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Aerodynamic Coefficient Response of Receiver during Aerial Refueling Process

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Abstract

While aerial refueling, the flow field of a receiver changes significantly compared with free stream because of tanker's wake vortex. This paper discusses the results of CFD simulation with and without jets spouting out of the tanker's aero-engines. The result indicates that aerodynamic derivative remains while the aerodynamic coefficient changes significantly particularly the drag coefficient and the jets have little effect.

Keywords: Aerial Refueling, Wake Vortex, Aerodynamic Coefficient, Aerodynamic Derivative, Angle of Attack

1. General Introduction

Aerial refueling is an important function for a receiver to improve its flight performance, such as flight range and cruise duration. According to ATP-56(B), there are usually five steps during a complete aerial refueling tasks, one of which is docking process. During the docking process, especially after establishing the visual connection with its tanker, receiver's aerodynamic characteristics are influenced and changed a lot because of the trailing vortex behind the tanker. It can be identified as level 1 risk subjects and it's a difficult and dangerous task for pilots. So their knowledge and skills of this process will directly affect the flight safety and the success rate of aerial refueling task.

The aerodynamic characteristics of docking process and the flow field of tanker have been well documented. In Ref[1], the KC-135 aircraft flow-field is generated by a vortex lattice code and integrated into a sensorcraft model to get the dynamic response of HALE aircraft to KC-135 flow field. Ref[2] studies the flow field in particular the downwash from aerial refueling flight test between KC-135 and Learjet 25 aircraft. The results show that during the docking process, the downwash was about 3-4 m/s. Ref[3] builds the tanker's flow field using stream function with various types of singularities and gets lift, drag and pitch moment coefficient of both tanker and receiver. Comparison with CFD results showed that this approaches were inadequate for drag coefficient. Ref[4] studies the flow field of KC-135 aircraft using CFD simulation and compared it with theory, vortex lattice results and wind tunnel data, results shows that Euler calculations should be sufficient to capture the trailing vortex behind the wing using a fine mesh out into the far field. In Ref[5], an three degrees aerodynamic model is build –only drag, lift and lateral forces are included. The drag coefficient is the quadratic function of angle of attack, elevator deflection and horizontal tail deflection. The lift coefficient is the linear function of dynamic derivative, elevator deflection and horizontal tail deflection, the quadratic function of angle of attack. The lateral coefficient is the linear function of sideslip angle, rudder deflection and aileron deflection. Ref[6] uses stream function to obtain the flow field around the receiver to reduce the amount of calculation. Ref[7] calculates the flow field using URANS method with SA one equation turbulence model. Ref[8] gives a tanker's flow filed wind tunnel data. Ref[9] considers a downwash angle distribution and additional roll moment to model the effect of tanker. In Ref[10] an experiment is carried out in FL-26 wind tunnel. The main conclusions are as follows, because of the wake vortex, the lift coefficient decreases, the pitch moment coefficient increases, and the drag coefficient has no clear law while the angle of attack is before stall point. And if the receiver is not exactly located in the centerline, because of the asymmetric flow field, the side force, the roll moment and the yawing moment have significant offsets.

In this paper, CFD simulations are carried out to get aerodynamic coefficient especially drag coefficient responding to a certain receiver with a centerline drogue.

2. Aerial Refueling Modeling

The solver is MFlow developed by CARDC. It solves the non-dimensional three-dimensional Reynolds Averaged Navier-Stokes Equation in conservation form. S-A and SST models are employed to evaluate their effects on this problem. Implicit LU-SGS and Roe scheme are used for equation dispersion. Multi block mesh is adopted to ensure the consistence of mesh. Non-structural grid is adopted in the tanker block, receiver block and the far field block, while the structural grid is adopted in the inter block so this area is fine enough to capture the trailing vortex as Ref[4]. Simulation reliability verification is studied so the proper number of grids for this problem is about 50 million.

While modeling the different attack of angle, the positions of the probe head and drogue are unchanged.

