After adding the preconditioning matrix to the time derivative term of the equation, a new convective eigenvalue can be derived. The comparison of eigenvalues is shown in reference [24]. As can be seen from reference [24], when the velocity is low, the eigenvalues of the equation keep at the same order of magnitude, and the numerical rigidity of the system is eliminated. When the velocity exceeds the velocity of sound, the preconditioning equation is transformed into N-S equation.

2.3. Discretization and Diagonalization

The right-hand side of the equation is discretized by the Roe scheme, and the dual-time method is used for the time advancement. The LU-SGS method divides the discrete equation into the following three parts:

$$(D + L)D^{-1}(D + U)AW^n = Res$$ \hspace{1cm} (7)

$L$ is the strict lower triangular matrix, $U$ is the strict upper triangular matrix, $D$ is the diagonal matrix. The above equation can be inverted in two steps - the front and back scans. $L$, $U$ and $D$ are in the following form:

$$D = SM^{-1}\left(\frac{Vol}{\Delta t} + \frac{1}{2} \sum_i \lambda_i S_i \right)$$ \hspace{1cm} (8)

$$L = \frac{1}{2} \sum_{i=L} S_i \left(\Delta F_{e,i} - SM^{-1} \lambda_i \Delta W \right)$$ \hspace{1cm} (9)

$$U = \frac{1}{2} \sum_{i=U} S_i \left(\Delta F_{e,i} - SM^{-1} \lambda_i \Delta W \right)$$ \hspace{1cm} (10)

$$S = \frac{1 + \phi}{\Delta t} \Delta t M + \Gamma$$ \hspace{1cm} (11)

Where, the concrete forms of $Res$, $\Delta F_{e,i}$ and $\Delta W$ can be seen in reference [24].

2.4. Overlapping grid interpolation technique and unstructured hybrid grid

Due to the complex unsteady flow phenomenon of the tiltrotor aircraft, the overlapping grid interpolation technology is used. The overlapping grid allows the sub-grid zones to overlap each
other, and reduces the difficulty of grid generation. Firstly, the wall surface intersection criteria is selected as the determination method of the hole boundary. After determining the hole boundary, alternative digital tree (ADT) method \cite{25} is used to find the corresponding grid cell of the hole boundary in the sub-grid wrapping objects. Finally, the information of overlapping zones is transmitted by hole digging and interpolation. Obviously, the technology which is flexible and suitable for the simulation of tiltrotor aircraft with complex shape and tilting process.

The reasonable design and high quality generation of computational grid are the premise of numerical simulation of tiltrotor aircraft. In this paper, the computational grid is unstructured hybrid grid, including triangular prism, pyramid and tetrahedron grid cells. Triangular prism grid cells are used to simulate the boundary layer, tetrahedron grid cells are used to simulate the isotropic region of space flow field, and pyramid grid cells are used to be transition grid cells of triangular prism grid cells and tetrahedron grid cells. With the unstructured hybrid grid technology, the viscous simulation accuracy in the boundary layer can be guaranteed. Compared with the structured grid, the unstructured hybrid grid is suitable for the simulation of the complex configuration of tiltrotor aircraft with its efficiency and flexibility.

2.5. Grid Generation

The TRAM model \cite{26} is sized to be a 1/4 tiltrotor rotorcraft reduction model. The rotor blades are of positive camber thick airfoils. Because the airfoil data of the model can not be found, some approximations are taken here.

![Surface grid of half-span S-TRAM model](image1)

**Figure.1** Surface grid of half-span S-TRAM model

![Slice mesh enlargement](image2)

**Figure.2** Slice mesh enlargement

![Isolated rotor mesh of I-Tiltrotor model](image3)

**Figure.3** Isolated rotor mesh of I-Tiltrotor model

![Isolated airframe mesh of S-TRAM model](image4)

**Figure.4** Isolated airframe mesh of S-TRAM model

There generates two models: S-TRAM model and I-Tiltrotor model. The S-TRAM model contains five parts: wings, fuselage, rotors, tails and engine nacelles. The grids of the two models are generated respectively.

