Research on Aerodynamic Design of Engine Nacelle under the Influence of Propeller Slipstream for the Turboprop Aircraft

Ruifei Xu[1,2], Wenping Song[*1,3], Xinghui Li[2], Ruizhan Qian[2], Yanjun Zhang[1,2], Jianhua Xu*,[1,3], & Xinlong Li[1,3]

[1] School of Aeronautics, Northwestern Polytechnical University, Xi’an, 710072 China
[2] AVIC The First Aircraft Institute, Xi’an, 710089 China
[3] National Key Laboratory of Aircraft Configuration Design, Xi’an 710072 China

Abstract

The mutual interference between propeller slipstream and engine nacelle directly affects the aerodynamic characteristics of turboprop aircraft, and it is an extremely important influencing factor which must be considered in the aerodynamic design of engine nacelle for turboprop aircraft. CFD numerical simulation method is used in this paper to study in detail the interference effect between propeller slipstream and engine nacelle. By comparing the condition with/without propeller, the influence of propeller slipstream on the flow field near the engine nacelle is analyzed. Then the optimization design of the engine nacelle installation angle considering the influence of propeller slipstream is completed. The results show that the engine nacelle installation angle has a significant impact on the aerodynamic characteristics of the turboprop aircraft, and the optimized configuration can increase the lift to drag ratio by 2%.

Keywords: Propeller Slipstream, Aerodynamic Design, Engine nacelle, Turboprop aircraft.

1. Introduction

The propeller slipstream has a critical impact on the aerodynamic characteristics of turboprop aircraft. Typically, the engine nacelle of turboprop regional civil aircraft is installed at the front of the wing and closely coupled with the wing. The high-speed rotating airflow generated by the propeller during operation completely changes the flow field properties near the wing. Due to the strong mutual interference between the slipstream, nacelle, and wing, the interference of slipstream on the aircraft can increase the airflow velocity behind the propeller compared to the free flow. The pressure gradient in the slipstream will also change accordingly due to the influence of slipstream. Meanwhile, due to the tilt and rotation of the airflow in the slipstream, the angle of attack at the lift surface will also change; when the slipstream passes over the lift surface, it will also cause non-uniform distribution of the airflow velocity in the spanwise and vertical directions, after mixing with the free flow, additional viscous effects will be generated among the airflow. These will cause significant changes in the aerodynamic characteristics of the aircraft, thereby affecting the overall aerodynamic performance of the aircraft.

Many researchers have conducted in-depth analysis and research on the interference between the nacelle, wings, and propeller slipstream of turboprop aircraft. Roosenboom et al [1-2] have used PIV to investigate the development of the slipstream over the wing for an 8-bladed propeller aircraft. A comparison of velocity(-derived) quantities has been made in the slipstream of a turboprop equipped transport aircraft between phase-locked experimental Particle Image Velocimetry (PIV) data and unsteady Reynolds Averaged Navier-Stokes (URANS) calculations. Deng Lei et al [3] have conducted an analysis on the influence of propeller slipstream on the surface flow and wake flow fields of the wing. Zhao Shuai et al [4] have used a twin engine turboprop regional airliner as the object and analyzed the influence of slipstream on wings, horizontal and vertical tails, as well as its flow mechanism. L.L.M. Veldhuis[5] has reviewed the mechanisms and describe the phenomena that play a role in the aerodynamic interference between tractor propellers and the wing, moreover, the effect of various parameters like the propeller position and inclination has been discussed in detail. Many other researchers at home and abroad have also used wind tunnel tests and numerical methods to carry out research on propeller slipstream calculation and testing methods [6-7], as well as the influence of slipstream on aircraft pressure distribution [8], and the interference between propeller slipstream and wings [9-14]; These studies provide a detailed analysis on the methods calculating the slipstream flow of turboprop aircraft, the characteristics of the slipstream flow field, and the interference effects of the slipstream flow between the different aircraft components such as wings and tails. It can be seen that under the conditions with the engine powered on, slipstream has a significant impact on the aerodynamic characteristic of aircraft components such as the nacelle and wing.