3. Simulation Verification

3.1 Free stream downwash

According to Ref[11] and Ref[12], a common way to acquire the average downwash angle of wing is Effectiveness of Horizontal Wing. The principle behind it is shown in Figure 1,-for a symmetric horizontal wing, when the local angle of attack is equal to its installation angle, the lift and pitch of it is zero. Thus,

$$\varepsilon = \varepsilon_0 + \alpha \cdot \varepsilon_\alpha \qquad (1)$$

where ε is downwash angle, ε_0 and ε_α is defined in Figure 2.

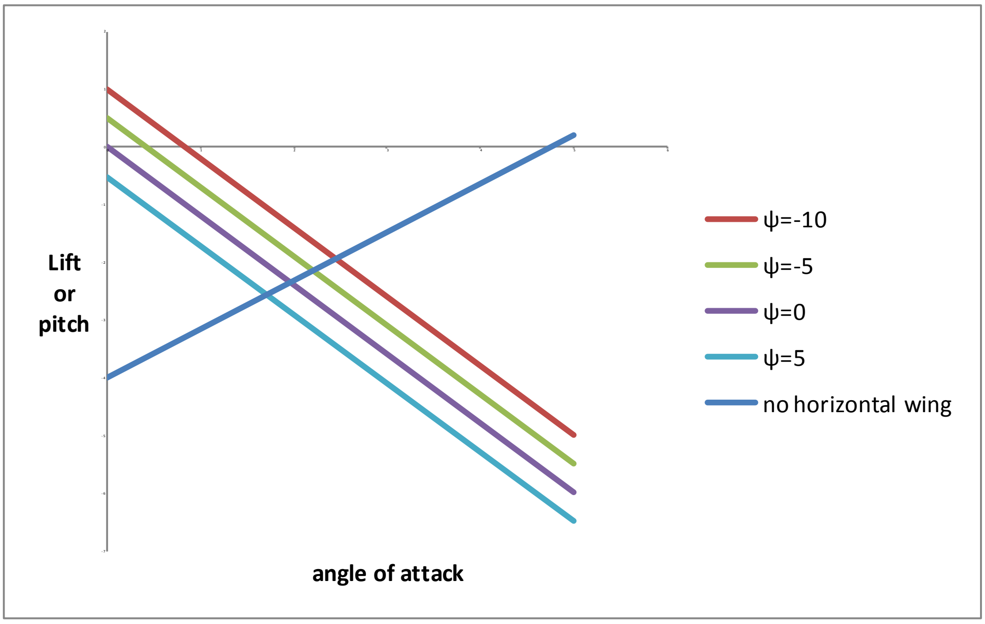

Figure 1 – Principle of Effectiveness of Horizontal Wing

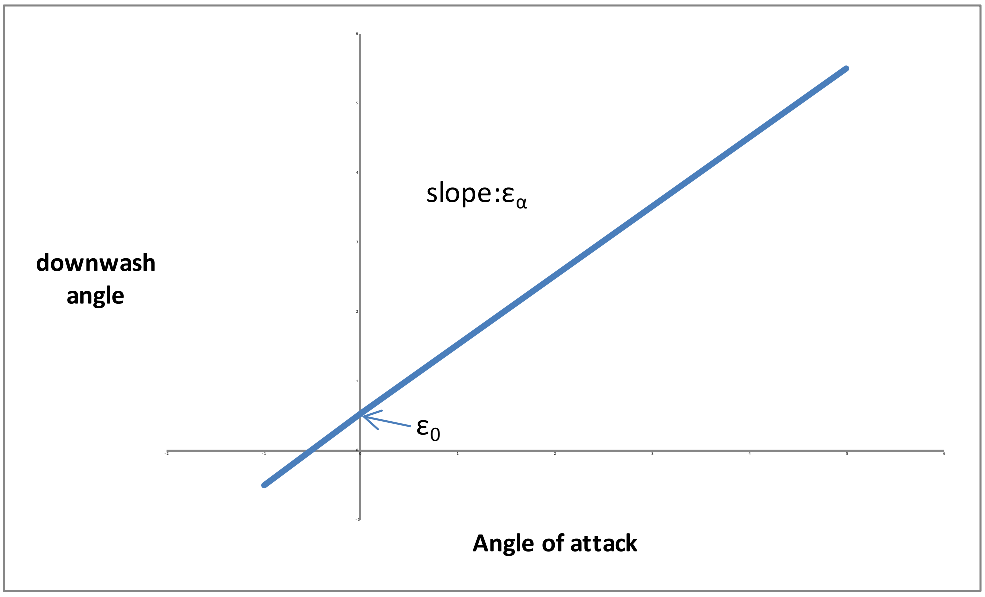

Figure 2 – Define ofε_0 and ε_α