Figure 1 shows the surface mesh of the half-span S-TRAM model. Red mesh is of the zone of the blades, blue one represents the zone of the engine nacelle, and black one represents the major-zone.
The 0.20$c_{\text{tip}}$ is the finest off-body space size and this grid surrounds the blades and extends. The subzone containing rotor blades and that containing the engine nacelle has 4.85 million cells and 0.84 million cells respectively. The other major-zone has 39.37 million cells. Figure 2 is an enlarged view of the overlapping grid sections, showing the mesh size in the interpolated boundary of the three zones is matched. Figure 3 and Figure 4 shows an isolated rotor mesh and an isolated airframe mesh respectively.

3. Test Cases

The numerical simulation ability of the numerical algorithm and grid technology to the forward flight flow field of propeller is examined by this example. The shape parameters of the six blades propeller are defined in reference [27-28], the propeller rotates anticlockwise from the front with the rotating speed $n_r = 1020$ rpm, and the calculated forward ratios $f$ are 0.716, 1.004, 1.292, 1.432 and 1.580 respectively. The parameters for the case are: calculation height $h = 0$ km, calculation angle of attack $\alpha = 0^\circ$, calculation angle of sideslip $\beta = 0^\circ$. The sub-grid containing propeller has 10.18 million cells, including 4.6 million tetrahedral grid cells, 8 million pyramid grid cells and 5.5 million prism grid cells. The major-grid containing shroud has 8 million, among which the numbers of the tetrahedral grid cell, pyramid grid cell and triangular grid cell are 7.03 million, 20 million and 95 million respectively.

Figure 5(a) and (b) show the X-section and Y-section of propeller overlapping grid. Mesh colored red represents the sub-grid of propeller, and mesh colored blue represents the major-grid. The meshes in the interpolated boundary of the two zones and the meshes behind the propeller are refined, and the extrapolated mesh is generated on the interpolated boundary surface.
Figure.5 Slice mesh of the both zones

Figure.6 shows the comparison of the experimental and calculated propeller thrust coefficient and torque coefficient with the propeller advance ratio. The numerical results show a good agreement with the experimental data, and the simulation methods for forward flight are verified well.

(a) Comparison of the thrust coefficient

(b) Comparison of the torque coefficient

Figure.6 Isolated-propeller aerodynamic characteristics

Figure.7 shows the iso-surface of the Q-criterion colored by Mach number, where f=1.292. The spatial vortex caused by rotation of the propeller can be clearly observed because meshes behind the propeller are refined.
4. Tiltrotor Aircraft Conversion Mode

4.1. Flow Field Analysis of Isolated-Rotor

The multigrid method is used to accelerate the computational convergence. The calculation condition for rotor's conversion mode: each time step rotor rotates 2 °, that is, 180 time steps per rotation period. The forward speed is 34m / s and the Mach number of rotor tip is 0.56. The nacelle is fixed at 0 °, 30 °, 60 ° and 90 ° respectively, and the computational grid is the isolated rotor grid of I-Tiltrotor model.

(a) $f = 1.292$

Figure 7 Q-criterion iso-surface of the propeller

(a) Tilting angle: 0°

(b) Tilting angle: 30°
In Figure 8, the iso-surface of the Q-criterion (colored Mach number) of an isolated rotor at a certain time with different tilting angles is shown. Different from the hovering state of the helicopter, the spiral vortex pulled out by the tip of the tilting rotor is not only transported downward by the induced velocity perpendicular to the rotor disk, but also backward by the incoming flow. When the rotor is not tilted, due to the influence of the incoming flow, the tip vortices gather and move backward in a large amount before developing downward at the front and back sides of the rotor. Therefore, the wake structure is composed of the tip vortex which develops spirally downward and linearly downward. After the rotor is tilted further, the flow induced by the rotor is parallel with the incoming flow gradually, and the tip vortex which develop linearly downward in the wake disappears. The wake structure is mainly composed of the backward spiral tip vortex.

