Numerical analysis and improvement of longitudinal moment pitch-up characteristics for civil aircraft

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Abstract. The longitudinal moment pitch-up ahead of the stall angle can decrease the available range of maximum lift coefficient. It has a major influence on take-off and landing performance, and safety of a civil aircraft. Numerical simulation by CFD (Computational Fluid Dynamics) is used to study the longitudinal moment characteristics of a civil aircraft with landing configuration in this paper. Combined with the flowfield post-processing interpolation technology, the reason of longitudinal moment pitch-up is analysed and discussed. According to the research results, the characteristics of longitudinal moment pitch-up are further improved by modification. The relevant research methods and results have some guiding significance for improving the moment characteristics of a civil aircraft.

1. Introduction
The longitudinal moment characteristics of a civil aircraft are important factors to evaluate the aerodynamic performance and handling quality of a civil aircraft. Many civil aircrafts have encountered the problem of longitudinal moment pitch-up ahead of the stall angle in the finalization design stage¹-⁷. The longitudinal moment pitch-up ahead of the stall angle can decrease the available range of maximum lift coefficient. It has a major influence on take-off and landing performance, and safety of a civil aircraft. When a typical large civil transport aircraft with twin-engine is landing at a fixed approach speed, the maximum lift increment of 1% can be converted into the equivalent of carrying 22 passengers or nearly 2000 kg of cargo⁸. For a civil aircraft, better longitudinal moment characteristics should be that the longitudinal moment does not appear pitch-up or the pitch-up occurs after the maximum lift coefficient⁹-¹⁰. A civil transport aircraft with better longitudinal moment characteristics can make good use of maximum lift and have better take-off and landing performance, and great economic value.

Wang et al. studied the pitching moment (i.e. longitudinal moment) characteristics of civil aircraft by low-speed and high Reynolds number wind tunnel test, and considered that the wake flow from the wing, engine room and pylon passing the horizontal tail can decrease the local dynamic pressure of horizontal tail, then the contribution of horizontal tail to longitudinal moment of whole aircraft is reduced¹⁰. Zhou et al. studied the wake flow of the wing and longitudinal moment characteristic by means of wind tunnel test and numerical simulation, and concluded that the loss of the dynamic pressure of horizontal tail is severe near the critical angle of attack, then reduces the aerodynamic efficiency of horizontal tail and causes the pitch-up of longitudinal moment of whole aircraft¹¹. Liu et al. studied the stall characteristics of a civil aircraft with landing configuration by numerical calculation method, and considered that the nonlinear phenomenon of pitching moment curve of horizontal tail is due to the
decrease of energy of local incoming flow near the root region of horizontal tail\cite{12}. Varun et al. studied the local flowfield of horizontal tail by numerical simulation method, and the results showed that the complex vortex from wing and engine room pylon affected the contribution of horizontal tail to the longitudinal moment of whole aircraft\cite{13}.

However, due to the limitation of technical methods such as the measurement of flowfield, the above wind tunnel tests and numerical calculations by CFD have not carried out further in-depth study on the flow details. The reason of longitudinal moment pitch-up is not clear to form unified understanding, and more detailed flow information and data need to be further explored. In this paper, the numerical simulation by CFD is used to study the longitudinal moment characteristics of a civil aircraft with landing configuration. Combined with the post-processing interpolation technology of flowfield, the reason of longitudinal moment pitch up is analysed and discussed. Then, the characteristics of longitudinal moment pitch-up are improved.

2. Numerical calculation method

2.1. Numerical method

A self-developed flow solver named PMB3D2.0 which is a large-scale parallel CFD program based on multi block structured grids including overlapping grid is used in this paper. PMB3D2.0 is suitable for the computation of subsonic, transonic and supersonic flows past the aircrafts, and has been widely used in some aerospace engineering projects. The governing equations are compressible Navier-Stokes equations in general curvilinear coordinate, which can be written as:

\[
\frac{\partial \tilde{Q}}{\partial \tau} + \frac{\partial \tilde{E}}{\partial \xi} + \frac{\partial \tilde{F}}{\partial \eta} + \frac{\partial \tilde{G}}{\partial \zeta} = NVIS \times \left( \frac{\partial \tilde{F}}{\partial \xi} + \frac{\partial \tilde{G}}{\partial \eta} + \frac{\partial \tilde{H}}{\partial \zeta} \right)
\]

The governing equations are discretized by finite volume method. LU-SGS which is an implicit time marching method is used to discretize the equations. ROE which is a flux difference splitting scheme with second order upwind is used for spatial discretization. In this paper, SA turbulence model is used due to less computation and better robustness. Low speed pre-processing technology\cite{14} and multi-grid technology\cite{15} are used to improve the convergence speed of the flowfield for civil aircraft.