The result shows that ε_α is accurate enough, while ε_0 is 0.2 degrees higher than the wind tunnel result.

3.2 Free stream aerodynamic coefficient

The aerodynamic coefficient of a certain plane in free stream is compared to flight test data, shown in Figure 3 and Figure 4. The results showing here and below are all unified by certain numbers. For elastic deformation is not considered here, differences are clear in higher angle of attack or non-linear part. Considering at real situation, it’s not the part in use. And in this paper, only qualitative conclusion matters, so the results are accurate enough.

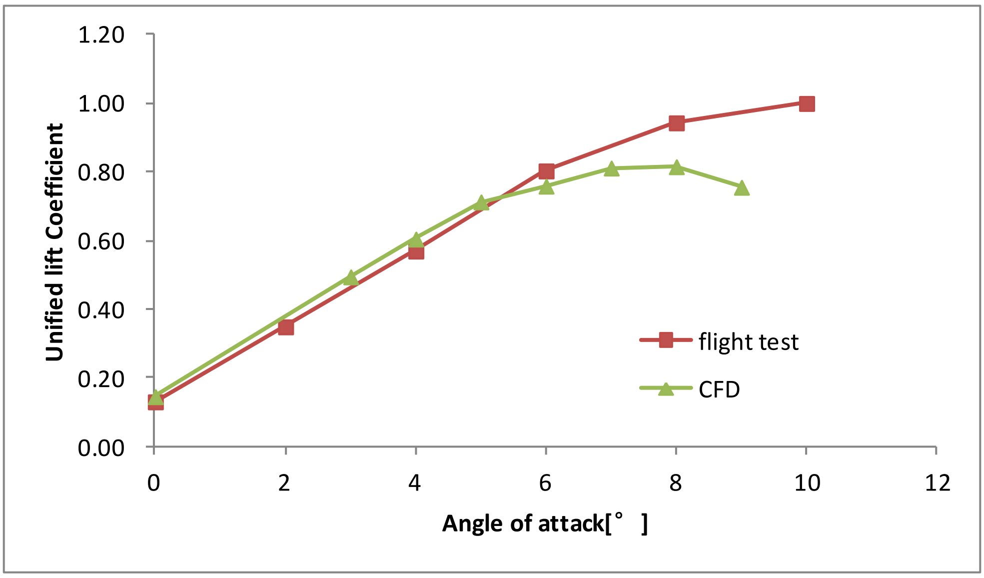

Figure 3 – Unified lift coefficient calculation results compared to flight test data