Most traditional engine nacelle design for turboprop aircraft is carried out without slipstream. For example, Li Xinghui et al [15] have started to improve the design of the engine nacelle for turboprop aircraft from two aspects: the upper and lower installation positions and the local shape. In the design process, the actual flow field under the action of slipstream flow during aircraft flight and the mutual interference between slipstream flow and wings and nacelle have been not considered, which have significant deficiencies in the aerodynamic design of turboprop aircraft. Therefore, based on the detailed analysis of the interference between slipstream and engine nacelle, wings, it is of great significance to carry out engine nacelle design considering the influence of propeller slipstream for the development of turboprop aircraft.

The influence of the engine nacelle on the aerodynamic characteristics of turboprop aircraft with the propeller slipstream is firstly analyzed in this paper, as well as its influence mechanism. And then the optimization design of the engine nacelle position is carried out, and different nacelle positions under the influence of slipstream are analyzed to provide support for the design of the engine nacelle for turboprop aircraft.

2. Calculation Method and Example Verification

The quasi-steady method used in the paper is based on multiple reference coordinate systems to calculate the slipstream flow of the turboprop aircraft. The turbulence model is SST, and multi-block structural grids are generated for the propeller rotation region and the external spatial flow field region, respectively, y+<1 is satisfied for all mesh near the wall. The grid amount is 42 million, and the smooth connection transition of the grid is achieved by using point to point patched grid.

The above method is used to evaluate and analyze the aerodynamic characteristic of wind tunnel test configuration. The experimental configuration is the cruising wing-body civil aircraft (as shown in Figure 1), which is a layout of two turboprop engines. The calculated configuration includes the fuselage, wings, wing-body faring, engine nacelle, propeller, etc. with the propeller rotating clockwise in the same direction. The wind tunnel test was conducted with a wind speed of 70m/s and the Reynolds number of 1.9E6, tc is equal to 0.024. The calculated condition is the same as the wind tunnel test. Figure 2 shows the comparison between the aerodynamic characteristics calculation and the test of the wing body configuration with the engine powered on. The results show that the lift and drag coefficient curves calculated using the method proposed in this paper are in good agreement with the experimental data (as shown in Figure 2), and the linear error is within 2%. This indicates that the method proposed in this paper has high accuracy in calculating the forces of the turboprop aircraft with the propeller slipstream.

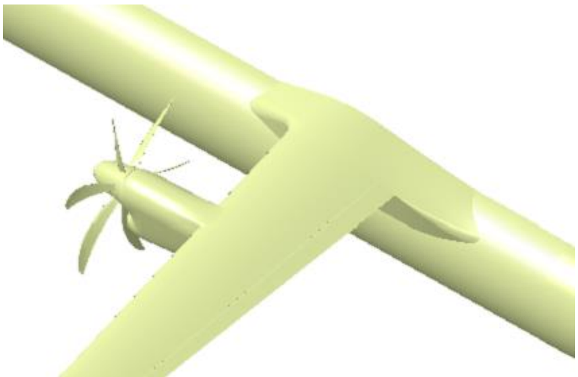
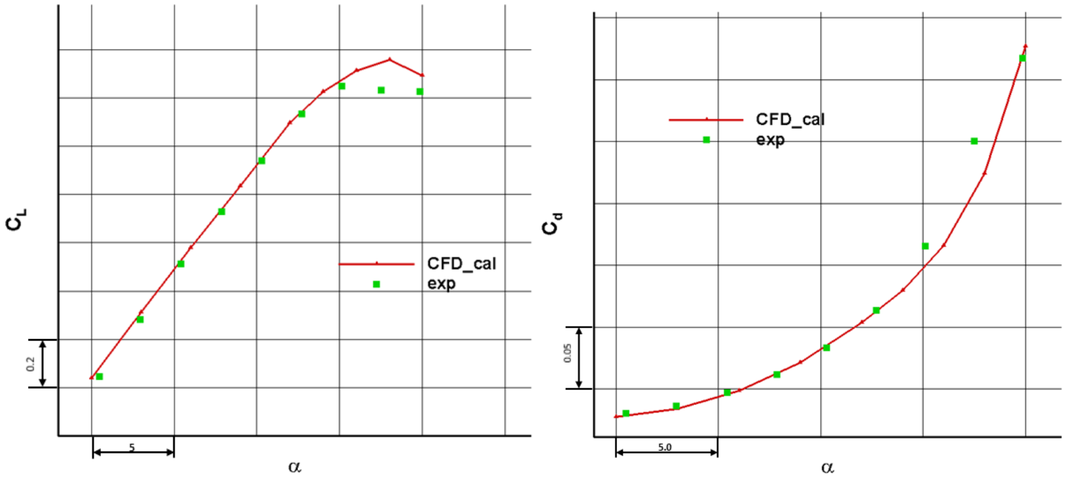