Figure 9 Streamline diagram at 0° tilting angle
Figure 10 Streamline diagram at 30° tilting angle

(a) $Y=1.83m$  
(b) $Y=3.3m$

Figure 11 Streamline diagram at 60° tilting angle

(a) $Y=1.83m$  
(b) $Y=3.3m$

Figure 12 Streamline diagram at 90° tilting angle

Figure 9– Figure 12 show the streamline diagram of some certain sections of the rotor at each tilting angle. Section $y = 1.83m$ passes through the center of rotor rotation axis, and section $y = 3.3m$ is the outer end of blade front edge blade disk. It can be clearly seen that the air stream through the rotor in the section $y = 1.83m$ flows downward, while the flow in the outer end of the rotor plate flows upward.
With the increase of the tilting angle of the rotor, the deflection effect of the rotor on the flow decreases gradually.

### 4.2. Flow Field Analysis of Rotor / Airframe

![Spatial streamline diagram of S-TRAM model](image)

Figure 13 Spatial streamline diagram of S-TRAM model

The flow phenomena of the conversion mode of the tiltrotor aircraft is complex. Figure 13 shows the spatial streamline near the rotor of the S-TRAM model. Figure 14 shows the spatial Q-criterion iso-surface of the S-TRAM model in the conversion mode (Q-criteria = 500, colored Mach number). It can be seen from the figure that the rotor causes the streamline distortion, which has obvious downward deflection and acceleration effect on the incoming flow. When the rotor is not tilted, the upper surface of the wing is not impacted vertically by the tip vortex wake pulled by the rotor, but the flat tail and vertical tail is impacted directly; When the rotor is tilted further, the aerodynamic interaction of the rotor wake on the wing / horizontal tail / vertical tail is strengthened.

![Spatial Q-criterion iso-surface of S-TRAM model](image)

(a) Tilting angle: 0°
Figure 14 Q-criterion iso-surface of S-TRAM model

Figure 15 shows the pressure coefficient distribution of the S-TRAM model in different tilt angles. From the figure, we can see that with the increase of the tilting angle, there is an obvious low-pressure area gradually expanding, outside the upper surface of the wing's leading edge, while the low-pressure area inside the upper surface of the wing's leading edge and the horizontal tail gradually reduces gradually. Obviously, the interaction law of the rotor wake on the wing is completely different in the inner side and the outer side of the wing.
4.3. Aerodynamic Performance Analysis of Rotor / Airframe

Figure 16 shows the change of the lift coefficient of S-TRAM model and I-Airframe model with time step. Installed_0° represents the S-TRAM model with the rotor tilting angle of 0°. As shown in figure 18, the aerodynamic performance of the S-TRAM model changes periodically with a period of 1/3 rotation, 120 °. When the tilting angle is 90°, the performance coefficient of the airframe changes most dramatically.

Table 1 shows the aerodynamic coefficient of the airframe components of the I-Airframe model and the S-TRAM model at different tilting angles. The results in the table are the periodical average values. From the helicopter mode to the fixed wing mode, with the increase of the tilting angle (0° ~ 90°), the lift coefficients of horizontal tail and fuselage of the S-TRAM model decrease gradually, but are still larger than those of the horizontal tail and fuselage of the I-Airframe model. It shows that the rotor wake has a positive effect on the lift generation of the fuselage and horizontal tail; The lift coefficient of the wing of the S-TRAM model decreases gradually in the tilting process of 30° ~ 90°, and the lift coefficient of the S-TRAM model is the smallest but still greater than that of the I-Airframe model (0°). The result shows that the rotor wake also has a positive effect on the wing lift, and the law
dominates the change of lift coefficient of the whole airframe, resulting in the increase of lift coefficient of airframe of the S-TRAM model (0° ~ 30°) and then decrease (30° ~ 90°).