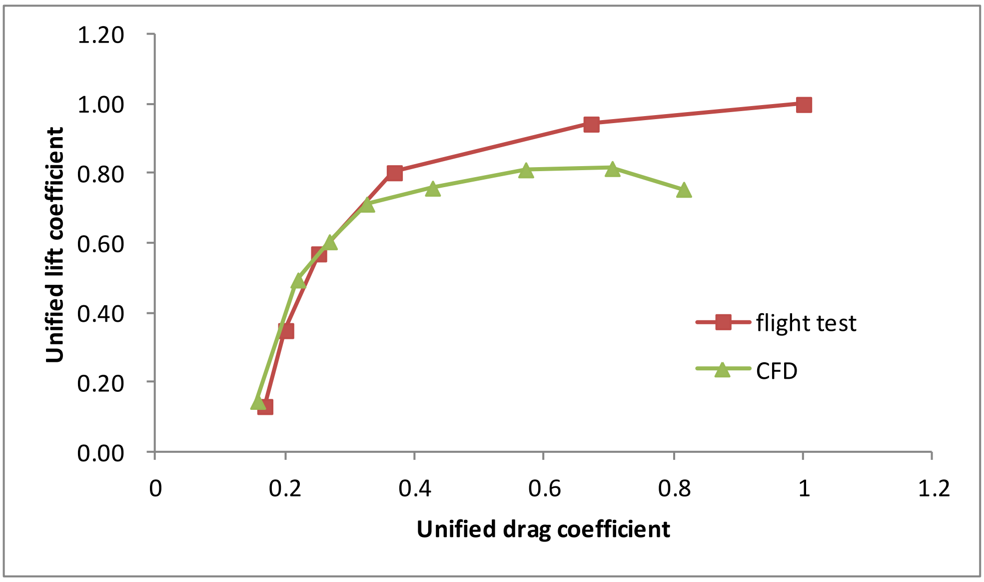

Figure 4 – Unified lift coefficient calculation results compared to flight test data

4. Simulation Results

The results, as shown in Figure 5, Figure 6 and Figure 7, are in accordance with the experiment results of Ref[10]. The horizontal axis of Figure 5 and Figure 6 is nominal angle of attack, which is the angle between flow direction from the far-field boundary and the body axis of receiver. The affect of downwash of the tanker is included here. The difference of the intercept between free stream and aerial refueling line in Figure 5 is about 1.2 degree which is mostly the downwash. Figure 8 shows a slice contour of downwash which gives a similar data. The receiver is at the exact position where the local downwash is between 1 to 3.5 degree.