Figure 1 –Configuration of wing-body civil aircraft



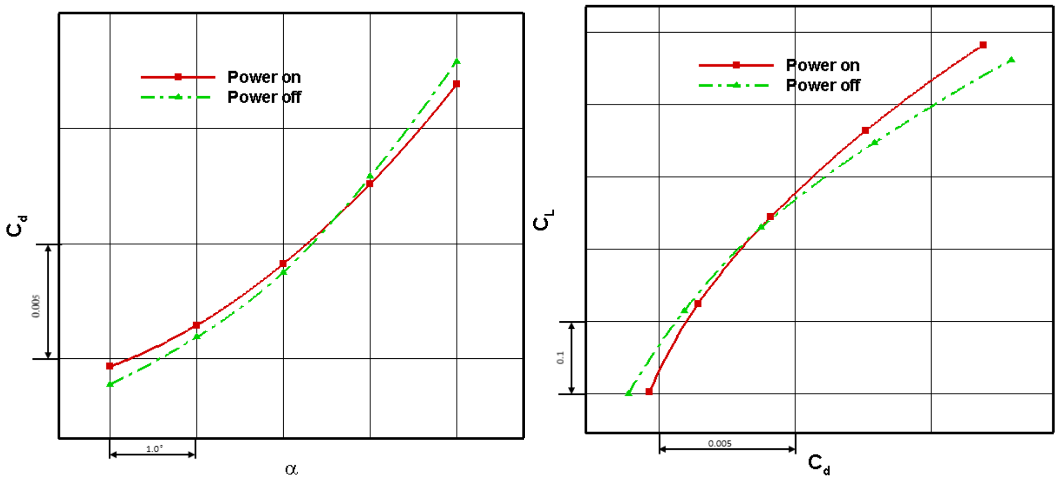
a) Lift coefficient curves b) drag coefficient curves

Figure 2 –Calculation and experimental comparison of aerodynamic characteristics for wing-body civil aircraft with the engine powered on

3. The interference and analysis of propeller slipstream on the engine nacelle

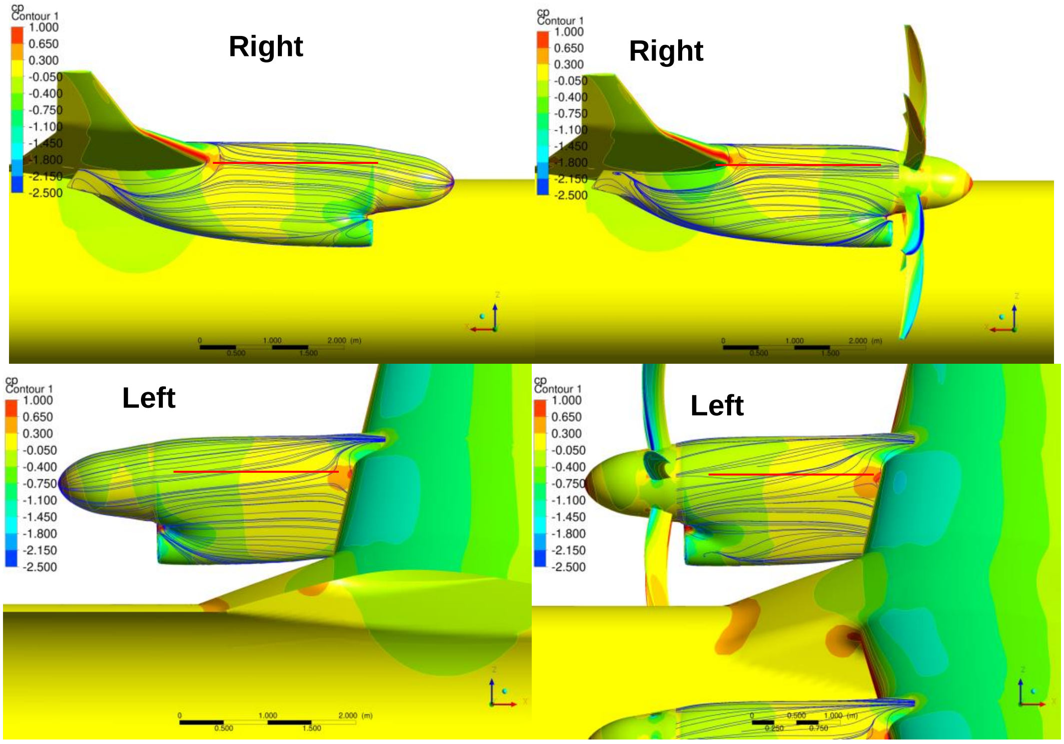
The engine nacelle of the turboprop aircraft is usually directly suspended at the leading edge of the wing, coupled closely with the wing. When the aircraft is flying with the engine powered on, the propeller slipstream causes significant changes in the flow field near the wing and nacelle, which directly affects the aerodynamic characteristics of the turboprop aircraft. When the aircraft is flying at cruising Mach number, the power mainly has a certain impact on the lift to drag ratio of the aircraft, which in turn affects cruising efficiency.

