Detection method of wash angle caused by wingtip vortex for formation flight

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Abstract. The largest civil aviation aircraft in operation, Boeing 787 and A380, have very strong wingtip eddies. Wingtip eddy currents generally have many adverse effects on the aircraft in its range of influence. The influence of tip eddy current will cause different wash angles in different areas after the aircraft. The purpose of this method is to obtain the wash angle at different positions by using the calculated data. The wash angle obtained has important reference significance for the wash correction and risk assessment of aircraft flying in the tip swirl region.

1. Introduction

"Tip Vortex" is also known as the wingtip vortices. Generally, the airplane's wing surface is based on Bernoulli principle, which makes the fluid flowing through the upper surface flow faster and has lower pressure, thus generating upward lift. The pressure on the lower wing surface is higher than that on the upper wing surface. Under the effect of the pressure difference between the upper and lower wing surfaces, the airflow on the lower wing surface flows around the tip of the wing to the upper wing surface, so that the streamline on the lower wing surface inclines from the wing root to the wing tip, while the streamline on the upper wing surface deflects from the wing tip to the wing root, but when it reaches the tip of the wing surface, there is no separation between the upper and lower wing surfaces, so that the high-pressure airflow follows the wing [1-5]. The tip-up rolling flow to the upper side of the lower pressure wing surface, coupled with the original flow to the rear, forms a spiral eddy motion, and the tip eddy is thus generated. As shown in Figure 1.

![Figure 1. Schematic diagram of washing effect.](image-url)
Because the tip eddy current comes from the difference of pressure and velocity between the lower and the upper airflow of the wing, and the pressure difference between the upper and lower airflow is the source of lift on the wing, the strength of the tip eddy current is proportional to the lift provided by the wing [6, 7]. The lift provided by the wing must be at least the weight of the aircraft, so that the aircraft can fly, so generally speaking, the larger the aircraft, the stronger the tip eddy current. At present, the largest civil aviation aircraft in operation, Boeing 787 and A380, have very strong wingtip eddies [8].

Wingtip eddy currents generally have many adverse effects on the aircraft in its range of influence. First, it affects flight safety. In the process of forward flight, the aircraft will also pull out strong wingtip eddies behind the left and right wingtips. This pair of strong vortices will strongly induce the velocity of the surrounding flow field, and the strength of the vortices is proportional to the weight of the aircraft. Large transport aircraft has a large weight and a strong wake. Its wingtip vortices can extend several kilometers behind the aircraft [9-12]. The tangential velocity component of the vortices will not disappear until 6 to 8 minutes after the formation of the vortices. Because the speed and direction of air in the swirl region change dramatically, small aircraft entering this region will flutter, sink, change the flight state, engine stop or even turn over, and even lead to flight accidents. Especially during takeoff and landing, the tip wake of the front aircraft will directly endanger the safety of the rear aircraft.

The purpose of this paper is to obtain the wash angle at different positions by using the calculated data. The wash angle obtained has important reference significance for the wash correction and risk assessment of aircraft flying in the wing tip vortex region.

2. Numerical method and strategy

2.1. CFD solver

For the three-dimensional unsteady turbulent flow, the main governing equation is the three-dimensional unsteady Reynolds mean NS equation. The optimization calculation emphasizes the accuracy and stability of the aerodynamic characteristic difference calculation after the shape change. It requires the high precision numerical calculations, the fine mesh and the accurate turbulence model [13]. The code used in this study was an in house code and the detail of this code can be found in reference [14, 15].

For formation flying, Navier-Stokes equation of three-dimensional unsteady viscous flow can be used as the governing equation to describe its physical phenomena, which can be written in Cartesian coordinates as follows:

$$\frac{\partial Q}{\partial t} + \left( \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} \right) = 0$$

$$Q = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ e \end{bmatrix}, \quad E = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho v \nu \omega \\ \rho v w \\ (e + p)u \end{bmatrix}, \quad F = \begin{bmatrix} \rho v \\ \rho v u \\ \rho v^2 + p \\ \rho v \nu \omega \\ (e + p)v \end{bmatrix}, \quad G = \begin{bmatrix} \rho w \\ \rho w u \\ \rho w v \\ \rho w^2 + p \\ (e + p)w \end{bmatrix}$$

$$e = \frac{p}{\gamma - 1} + \frac{1}{2} \rho \left( u^2 + v^2 + w^2 \right)$$

here:

In the formula, $\rho$ is the density of the flow field, $p$ is the pressure of the flow field, $T$ the temperature of the flow field, $u$ is the velocity component in the X direction, $v$ is the velocity component in the Y direction and $w$ is the velocity component in the Z direction $\mu$ is the dynamic viscous coefficient.
In order to consider the turbulence effect, a turbulence model $k-\omega$ SST (shear stress transport) is further adopted. The model can simulate large separated flows and has good model stability. It is a commonly used turbulence model in engineering operations. The dimensionless $k-\omega$ SST model equation is given directly below [16]. Compressible modification has been added to the equation in the form of:

$$
\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho u_i k) = \frac{\partial}{\partial x_i} \left[ \left( \frac{\mu + \mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + C_{t1} \frac{\partial P}{\partial x_i} - C_{t2} \rho k \omega
$$

$$
\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho u_i \omega) = \frac{\partial}{\partial x_i} \left[ \left( \frac{\mu + \mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_i} \right] + C_{\omega1} \frac{\partial P}{\partial x_i} - C_{\omega2} \rho k \omega^2
$$

Here: $\mu_t = C_{\mu} \frac{\rho k}{\omega}$

In the formula, $k$ is the turbulent kinetic energy and $\omega$ is the vorticity of the fluctuating velocity, and the model parameters are usually taken as follows:

$\sigma_k = 2.0$, $\sigma_\omega = 1.4$, $C_{t1} = 1.0$, $C_{t2} = 0.09$, $C_{\omega1} = 0.555$, $C_{\omega2} = 0.83$, $C_{\mu} = 0.09$

The corresponding far-field boundary conditions are given by giving the velocity, pressure and density of the incoming flow. For the wall, the non-slip boundary conditions are adopted. The governing equations (1) and (2) constitute the governing equations for simulating the whole turbulent flow. With the corresponding boundary conditions, the governing equations can be solved numerically. For the flow governing equations and boundary conditions, the finite volume method is used to solve them numerically. The first term in equation (1) (2), i.e., the unsteady time derivative term, is treated by a two-time step method, in which the real time derivative is discretized by a three-level second-order accurate TLFI (Three Layer Fully Implicit) scheme and is advanced in the virtual time step. The implicit LU-SGS approximation method is used in the calculation. Roe's flux difference method is used to discretize the space convection term in the governing equation, while the central scheme is used to discretize the viscous term. After convergence of flow field calculation, aerodynamic forces and moments can be obtained by surface integration of the winch.

2.2. Grid updating method for formation flight

Formation flying involves the relative motion of complex shapes. Parametric modeling is difficult. It not only needs to satisfy large-scale shape adjustment, but also needs to maintain good consistency and grid viscous characteristics before and after deformation. Otherwise, it will lead to large numerical error. The small number of modeling parameters cannot satisfy the smooth transition between the control point and the overall shape of the profile, while the large number of modeling parameters leads to inefficient optimization calculation, and the grid intersection affects the optimization calculation. Therefore, reasonable parametric modeling technology should minimize the number of modeling parameter points on the premise of ensuring smooth and stable shape transition.

According to the displacement, the mesh is updated by the over-limit interpolation method. Transfinite Interpolation (TFI) is a TFI interpolation method based on arc length. This method can effectively avoid the grid distortion caused by non-uniform distribution of edge grids, and obtain better grid quality.

Structure grid was used in this study, the total grid point is about 10 million, the grids of formation flight were showed in Figure 2.
2.3. Establishment of aerodynamic response model

Based on the flow field data, the first aerodynamic force and the first moment, the numerical response surface model of the aerodynamic coefficients of the winch is established by using the Kriging method [14, 15].

Specifically, the proxy model of each objective function (where lift-drag ratio and lift coefficient, drag coefficient, lateral force coefficient, pitch moment, yaw moment and roll moment are selected as objective functions) is established by using the calculated data of all sample points (flow field data, first aerodynamic force and first moment). Here, the Kriging method is used to establish the numerical response surface model. Type F_{CFD, prediction}.

Kriging method is an interpolation method which predicts the response of unknown points by known points and their response values. It generally has the following forms:

\[ Y(x) = F^T(x) \beta + Z(x) \]  

(3)

3. Application and verification

The compare study was conducted between CFD and experiment, Figure 3 show the comparison between CFD and Experiment for lift coefficient, the results compared well and it can provide a good proof of the correctness of the calculation result.

![Figure 3. Comparison between CFD and experiment. (lift force coefficient)](image)

Figure 2. Grids of formation flight: a) original grids, b) altered grids.
The wash angle was evaluated for the two-plane formation flight of the upper single-wing transport aircraft. Firstly, the single machine numerical calculation of the bureaucracy is carried out, $C_L - \alpha$ and $C_D - \alpha$ the curves are obtained. Through linear fitting, the results are as follows:

$$C_L = 0.1684 + 0.1144\alpha$$

$C_D$ was obtained by third-order fitting.

$$C_D = 0.0235 + 0.0006\alpha + 0.00003\alpha^2 + 0.0003\alpha^3$$

In the range of flow direction 1.5b-5.0b, spread direction -0.35b-0.25b and normal direction -0.25b-0.25b, the position parameters are experimentally designed to obtain n groups of sample points of formation position, where n takes 200 DOE (design of experiment) points for kriging surrogate model. Figure 4 shows a Typical Flow field structure at formation flight.

The aerodynamic force $C_{L1} - C_{D1}$ was obtained by numerical calculation at 200 different locations. The Kriging response surface model with different formation parameters is constructed by variable group $(x_i, y_i, z_i)$ and function, and the Kriging response surface model with different formation parameters is constructed by variable group $(x_i, y_i, z_i)$ and function. Figure 5 show the Vortex-induced force and moment coefficients.

![Figure 4. A typical flow field structure at formation flight.](image)

- a) Vortex-induced lift coefficient
- b) Vortex-induced drag coefficient

![Figure 5. Vortex-induced force and moment coefficients.](image)
The formation space is meshed, the lifting force of each grid point is predicted by Kriging response surface model, and the resistance of each grid point is predicted by Kriging response surface model. Using lift and drag equivalent wash angles for each grid point, respectively. Figure 6 and Figure 7 give the wash angle of flow cross section respectively. The wash angle predicted by the two equations is basically the same.

4. Conclusions
In this paper, CFD and surrogate model are used to accurately obtain the wash angles of different flow directions and cross sections during formation flying. The wash angle obtained by drag coefficient and lift coefficient is in good agreement, which proves the correctness and high accuracy of this method. The wash angle obtained has important reference significance for the wash correction and risk assessment of aircraft flying in the tip swirl region.

![Figure 6. Up washing angle of longitudinal section of formation flight solved by drag coefficient.](image)

![Figure 7. Up washing angle of longitudinal section of formation flight solved by lift coefficient.](image)

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