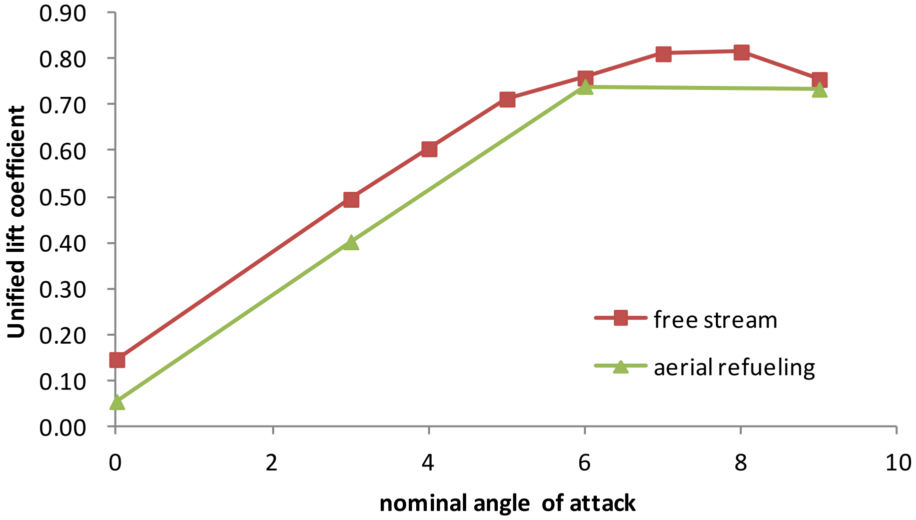

Figure 5 – Wake vortex effects on lift coefficient

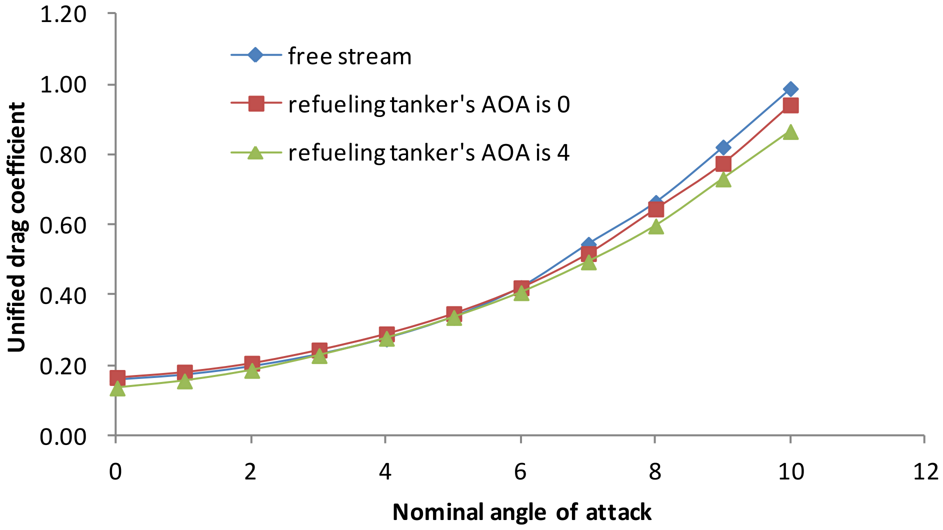

Figure 6 – Wake vortex effects on drag coefficient

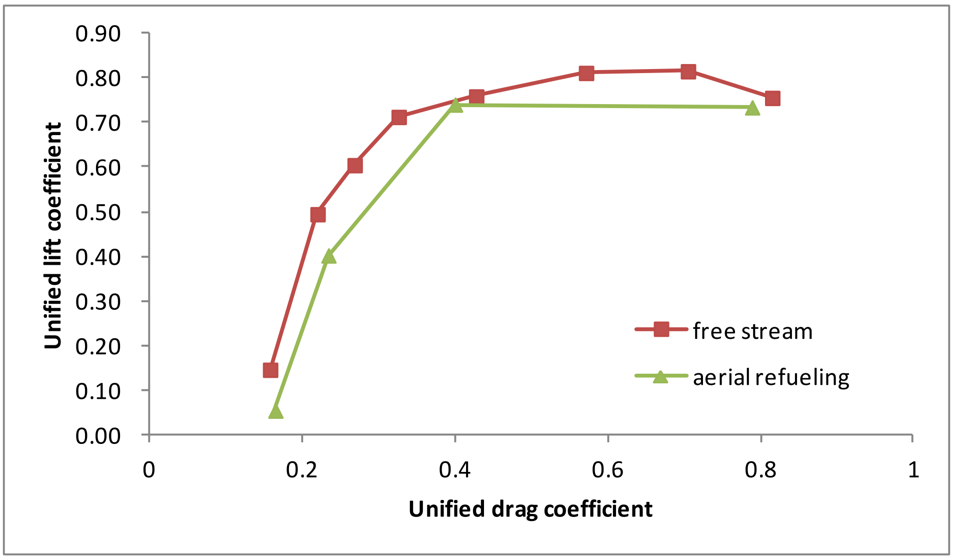

Figure 7 – Wake vortex effects on drag coefficient

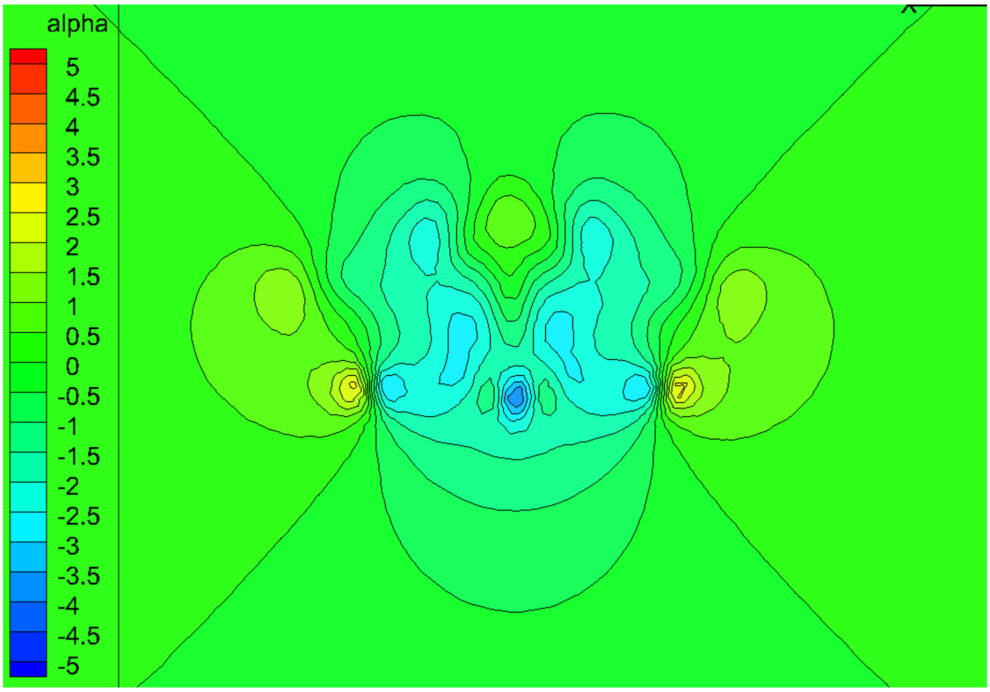

Figure 8 – Downwash of the tanker

As shown in Figure 6, in the minor nominal angle of attack, the drag coefficient has no clear changing law. In the large nominal angle of attack, mostly after buffeting, the drag coefficient decreases significantly. Figure 9 gives a possible theory to explain this. The downwash of the tanker tends to decrease the drag coefficient, while the non-uniform wake vortex of the tanker tends to increase the drag coefficient. The drag coefficient is the quadratic function of angle of attack.

$$
\begin{aligned}
C_D=f(\alpha,\alpha^2,\ldots) &= C_{D0}+C_{D\alpha}(\alpha_{norm}-\varepsilon)+C_{D\alpha 2}(\alpha_{norm}-\varepsilon)^2+\ldots \\
&= C_{D0}+C_{D\alpha}(\alpha_{norm}-\varepsilon)+C_{D\alpha 2}\bullet\alpha_{norm}^2-2C_{D\alpha 2}\bullet\alpha_{norm}\bullet\varepsilon+C_{D\alpha 2}\bullet\varepsilon^2+\ldots \qquad (2)
\end{aligned}
$$

According to Figure 5 and Figure 8, the effective downwash remains nearly constant despite the change of nominal angle of attack. So the term $-2C_{D\alpha 2}\bullet\alpha_{norm}\bullet\varepsilon$ has larger effect in the large nominal angle of attack than the minor nominal angle of attack. And the slightly change of relative position due to the attack of angle can be neglected. So, in minor nominal angle of attack, the drag is affected both at relatively same scale, but in large nominal angle of attack, it is affected mostly by the downwash.