Taking the model provided in Section 2 as the research object, the calculation and analysis of aerodynamic characteristics with the engine powered on and off is carried out. The calculated condition is Ma=0.5, Re=11 million, the angle of attack sequence is 0 ° -4 °, tc is equal to 0.024. Figure 3 shows the comparison of aerodynamic characteristics of wing-body civil aircraft configuration with the engine powered on and off. The results show that compared to the state with the engine powered off, the drag increases first and then decreases when the engine is powered on, and the lift to drag ratio of the configuration decreases first and then increases. Figure 4 shows the comparison of the streamline on the outer surface of the nacelle with the engine powered on and off. Due to the rotation of the propeller, the inner side of the engine nacelle is affected by upward airflow, and the streamline tends to shift upwards; on the outer side of the engine nacelle, the slipstream increases the velocity in the downward direction, causing the streamline to have the downward deviation trend. Due to the influence of this asymmetric airflow, the asymmetric pressure distribution on the left and right surfaces of the engine nacelle will increase, and the separation on the trailing edge of the nacelle will intensify. Figure 5 shows the pressure distribution on the left and right surfaces of the nacelle, and it can be seen that the asymmetry of pressure distribution on both sides has intensified, which has also brought difficulties to the design of the engine nacelle.



a) drag coefficient curves b) Lift to drag ratio curves

Figure 3 –Comparison of aerodynamic characteristics of wing-body civil aircraft configuration with the engine powered on and off



a) power off b) power on

Figure 4 –Comparison of streamline on the outer surface of the engine nacelle with power on and off

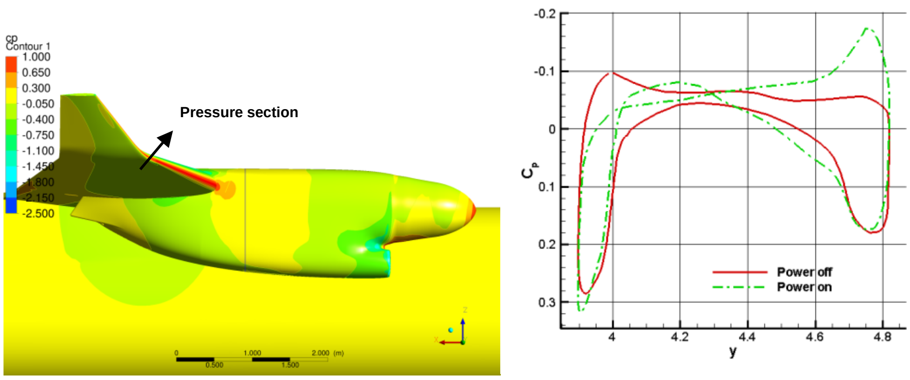
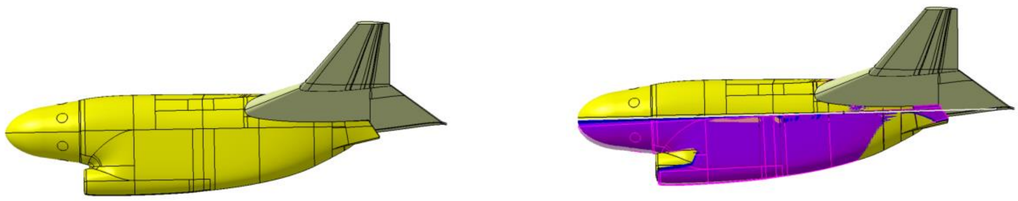