2.2. Verification of numerical method

In order to verify the reliability of numerical method, a standard model of trapezoidal wing is selected as verification example\cite{16-17}. The model has rich experimental data and is used for the verification and validation of many CFD softwares\cite{18-19}. The deflection angles of the leading-edge slat and the trailing-edge flap are 30° and 25° respectively. The model is a typical landing configuration. The calculation grid shown in Figure 1 is overlapping grid. Figure 2 shows the aerodynamic coefficient of computation vs. experimental results under the condition of Ma=0.15 and Re=1.5\times10^7. The comparison results show that the lift coefficient and pitching moment coefficient calculated by CFD are in good agreement with experimental results. The calculated curve can reflect the change trend of lift and pitching moment with the angle of attack. This verification example suggests the numerical method and grid generation strategy are reasonable and credible, which can meet research needs of this paper.

Figure 1. Overlapping grid of transport aircraft with typical landing configuration
2.3. **Post-processing interpolation technology of flowfield**

In order to analyze the flow characteristics at any point in the flowfield and get surface load for convenience, a post-processing interpolation technology is established. The interpolation method of flowfield adopts the adaptive binary tree method to locate the interpolation points\(^{[20]}\), in order to improve the retrieval efficiency. After the interpolation points are located, the flowfield variables are obtained by the following tri-linear interpolation relationship which can be written as:

\[
\phi = a_1 + a_2 \xi + a_3 \eta + a_4 \zeta + a_5 \xi \eta + a_6 \xi \zeta + a_7 \eta \zeta + a_8 \xi \eta \zeta
\]

Where \(0 < \xi < 1, 0 < \eta < 1, 0 < \zeta < 1\). \(a_i - a_8\) depend on the coefficient of flow parameters at 8 vertices of the cube.

3. **Calculation model and grid**

The object of this paper is a civil transport aircraft with landing configuration, which is named model A in this paper, and the specific geometry is shown in the Figure 3 (a). The configuration with three-stage high-lift-device is complex, including the engine nacelle, vortex generator, vertical and horizontal tails, flap slide cabin and other parts. Overlapping grid technology is adopted to generate the structural grid conveniently\(^{[21]}\). The overlapping grid is composed by a background grid which is generated for the fuselage, main wing, vertical and horizontal tails et al. and two sub-grids which are generated for the leading-edge slats and the trailing-edge flaps. In the region with large variation of flow parameters, such as the area of wake flow of wing, local mesh refinement is carried out. The attached layer grid is O-type grid, the height of the first layer grid is about 0.02mm, and the growth rate of O-type grid is about 1.2. The computational grid scale is nearly 30 million.

![Figure 2. The aerodynamic coefficient of computation vs. experimental results](image1)

![Figure 3. The configuration and computational grid of model A](image2)
4. Calculation results and analysis

In this paper, the computational conditions are: Mach number of free stream is 0.2, and Reynolds number based on average aerodynamic chord length is about $1.98 \times 10^7$.

4.1. Calculation results of aerodynamic characteristics

Figure 4 and Figure 5 show the curves of lift coefficient and pitching moment coefficient of whole aircraft and main components with the angle of attack for model A, respectively. It can be observed that the lift coefficient and pitching moment coefficient of whole aircraft increase linearly with the increase of AoA (AoA is the nomenclature of ‘angle of attack’ in this paper) for model A. The longitudinal moment of whole aircraft appears pitch-up at AoA of $\alpha_2$. The lift coefficient reaches the maximum at AoA of $\alpha_4$, which is the stall angle. For model A, the longitudinal moment pitch-up ahead of the stall angle not only decreases the available range of the designed maximum lift coefficient to make the aerodynamic performance of the aircraft underutilized, but also has important impact on the landing performance and the control quality of the civil aircraft. The discontinuous change of the control lever force may lead to the pilot's over control and bring flight safety problems. Therefore, it has great significance to study the reason of longitudinal moment pitch-up for improving the longitudinal moment characteristics.

According to the force of main components, the main contribution to longitudinal moment pitch-up for whole aircraft comes from the horizontal tail. The pitching moment of horizontal tail is the product of lift and force arm of horizontal tail. Generally, the lift of horizontal tail increases with increase of AoA. However, in the range of $[\alpha_1, \alpha_4]$, the lift of horizontal tail does not increase with increase of AoA for model A. Therefore, it can be inferred that the almost unchanged lift of horizontal tail leads to the decrease of contribution of horizontal tail to the moment, and then causes the longitudinal moment pitch-up ahead of the stall angle for horizontal tail.