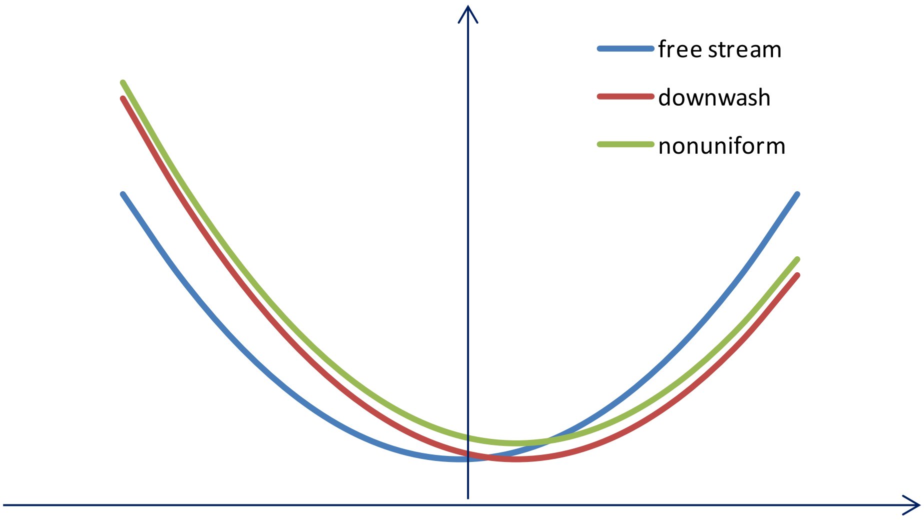

Figure 9 – Theory of wake vortex effects on drag coefficient

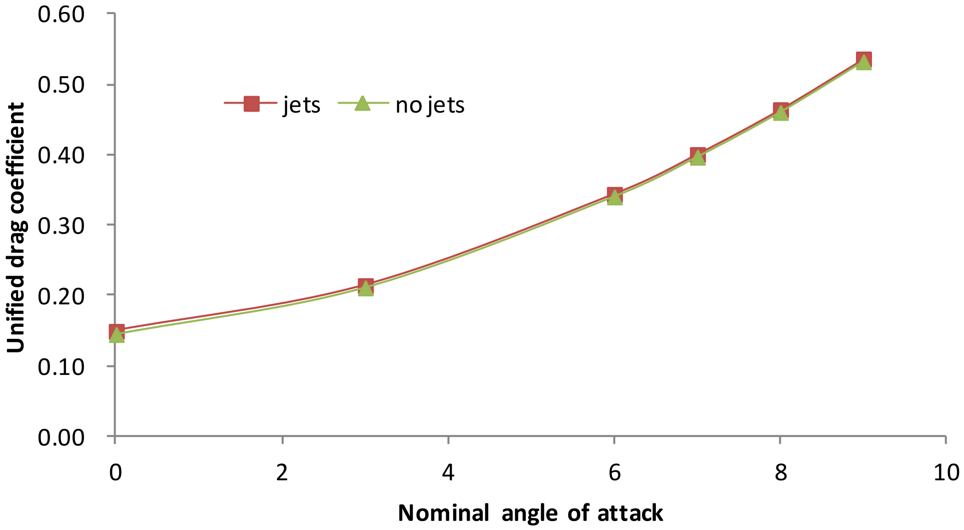

Figure 10 – Jets effects on drag coefficient

Figure 10 shows the effects of jets spouting out of the tanker's aero-engines. The jets diffuse completely not far from its nozzle and hardly affect the downwash distribution. So jets will not affect receiver's aerodynamic characteristics even if the receiver is at the closest distance from the tanker in the whole air refueling process.

Important components aerodynamic characteristics are shown in Figure 11 and Figure 12. Figure 11 is a comparison result of a typical flight condition whose nominal angle of attack is 3. It indicates that the drag coefficients of the fuselage, horizontal tail, vertical tail and engine nacelle components decrease while the drag coefficients of wing components increase because of the wake vortex. As shown in Figure 8, the downwash is larger in the centre which is near the receiver's fuselage, horizontal tail, vertical tail and engine nacelle components than the two sides which are near the receiver's wings. This is consistent with the theory above.