Figure 5 –Comparison of pressure distribution in typical profiles with power on

4. Optimization design of nacelle installation angle

The design of the engine nacelle for turboprop aircraft is crucial for the overall aerodynamic performance of the aircraft. Usually, when designing the shape of the nacelle, it is necessary to comprehensively consider the impact of the nacelle on the aerodynamic characteristics of the aircraft while ensuring the effective envelope of the engine's outer contour. The shape and position of the engine nacelle not only affect the low-speed stall characteristics, but also for high-speed cruising characteristics, the additional resistance brought by the engine nacelle itself can increase the total drag and reduce the cruising efficiency of the aircraft. this paper comprehensively considers the influence of the engine nacelle on the high and low speed aerodynamic characteristics of the aircraft, and completes the design of the engine nacelle Based on the existing baseline configuration, as shown in Figure 6 (a). As analyzed in the second section, under the influence of slipstream, there is significant asymmetry on both sides of the engine nacelle. Meanwhile, the up and down wash caused by slipstream will cause significant changes in the aerodynamic characteristics of the wing/nacelle configuration. Therefore, it is necessary to carefully optimize the installation angle of the nacelle when considering the influence of slipstream during the cruise flight phase of the turboprop aircraft.

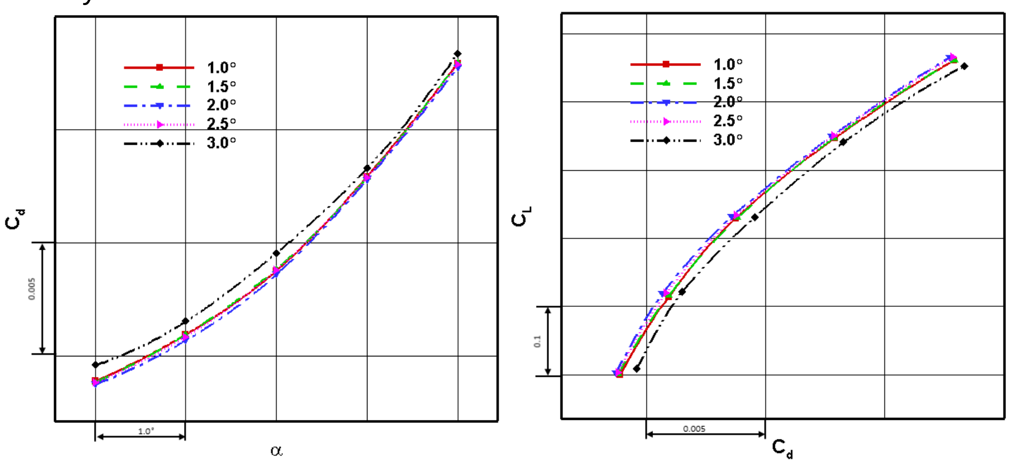
Figure 6 (b) shows a schematic diagram of different engine nacelle installation positions. The engine nacelle rotates around a certain point on the thrust axis, with angles ranging from 1 ° to 3 °, with a 0.5 ° interval between them. After the engine nacelle rotates around a fixed axis, the overall modification of the junction area between the nacelle and the wing is carried out to ensure a smooth transition in aircraft shape.



a) Baseline configuration of the nacelle b) Schematic of the different nacelle installation angle