4.2. Analysis of lift characteristics of horizontal tail

The lift coefficients of two-dimensional airfoils at different station along the span direction of the horizontal tail for various AoA are obtained by post-processing interpolation technology of flowfield, which are shown in Figure 6. It can be seen that the root region of horizontal tail contributes most of the lift of horizontal tail. In the range $[\alpha_1, \alpha_4]$, the lift in the root region of horizontal tail basically remains unchanged with increase of AoA, which is the main reason for the almost unchanged lift of horizontal tail.
tail when the AoA increases from $\alpha_1$ to $\alpha_4$. This is further proved by the pressure coefficient distribution of two-dimensional airfoils at $Z_1$ station for different AoA shown in Figure 7. In fact, the pressure distribution and the lift provided by the airfoil are directly related to the local AoA of airfoil at different station of horizontal tail. It should be pointed out that in the above analysis, $\alpha_1$ - $\alpha_4$ are the AoA of fuselage.

![Figure 6. The lift coefficients for various AoA at different station along the span direction of horizontal tail (model A).](image)

![Figure 7. The CP distribution for various AoA at Z1 station of horizontal tail (model A).](image)

The variation of local AoA of horizontal tail with AoA of fuselage at $Z_1$ station is shown in Figure 8, which is obtained by statistical weighted average of AoA of incoming flow in a certain area upstream of the horizontal tail. It can be seen that in the range $[\alpha_1, \alpha_4]$, the local AoA of horizontal tail increases gradually with increase of the AoA of fuselage. Therefore, the lift of horizontal tail increases gradually, and the contribution to the longitudinal moment of whole aircraft increases accordingly. When the AoA of fuselage increases from $\alpha_1$ to $\alpha_2$, the local AoA in the root region of horizontal tail does not increase monotonously, so that the lift of horizontal tail does not increase, which reduces the contribution of horizontal tail to the moment and causes the longitudinal moment pitch-up ahead of the stall angle for the whole aircraft and horizontal tail.

![Figure 8. Variation of local AoA of horizontal tail with AoA of fuselage at Z1 station (model A).](image)

Figure 9 shows the spatial streamlines near the wing-body junction for AoA of $\alpha_1$ and $\alpha_2$. It can be observed that there exist obvious spatial vortices surrounded by the purple elliptical coil in Figure 9 at the trailing edge of the wing-body junction. The spatial vortices flow downstream and form wake flow.
At AoA of $\alpha_1$ and $\alpha_2$, the wake flow has great impact on the local flowfield in the root region of horizontal tail. It can be inferred that at high AoA the spatial vortices developed from the trailing edge of the wing-body junction are strong, and they are not dissipated quickly under the viscosity action of air. One of the effects of the wake flow on the local flowfield of the horizontal tail is to change the trend of the monotonic variation of the local AoA in the root region of horizontal tail with the AoA of fuselage.

In addition to the local AoA of horizontal tail, the local velocity is another physical parameter that affects the pressure distribution and the lift provided by airfoils. The change of local velocity may also lead to the change of the lift of horizontal tail. At high AoA, the free stream passing through complex geometry details of high lift device generally produces separated low-power vortices and low-momentum wake flow[22]. The spatial streamlines diagram colored by Mach number shown in Figure 9 also shows that the momentum of the wake flow pulled out from the wing-body junction is low.
Therefore, another effect of the wake flow on the local flowfield of horizontal tail is to decrease the local dynamic pressure as shown in Figure 10.

Figure 10. Kinetic pressure distribution on axial position of 20% chord of horizontal tail at AoA of $\alpha_1$ and $\alpha_2$ (model A).

It can be seen that the low dynamic pressure region shown in blue does exist in the local flowfield of horizontal tail. The low dynamic pressure region contacts the root of horizontal tail at AoA of $\alpha_1$. At AoA of $\alpha_2$, the low dynamic pressure region contacting the horizontal tail expands from the root to the middle of horizontal tail, and the influence range increases. The decrease of local dynamic pressure can decrease the efficiency of elevator which is an important part of horizontal tail, and may lead to pitching moment non-linear characteristics in some cases. However, for the example of model A in this paper, we consider that the decrease of local dynamic pressure of horizontal tail has little impact on the longitudinal moment pitch-up of horizontal tail. Since the low dynamic pressure region has contacted with the root area of horizontal tail, it is obvious that the loss of local dynamic pressure is severe at AoA of $\alpha_1$. If the decrease of local dynamic pressure of horizontal tail has great impact on the longitudinal moment pitch-up of horizontal tail, the longitudinal moment curve of horizontal tail should have appeared pitch-up phenomenon or non-linear characteristics at AoA of $\alpha_1$ rather than at AoA of $\alpha_2$.