![Figure 16](image1)

**Figure 16** Comparison of the thrust coefficient

|                     | horizontal tail | fuselage | wing | airframe |
|---------------------|-----------------|----------|------|----------|
| Installed_0°        | 41.16           | 30.70    | 51.85| 123.71   |
| Installed_30°       | 25.71           | 29.85    | 85.93| 141.49   |
| Installed_60°       | 7.47            | 7.59     | 72.57| 87.63    |
| Installed_90°       | -1.65           | -4.58    | 59.06| 49.83    |
| I-Airframe          | -3.20           | -5.41    | 43.59| 34.98    |

**Table 1** Aerodynamic characteristics of the components (unit: 10^{-5})

![Figure 17](image2)

**Figure 17** Different sections diagram
Figure 17 shows the location of different sections. \( Y = 0.06 \text{m} \) is the section passing through the fuselage, \( Y = 0.6 \text{m} \) is the section passing through the wing and horizontal tail, \( Y = 1.2 \text{m} \) is the section passing through the outside of the wing. \( X = 1.8 \text{m} \) is a section above the leading edge of the wing.

Figure 18 Velocity distribution diagram

Figure 18 shows the velocity in \( Z \) direction and \( X \) direction distribution in front of the leading edge of the wing (the intersection line of \( X = 1.8 \text{m} \) section and \( Z = 1.7 \text{m} \) section). \( Y = 0 \text{m} \) section passes the inside of the fuselage, \( Y = 1.6 \text{m} \) section passes the wing tip. It can be seen that the velocity \( X \) inside the fuselage keeps same basically. the velocity \( Z \) near the fuselage and the wing at 0° and 30° tilting angles match well, also at 60° and 90° tilting angles, but the overall trend is that with the increase of the tilting angle, the up wash effect of the rotor wake on the inside of the fuselage decreases. Therefore, the positive effect of rotor wake on the fuselage lift is the improvement of local angle of attack. From figure 19 showing the streamline and pressure distribution at \( Y = 0.06 \text{m} \) section, the increase of local attack angle of fuselage can be seen more clearly. Figure 22 also shows that the positive effect of rotor wake on the horizontal tail lift is the improvement of local attack angle. With the increase of the tilting angle, the local angle of attack of the airflow at the wing and the horizontal tail decreases gradually. When the tilting angle is 90°, the local angle of attack of the horizontal tail is negative.

(a) I-Airframe

(b) I-Tiltrotor
Figure 19 Streamline diagram at Y=0.06m section

(c) Installed_0°
(d) Installed_30°
(e) Installed_60°
(f) Installed_90°

(a) I-Airframe
(b) I-Tiltrotor
Figure 20: Streamline diagram at Y=0.6m section

(c) Installed_0°
(d) Installed_30°
(e) Installed_60°
(f) Installed_90°

(a) I-Airframe
(b) I-Tiltrotor
Figure 21 is the pressure distribution cloud diagram and streamline diagram at section $Y = 1.2m$. Even when the rotor is not tilted, the downwash flow does not impinge on the upper surface of the wing vertically, which is related to the relative height between the rotor disk and the wing, as well as the downwash flow speed and the incoming flow speed of the rotor. With the increase of the tilting angle, the impact of the downwash flow on the wing is further weakened. Combined with Figure 20, it can be seen that the influence of the rotor on the wing is different at the inner side ($Y = 0.6m$) and the outer side ($Y = 1.2m$). At the inner side of the wing, the airstream through the rotor disk flows up and away from the fuselage surface; At the outer side of the wing, the airstream through the rotor disk flows down and near the fuselage surface, but only when the velocity of the incoming flow is small, the downward flow of the airstream can form a certain impact on the upper surface of the fuselage. Therefore, the law of the influence of rotor wake on the wing is not obtained simply.
Figure 22 History of rotor aerodynamic characteristics

