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Investigation on the Flow Characteristics of Sudden Deceleration Phenomena in Aircraft with Forward-Mounted Air Intakes

Cunjian Lyu

Zhixin High School, Guangzhou, 510000, China
18520221501@163.com

Abstract: *An aircraft with a forward air intake may encounter the phenomenon of sudden flight stall during maneuvers at a high angle of attack, which reduces the aircraft's controllability and safety. In order to clarify the causes and essence of the aircraft's sudden flight stall phenomenon. In this study, based on the model of an aircraft with a forward air intake, we aim at the air flow rate around the air intake and adopt numerical simulation technology to conduct research. By studying the air flow rate, flow structure, and aerodynamic characteristics of the aircraft's air intake. It is found that during the aircraft's climbing maneuver the air flow rate of air intake will be decreased. This is the primary cause of the sudden flight stall phenomenon. On the other hand, with the increase of the angle of attack, the influence of flow separation on the air flow rate at the air intake also intensifies. This research is of great practical significance for designing the flight envelope of an aircraft with a forward air intake and preventing undesirable flight modes for pilots.*

Keywords: *Numerical simulation; Front inlet; High angle of attack; Aerodynamic characteristics; Inlet flow rate*

1. Introduction

In the 20th century, China developed its second-generation high-altitude and high-speed interceptor aircraft. It was developed according to the Soviet MiG-21. This aircraft mainly adopted a large-sweepback delta wing and forward air intake layout. It had the advantages of low wave drag, undisturbed incoming flow and very little total pressure distortion[1]. However, in actual flight training and combat exercises, it was found that during the rapid pull-up process of the aircraft with a forward intake at high speed it will cause the intake conditions of the propulsion system to deteriorate, the total pressure distortion to increase, and the engine performance to decline[2].This phenomenon causes the aircraft to suddenly lose speed and maneuverability, accompanied by the risk of losing control. It not only threatens flight safety but also reveals inherent flaws in the energy maneuverability and flight control system of this model. Therefore, we need to conduct research on the sudden stoppage phenomenon of aircraft with forward air intakes in order to provide references for the design of flight envelopes and the avoidance of dangerous states during pilot operations.

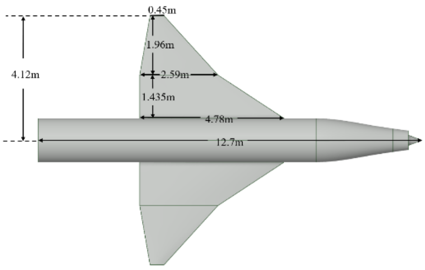
During the aircraft maneuver pull-up process, the angle of attack constitutes a critical parameter influencing engine stall. Since the 1980s, researchers have conducted comprehensive investigations into steady-state and dynamic distortion measurement techniques for aircraft full-scale model high-angle-of-attack inlets, aiming to address the compatibility issues between inlets and engines during high-angle-of-attack maneuvers. Through wind tunnel experiments and flight tests, internal flow measurements of inlets have been performed to enhance the predictive capability of inlet flow field dynamic distortions, thereby guiding the development, improvement, and finalization of aircraft inlets[3]. NASA concurrently initiated the High Angle of Attack Research Program (HATP), conducting a series of experimental and computational studies utilizing the F/A-18 as the carrier aircraft[4]. Furthermore, Zhang Shiying et al. conducted numerical simulations to investigate the flow field structures of both isolated inlets and the integrated fuselage/inlet configuration, and compared the aerodynamic performance of the inlets under these two conditions[5]. Zhu Yu et al. conducted a comprehensive analysis and comparison of the impact of four distinct forebody inlet configurations on internal flow characteristics through numerical simulations and wind tunnel experiments[6]. Xie Wenzhong et al. conducted wind tunnel experiments to compare the maneuverability characteristics of the air intake system, including velocity, angle of attack, and sideslip angle, under four different configurations[7].

In summary, research on the emergency stop phenomenon of aircraft with forward air intakes is still insufficient. This study conducts a numerical simulation study on the emergency stop phenomenon of aircraft with forward air intake layout during the maneuvering pull-up process, analyzes the angle of attack characteristics of the aircraft, and reveals the flow mechanism of the emergency stop phenomenon.