4.3. Improvement of longitudinal moment characteristics

According to the above research results of model A, a local modification is carried out on the fuselage near the trailing edge of the wing-body junction of model A in the process of aerodynamic optimization design. The modified configuration is represented by model B. Figure 11 shows the shape comparison of model A and model B in the modified parts which are the fuselage area surrounded by the red elliptical coil. The purpose of modification is to reduce the influence of wake flow on the local flow of horizontal tail, especially to improve the local AoA characteristics, so as to ensure the high aerodynamic efficiency of horizontal tail even under the interference of upstream wake flow.
Figure 11. Shape comparison of model A and model B in the modified parts.

Figure 12 and Figure 13 show the aerodynamic characteristics of model B. The lift coefficient of model B aircraft reaches the maximum at AoA $\alpha$. Obviously $\alpha$ is the stall angle which is about 1° smaller than that of model A. The linear range of curves of pitching moment coefficient varying with AoA is further expanded. Ahead of the stall angle, the longitudinal moment does not appear the phenomenon of pitch-up or moment platform, which indicates that after the modification, the longitudinal moment characteristics and the control quality of the whole aircraft have been significantly improved. Although the stall angle of model B is advanced, the available range of maximum lift coefficient increases, which indicates that civil aircraft named model B has better landing performance and great economic value. The improvement of model A is success.

Figure 12. Curves of lift coefficient with AoA (model B).

Figure 13. Curves of pitching moment coefficient with AoA (model B).

Figure 14 shows the lift coefficients of two-dimensional airfoils at different station along the span direction of horizontal tail of model B for various AoA. It can be seen that the aerodynamic efficiency of horizontal tail has been greatly improved, especially in the root region of horizontal tail near the fuselage. The lift coefficient of two-dimensional airfoils at different station in most regions of horizontal tail increases gradually with increase of AoA, and the horizontal tail has better aerodynamic
characteristics. The variation of local AoA of horizontal tail along AoA of fuselage at Z₁ station of model B is shown in Figure 15. When the AoA of fuselage increases from \( \alpha_1 \) to \( \alpha_2 \), the local AoA in the root region of horizontal tail continues to increase. As mentioned in reference[11], the monotonic increase of the local AoA of horizontal tail with AoA of fuselage can increase the local aerodynamic force of horizontal tail and the contribution to longitudinal moment of the whole aircraft, so the longitudinal moment of the horizontal tail does not pitch up or the moment platform phenomenon does not appear.

Figure 14. Lift coefficient for various AoA at different station along the span direction of horizontal tail (model B).

![Figure 14](image)

Figure 15. Variation of local AoA of horizontal tail with AoA of fuselage at Z₁ station (model B).

![Figure 15](image)

Figure 16 shows the dynamic pressure distribution in the longitudinal section of the horizontal tail of model B. The low dynamic pressure region colored in blue still exists in the local flowfield of the horizontal tail of model B. The loss of local dynamic pressure of horizontal tail is inevitable. Similar to the case of model A, the low dynamic pressure region contacting the horizontal tail expands from the root to the middle of horizontal tail, when the AoA increases from \( \alpha_1 \) to \( \alpha_2 \). It further suggests that the loss of local dynamic pressure of horizontal tail has little effect on the longitudinal moment pitch up of horizontal tail and whole aircraft.

![Figure 16](image)

Figure 16. Kinetic pressure distribution on axial position of 20% chord of horizontal tail at \( \alpha_1 \) and \( \alpha_2 \) (model B).
5. Conclusion

In this paper, the longitudinal moment characteristics of a civil aircraft with landing configuration (model A and B) are studied by CFD method and post-processing interpolation technology of flowfield. The longitudinal moment of model A appears pitch-up ahead of the stall angle. The main contribution to longitudinal moment pitch-up comes from the horizontal tail. The direct reason for longitudinal moment pitch-up of model A is that the local AoA of horizontal tail no longer increases monotonously with increase of the AoA of fuselage, then the lift of horizontal tail does not increase, which reduces the contribution of horizontal tail to longitudinal moment. While the fundamental reason for longitudinal moment pitch-up is that At high AoA the wake flow developed from the spatial vortices at the trailing edge of the wing-body junction has impact on the aerodynamic characteristics of horizontal tail and changes the trend of the monotonic variation of the local AoA in the root region of horizontal tail with the AoA of fuselage.

Model B is obtained by modification on the configuration of model A. The longitudinal moment of model B does not appear pitch-up ahead of the stall angle. The longitudinal moment characteristics of civil aircraft are better improved. Although the stall angle of model B is advanced, the available range of maximum lift coefficient increases. Another effect of the wake flow on the local flowfield of horizontal tail is to decrease the local dynamic pressure. The loss of the local dynamic pressure of horizontal tail occurs in both model A and model B, but it has little effect on the longitudinal moment pitch-up of horizontal tail in the cases of this paper. The relevant research methods and results have certain guiding significance for improving the moment control quality of large civil aircraft.

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