Figure 6 –Schematic diagram of different engine nacelle installation angles

A detailed computational evaluation is conducted with the CFD method for different installation angles of the designed nacelle. The calculation condition are Ma=0.5, Re=11 million, angle of attack sequence is 0 ° -4 °, tc is equal to 0.024. Figure 7 shows the influence of different nacelle installation angles on the aerodynamic characteristics of wing-body civil aircraft configuration with the engine powered on. The results show that the installation angle of the nacelle has the strong nonlinear effect on the aerodynamic characteristics of aircraft during the cruising phase. When the design lift coefficient C_L is equal to 0.5 and the installation angle is 2.0 °, the total drag of the turboprop aircraft is the smallest. Compared to the installation angle of 3 °, this optimal configuration can increase the lift to drag ratio by 2%.



a) drag coefficient curves b) Lift to drag ratio curves

Figure 7 –the influence of different nacelle installation angles on the aerodynamic characteristics of wing-body civil aircraft configuration with the engine powered on

The change in the installation angle of the engine nacelle will cause significant changes to the influence of slipstream on the upper and lower surfaces of the wing. Figure 8 shows the Mach number contour on the trailing edge of the wing for wing-body civil aircraft under the different nacelle installations. The range of low Mach number regions (lower than 0.45) are showed. The results show that the low Mach number region on the upper surface of the wing is mainly concentrated in the rear area of the engine nacelle. This is mainly due to the presence of the nacelle, the acceleration and rotation effects of the slipstream will cause mixing of the flow around the wing/nacelle junction area with the airflow on the upper surface of the nacelle, dissipating airflow energy, and ultimately leading to significant flow separation at the trailing edge of the wing. When the installation angle of the engine nacelle is 3 °, the range of the low Mach number region on the inner side of the right wing is significantly larger than that of other installation angle configurations. This indicates that at this installation angle, the beneficial effect of propeller slipstream on the wing surface is insufficient, resulting in insufficient flow acceleration on the wing surface, which may cause flow separation phenomenon. When the installation angle is 2 °, the low Mach number region on the upper surface of the wing behind the engine nacelle is the smallest, and the range of the separation zone on the trailing edge of the wing is also the smallest, and it can lead to the aircraft has the minimum flight drag at this nacelle installation angle.