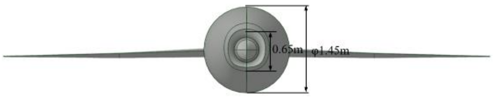
2. Research Methodology

2.1 Research Model

Figure 1 depicts the fore - inlet aircraft model of this study, presenting two perspectives: a top view and a front view. Figure 1(a) showcases the overall axisymmetric aerodynamic shape of the aircraft. The total length of the fuselage is 12.7 m, and the maximum body height is 4.12 m. The fore- body section adopts a regional tapering design, and the tail wings are arranged in a delta- wing configuration. The root chord length of the tail wings is 2.59 m, the vertical height of the wingtip is 1.96 m, the longitudinal height of the anhedral angle region is 1.435 m, the axial distance from the leading edge of the tail wing to the end of the fuselage is 4.78 m, and the maximum thickness of the airfoil is 0.45 m. Figure 1(b) shows the radial dimensions of the model's nose tip. The outer diameter of the nose is φ1.45 m, and the inner cavity diameter is φ0.65 m.



(a) Top View

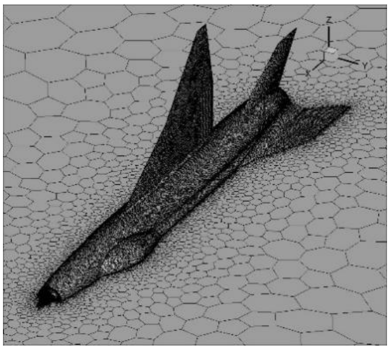


(b) Front View

Figure 1 Aircraft Model with Forward-Mounted Air Intake

2.2 Numerical Simulation and Grid Generation

In the present study, the commercial software STAR - CCM+ was employed for numerical simulation. STAR - CCM+ utilizes polyhedral meshes which, when compared with tetrahedral meshes, can enhance computational performance by approximately 3 - 10 times while maintaining the same computational accuracy. To conserve computational resources, a computational task for a half - specimen was carried out in this study, as shown in Figure 2. The flow velocity was 0.74 Mach. The inlet of the air intake was specified as the inlet pressure to ensure the flow during the simulation process.



(a) Semi-modular structure

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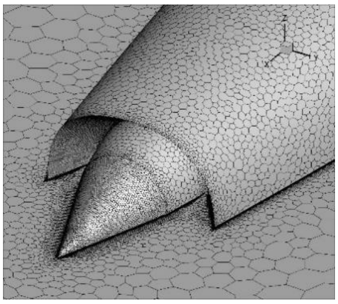

(b) Inlet grid

Figure 2 Computational Model and Wall Grid

2.3 Grid Independence Verification

Within the scope of numerical simulation, verification analyses were conducted on grids of various densities to ensure the independence of calculation results from the grid. As shown in Figure 3, a trend of the change in the lift coefficient with an increase in the number of grid cells is presented: when the number of cells increased from 1.07 million to 1.35 million, the lift coefficient decreased from 0.221 to a minimum value of 0.218; upon further refinement of the grid to 2.16 million cells, the lift coefficient gradually recovered to a value of approximately 0.221. The overall amplitude of fluctuations was less than 2.3%, and when the number of cells exceeded 1.5 million, the calculation results converged. Verification indicated that the simulation results are stable with respect to changes in grid size. Consequently, it was determined that the optimal number of cells is 1.07 million, which ensures both calculation accuracy and efficiency, thereby providing a reliable foundation for further analysis of aerodynamic characteristics.

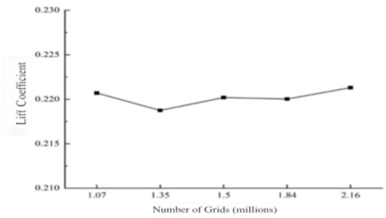

Figure 3 Grid Independence Verification

3. Results and Analysis

For aircraft with a front air intake, Vortex Jet 13 type engines are typically employed. The air supply of this engine is 66 - 67 kg/s (WP13/WP13AII/WP13F) or 68 - 69 kg/s (WP13F1). Consequently, when the air supply to the air intake is less than 66 kg/s, the engine shuts down due to insufficient incoming air. Based on the above data, in this study, an analysis of the aerodynamic characteristics of the aircraft model with a front air intake and an analysis of the air supply to the air intake were conducted. The angle of attack at which the aircraft suddenly stops was determined, which provides a basis for aircraft design and the prevention of similar situations during piloting.

