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An experimental investigation on static directional stability

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Abstract A generic aircraft usually loses its static directional stability at moderate angle of attack (typically 20–30°). In this research, wind tunnel studies were performed using an aircraft model with moderate swept wing and a conventional vertical tail. The purpose of this study was to investigate flow mechanisms responsible for static directional stability. Measurements of force, surface pressure and spatial flow field were carried out for angles of attack from 0° to 46° and sideslip angles from −8° to 8°. Results of the wind tunnel experiments show that the vertical tail is the main contributor to static directional stability, while the fuselage is the main contributor to static directional instability of the model. In the sideslip attitude for moderate angles of attack, the fuselage vortex and the wing vortex merged together and changed asymmetrically as angle of attack increased on the windward side and leeward side of the vertical tail. The separated asymmetrical vortex flow around the vertical tail is the main reason for reduction in the static directional stability. Compared with the wing vortices, the fuselage vortices are more concentrated and closer to the vertical tail, so the yawing moment of vertical tail is more unstable than that when the wings are absent. On the other hand, the attached asymmetrical flow over the fuselage in sideslip leads to the static directional instability of the fuselage being exacerbated. It is mainly due to the predominant model contour blockage effect on the windward side flow over the model in sideslip, which is strongly affected by angle of attack.

1. Introduction

In the late 1970s and early 1980s, the tactical advantages of super maneuverability for fighter aircraft increased interest in post-stall maneuverability.[1,2] Requirement and expectation for the aerodynamic design of moderate to high angle of attack have become higher for modern fighter aircraft. On the other hand, static stability has always been critical and inevitable in the process of modern aircraft design. In the third generation fighter aircraft, static stability was achieved by triaxial

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design and the operational envelope was kept within a certain essential static stability margin.[3] With the development of active control technology, it is applied in the third generation of aircraft with relaxed static stability and local static longitudinal instability, but the design for the static lateral-directional stability was generally stable. Su-27 is a typical example of aircraft with local longitudinal static instability, and the lateral-directional stability remained within the stable range. Although it is able to perform post-stall maneuverability like a cobra (Su-27 cobra maneuver), the stall was temporary and only lasted for a few seconds. Even when thrust vectoring technology was employed, the aircraft could not maneuver in the post-stall range for a long time due to severe flutter of the aircraft caused by separating flow, which was unbearable for the pilots. Therefore, the design of static lateral-directional stability is still stable so far, which is also the case for aircrafts with highly advanced active control technology like F-22.[3] However, the current study shows that the modern aircrafts, especially aircrafts with conventional layout design following principles of static stability, are prone to problems of lateral and directional nonlinear and insufficient stability at moderate and high angle of attack, which largely limit the maneuverability of the aircraft's performance, and may endanger the flight safety.[4,5]

Yawing moment coefficient C_n represents the aerodynamic moment coefficients generated about the vertical axis.[6] The yawing moment coefficient C_n derivatives of the sideslip angle β are called static directional stability derivatives $C_{n\beta}$. When $C_{n\beta} > 0$, it indicates that the aircraft is stable, whereas $C_{n\beta} < 0$ suggests that the aircraft is unstable, and the angle of attack while $C_{n\beta} = 0$ is the critical angle of attack of directional stability.[3,4] The greater the values of critical angle of attack are, the larger the range of static stability is, and hence the smallest one among the longitudinal, lateral and directional critical angles of attack determine the degree of the available angle of attack for the aircraft. Therefore, the aircraft aerodynamic design should maximize the smallest angle of attack among longitudinal, lateral and directional critical angles of attack in order to increase the available angle of attack range and available flight envelope of the aircraft. However, the directional critical angle of attack of many modern aircrafts is less than the longitudinal and lateral critical angle of attack, which limits the available range of the angle of attack of the aircraft. We take the F-15 as an example[7]; its stall angle is 35°, while its directional critical angle of attack is approximately 22°. Besides, the angle of attack corresponding to the lift coefficient peak is 35° for F-16, but its directional critical angle of attack is 28.[8] In conclusion, improvement of the directional critical angle of attack is very important to increase the available range of the angle of attack of modern aircraft.

A number of techniques used to control forebody vortex systems and their associated yawing moments are gradually making the transition from laboratory curiosities to practical applications on highly maneuverable aircraft to increase available flight envelope of the aircraft.[9,10] In particular, applications of pneumatic vortex control techniques[11] are being considered for use in the aircraft industry, and it is being done without a complete understanding of the flow field physics responsible for the formation of vortex asymmetry. The issues raised by developing new aircraft can often be used to focus research goals at the fundamental level. When the basic understanding is lacking and models are not available for guidance, the design engineer is forced to rely on extrapolations of empirical measurements and the "cut and try" approach.[1,10] The objective of this study was to identify some areas of weakness in directional stability especially the flow field over the conventional aircraft at directional critical angle of attack, so it could establish the foundation for the improvement measures of static directional stability.

In this research, wind tunnel tests on a generic fighter model with high-mounted swept ($\Lambda = 47.5°$) wings, single conventional vertical tail, ventral fins and horizontal tails were conducted in Beihang University D4 low speed wind tunnel. The main components generating yawing moment were identified through the force tests. Furthermore, the flow field of the main components responsible for the directional stability at moderate angles of attack was investigated by pressure tests and particle image velocimetry (PIV) tests. The corresponding flow mechanism on the static directional instability of the model was then discussed.

2. Experimental methods

2.1. Wind tunnel facility and procedure

Experiments were conducted in D4 low-speed return wind tunnel at Beihang University. The tests were carried out in the open test section which was 1.5 m × 1.5 m with the length of 2.5 m and free stream turbulence level at 0.08%. The tests were carried out at velocity of free stream $V_\infty = 35$ m/s, which corresponded to a Reynolds number $Re = 1.54 \times 10^5$ based on chord length of the wing. The model was sting-mounted on a supporting mechanism which could provide α variation shown in Fig. 1. Tests were performed at fixed angles of attack from 0° to 46°, together concurrent with a sideslip range from −8° to 8°.

Side force and yawing moment were acquired with an internally-mounted six-component force balance. The pressure data acquisition system consisting primarily of a DTC Initium and an ESP module with pressure transducer accuracy of 0.1% FS (FS = ±1 psi) was used for surface pressure measurements. FlowMap digital particle image velocimetry (DPIV) system was used for measuring sectional spatial velocity and vorticity field. PIV images were obtained by averaging 50

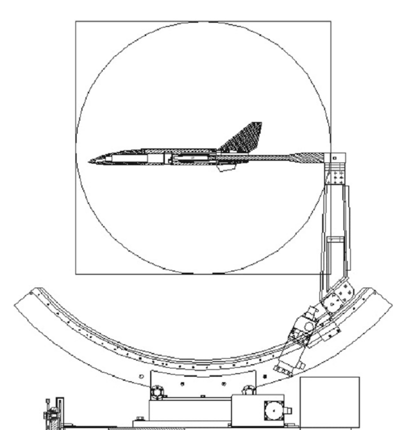

Fig. 1 Support system in D4 open-section wind tunnel.