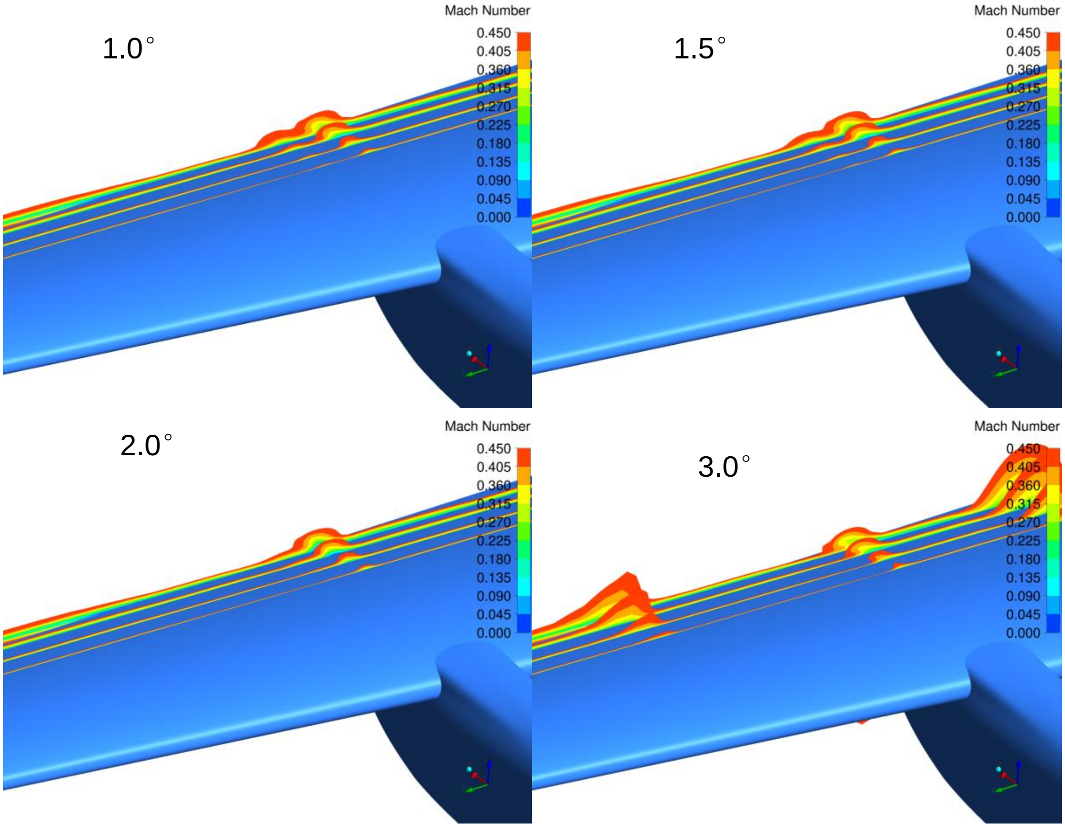


Figure 8–the Mach number contour on the trailing edge of the wing for wing-body civil aircraft under the different nacelle installations

For the nacelle design of the turboprop aircraft, flow separation can easily occur at the rear of the engine nacelle, which will lead to the increase the drag of the aircraft. During the design process, the optimization of the installation angle for the engine nacelle can also reduce the flow separation at the trailing edge. Figure 9 shows the comparison of the surface streamlines for wing-body civil aircraft configuration under the nacelle installation angles of 2.0 ° and 3.0 °. It can be seen that the configuration with an installation angle of 3.0 ° has significantly greater trailing edge separation than the configuration with an installation angle of 2.0 °.

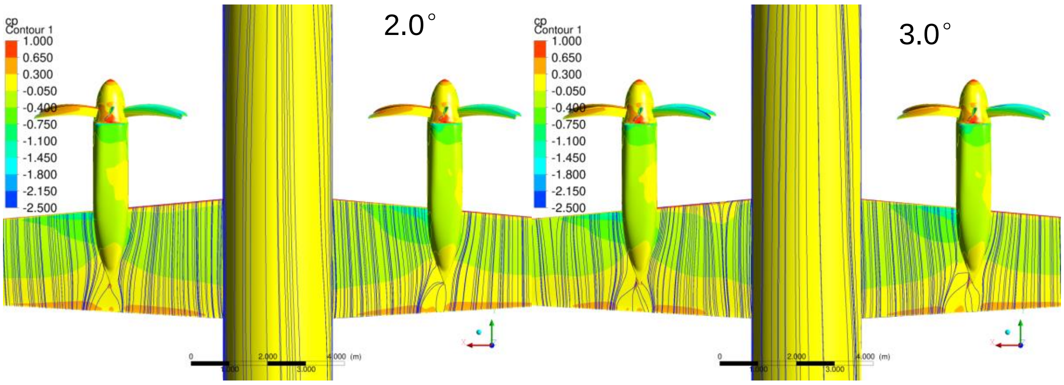


Figure 9–Comparison of Surface Streamlines of the wing-body civil aircraft Configuration under different nacelle installations.

5. Conclusion

Numerical simulation methods are used in the paper to study the influence of slipstream on aircraft aerodynamic characteristics with/without propeller, and analyze the interference between propeller slipstream and the engine nacelle. Then the influence of nacelle installation angle on aircraft aerodynamic characteristics is studied. The research has shown that:

1) The aerodynamic characteristics of turboprop aircraft change with the influence of slipstream. There is the side-wash effect near the nacelle, the streamline tends to shift upwards on the outer side of the nacelle; on the inner side of the nacelle, the streamline tends to shift downwards;

2) The installation angle of the engine nacelle has a significant impact on the aerodynamic characteristics of the turboprop aircraft. Through aerodynamic analysis of different installation angle for nacelle configurations with the engine powered on, it is found that in the design point (CL=0.5), when the installation angle of the engine nacelle is 2 °, the wing-body configuration has the highest lift to drag ratio and the best aerodynamic characteristics. Compared to the 3 ° installation angle configuration, this optimal configuration can increase the lift to drag ratio by 2%;

3) In the design of turboprop aircraft, the optimization of the installation angle for the engine nacelle while considering the influence of propeller slipstream can greatly improve the aerodynamic performance of the turboprop aircraft.

6. Contact Author Email Address

Wen-Ping Song *, wpsong@nwpu.edu.cn.

Jian-Hua Xu *, xujh@nwpu.edu.cn.

7. Copyright Statement

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