In Figure 22, the unsteady change curve of rotor aerodynamic performance is shown. Isolated_0° refers to the rotor of the I-Tiltrotor model at tilting angle 0°, and Installed_0° refers to the rotor of the S-TRAM model at tilting angle 0°. It can be seen from the figure that the aerodynamic performance changes periodically with a period containing 60 time steps, 1/3 rotation period or 120°. With the increase of the tilting angle, the speed difference of the airstream between the front and back sides of the rotor gradually reduces until the speed is the same, and the amplitude of the aerodynamic cycle change gradually decreases; it can also be seen from the figure that the thrust coefficient and torque coefficient gradually decrease with the increase of the tilting angle. According to the blade element theory, the local angle of attack of the rotor blade decreases due to the rotor's tilt. As the forward flight speed and rotor speed remain unchanged, the lift generated by the rotor blade decreases with the decrease of the angle of attack, so that the thrust coefficient of the rotor decreases. The reduction of the torque coefficient is also related to the reduction of the lift coefficient of the rotor blade. Table 2 shows the comparison of rotor aerodynamic coefficients. In the table, "Isolated rotor" is the isolated rotor, and "Installed rotor" is the rotor of the S-TRAM model. Compared with the isolated rotor, the thrust coefficient and torque coefficient of the rotor of the S-TRAM model increases slightly by 0 ~ 5% during the tilting process.

Table 2 Comparison of rotor aerodynamic characteristics (unit: 10⁻⁵)

| Tilting angle | CT | Isolated rotor | Calculated value | Installed rotor | Calculated value | relative value (%) | CQ | Isolated rotor | Calculated value | Installed rotor | Calculated value | relative value (%) |
|--------------|----|----------------|------------------|----------------|-----------------|-------------------|----|----------------|-----------------|----------------|-----------------|-------------------|
| 0°           | CT | 1517.81        | 1533.49          | 101.03         | 203.49          | 210.98            | 103.20 |                |                  |                 |                  |                   |
| 30°          |    | 953.79         | 1005.30          | 105.40         | 188.42          | 194.83            | 103.40 |                |                  |                 |                  |                   |
| 60°          |    | 476.72         | 482.54           | 101.22         | 147.19          | 147.70            | 100.35 |                |                  |                 |                  |                   |
| 90°          |    | 254.67         | 258.6            | 101.54         | 118.43          | 118.66            | 100.19 |                |                  |                 |                  |                   |

5. Conclusion

In this paper, the numerical simulation of the S-TRAM model of the tiltrotor aircraft is completed. The following conclusions can be obtained:

- The airstream through the rotor in the center section of the isolated rotor flows backward and downward, while the airstream through the rotor at the outer end of the rotor flows backward and upward. With the increase of the tilting angle, the deflection effect of the rotor on the airstream decreases gradually.
At a fixed tilting angle, the aerodynamic performance of the airframe changes periodically. When the tilt angle is 90°, the lift coefficient of the airframe changes most dramatically, and the rotor wake has a strong unsteady aerodynamic interaction on the airframe.

- The interaction law of rotor wake on wing is totally different in the inner side and the outer side of wing. At the inner side of the wing, the airstream through the rotor flows up and away from the fuselage surface; At the outer side of the wing, the airstream through the rotor flows down and near the fuselage surface.

- The rotor wake increases the local angle of attack of the fuselage and the horizontal tail. With the increase of the tilting angle, the lift coefficients of the horizontal tail and the fuselage of the S-TRAM model decrease gradually, but are still larger than the lift coefficients of the horizontal tail and the fuselage of the I-Airframe model.

- The existence of fuselage / wing improves the thrust coefficient and torque coefficient of rotor. Compared with the isolated rotor, the thrust coefficient and torque coefficient of the rotor of the S-TRAM model increases slightly by 0 ~ 5% during the tilting process. The thrust coefficient and torque coefficient of the rotor decrease with the increase of the tilting angle.

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