3.1 Aerodynamic Characteristics Analysis

Figure 4 illustrates the variation of the aircraft's lift coefficient with respect to the angle of attack. Lift coefficient $C_L=\frac{2L}{\rho V^2 S}$, Where L represents the lift force of the aircraft, V denotes the velocity of the oncoming flow, S stands for the projected area onto the oncoming flow, and ρ represents the air density. As the angle of attack increases, the lift coefficient rises. Additionally, at an angle of attack of 12 °, there was a significant change in the aerodynamic forces, which may be associated with the flow structure induced by the aircraft's design. Since this is beyond the scope of the present study, no analysis or discussion of this phenomenon will be conducted here.

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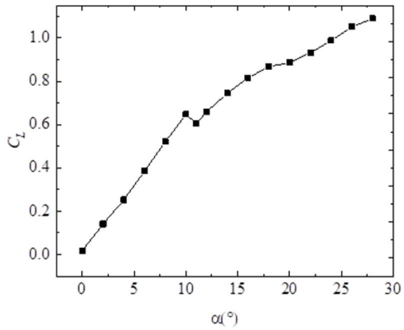


Figure 4 Aircraft lift coefficient variation with angle of attack

In summary, the aerodynamic state of the aircraft is normal. Therefore, the structural component of the aircraft itself has a negligible impact on the sudden engine shutdown.

3.2 Investigation of Airflow in the Intake Duct

Figure 5 depicts the curve of the mass flow rate at the inlet of the air intake varying with the angle of attack. As can be seen from the figure, with the increase of the angle of attack, the mass flow rate at the inlet of the air intake constantly decreases. Especially when the angle of attack exceeds 10 °, the flow rate decreases rapidly. That is to say, the amount of air that can support combustion in the engine decreases as the angle of attack increases. When the air supply at the inlet of the air intake falls below the level required for the engine to operate, the engine stops working, which means that the engine shuts down unexpectedly during flight. As shown in the figure, when the angle of attack is 22 ° and the air flow rate in the air intake is less than 66 kg/s, an emergency shutdown of the aircraft occurs.

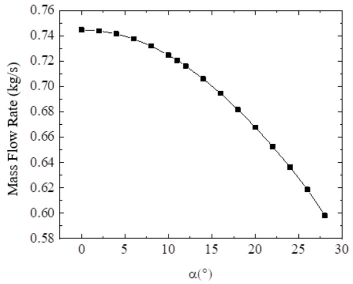
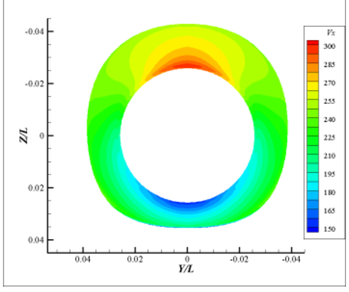


Figure 5 Inlet mass flow rate variation with angle of attack

3.3 Analysis of Flow Structure at the Inlet Section

Since the aircraft may experience a sudden stall at an angle of attack of 22 °, this section examines the flow field structures of the air intake at angles of attack of 18 °, 22 °, and 26 ° to analyze the influence of the flow in the sudden - stall state.

Figure 6 presents the distribution maps of the flow velocity along the longitudinal axis of the aircraft at the air - intake inlet under different angles of attack. It can be observed that as the angle of attack increases, the average velocity at the air - intake inlet gradually decreases, indicating that the mass flow rate also decreases, which further validates the aforementioned conclusion.



(a)α=18 °

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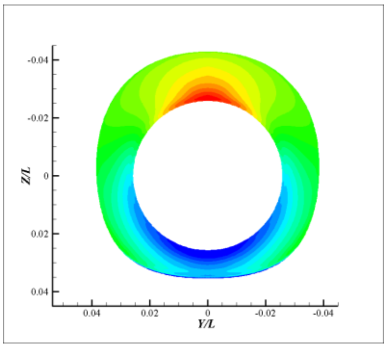
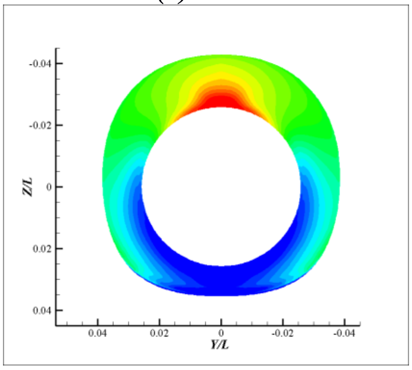