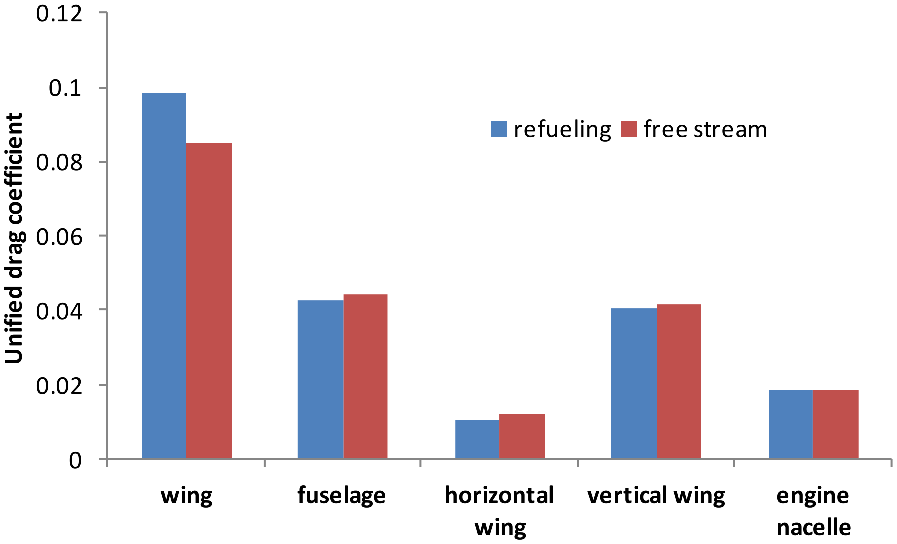

Figure 11 – Unified drag coefficient comparison with and without tanker

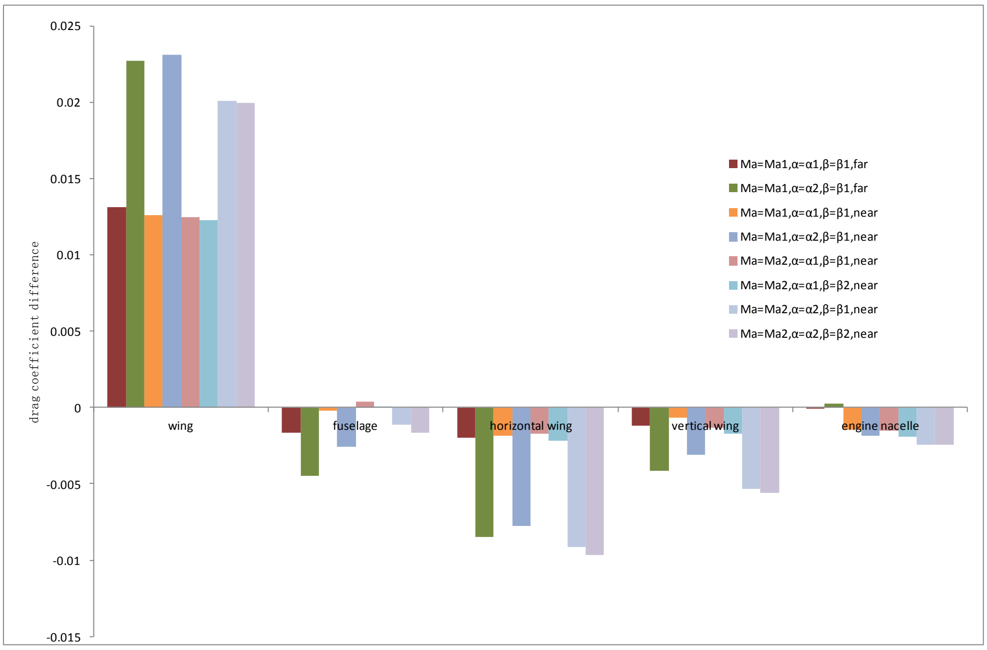

Figure 12 – Unified drag coefficient difference

Figure 12 shows unified drag coefficient differences of main components in other flying conditions. Influencing factors like flight velocity, tanker’s angle of attack, tanker’s sideslip angle, relative positions are all considered here. Positive value means the drag coefficient increase. The following rules can be concluded

1）With the increase of tanker’s angle of attack, drag coefficient difference of wing components increases, and which of other components decrease. This can be explained by the downwash and non uniform theory as well. While the tanker’s angle of attack is large, it mostly affects the wingtip vortex strength instead of the rear section. Thus the wing component is affected mostly.

2）Flight velocity, tanker’s sideslip angle and relative positions do not affect drag coefficient difference. This may because the distance is relatively small and the wake vortex strength remains the same yet.

5. Conclusion

CFD simulation models are built to acquire the aerodynamic coefficients of receiver and the flow field of tanker. The effect of tanker’s angle of attack, sideslip angle, flight velocity, relative position, and receiver’s nominal angle of attack are all considered. The lift coefficient decreases a lot due to the downwash, while the drag coefficient has no clear changing law because of the combined effect of downwash and non uniform of tanker’s wake vortex. The tanker’s jets hardly affect the receiver for it diffuses not far from its nozzle.

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