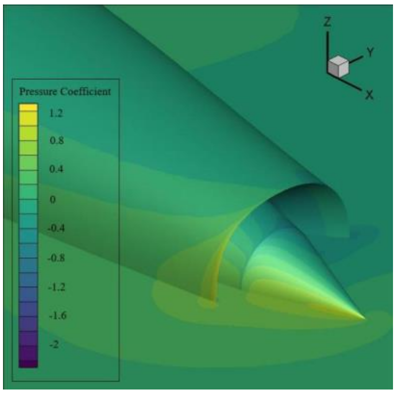
(b)α=22°



(c)α=26°

Figure 6: Contour Plot of Axial Velocity in the Inlet at Various Angles of Attack

Figure 7 depicts the pressure distribution at the nose of the aircraft at angles of attack of 18°, 22°, and 26°. It can be observed that as the angle of attack increases, the position of the maximum pressure on the lower surface of the aircraft shifts backward along the plane of symmetry. That is to say, the stagnation point continuously moves backward and may even extend beyond the inlet cross - section of the air intake. Consequently, the amount of air entering the air intake steadily decreases.



(a)α=18°

(b)α=22°

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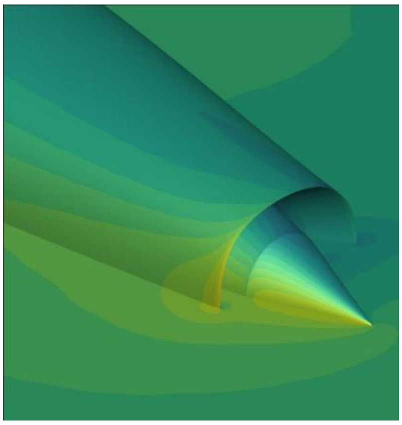
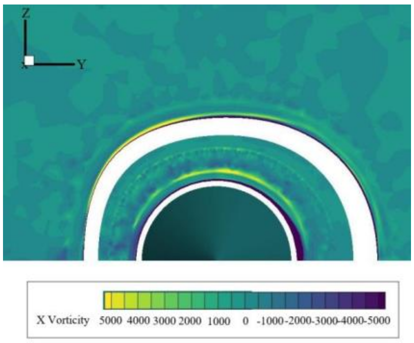


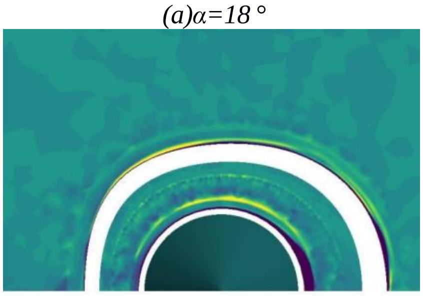
(c)α=26°

Figure 7: Pressure Distribution at the Forebody of the Aircraft

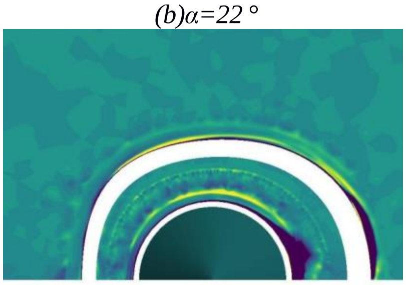
Figure 8 depicts the distribution of vorticity in the cross - section of the aircraft's nose, perpendicular to its longitudinal axis. As can be observed from the figure, with an increase in the angle of attack, the separation of the shear layer at the aircraft's nose intensifies, that is, the vorticity of the separated vortices increases. Consequently, the resulting low - pressure area further reduces the air intake into the air inlet.



(a)α=18°



(b)α=22°



(c)α=26°

Figure 8: Vorticity Distribution at the Aircraft Nose Section

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4. Conclusion

In the present study, we carried out the numerical modeling of the problem of engine shutdown during the flight of an aircraft with a forward air intake at a high angle of attack. The main conclusion is that the engine shutdown of the aircraft occurs at an angle of attack of 22° due to an insufficient amount of air entering the air intake. The main reasons for the insufficient amount of air can be divided into three points: (1) a decrease in the air intake velocity leads to a reduction in the mass flow rate; (2) a decrease in the area of the air intake facing the flow, that is, the downward and backward displacement of the stagnation point, results in a smaller amount of incoming air; (3) on the front part of the aircraft, the boundary layer separates, forming separation vortices that carry away part of the flow.

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