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Analytical study on the synthetic jet control of asymmetric flow field of flying wing unmanned aerial vehicle

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A R T I C L E   I N F O

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A B S T R A C T

The aim of the present paper is to study the active control of flow fields based on synthetic jet technology, taking into account the asymmetric flow field of a flying wing unmanned aerial vehicle (UAV) in zero sideslip state. The study designs eight sets of array of synthetic jet control actuators arranged on the leading edge of aircraft, to study the effect of synthetic jet technology on control of asymmetric flow field and analyze the influence of typical flow control parameters on control efficacy. The results indicate that synthetic jet control could not only effectively improve the influence of asymmetric vortex on lateral–directional aerodynamic characteristic of the model in zero sideslip state, but also achieve the goal of lateral–directional aerodynamic control of the model by interacting with asymmetric vortex. In fact, the mutual induction between the periodic energy perturbations injected by jet and the main separation vortex enhances the adverse pressure gradient resistance of the main vortex to control the development of asymmetric separation vortex.

1. Introduction

High maneuverability and agility of aircrafts are both achieved flying at high angle of attack or even at post-stall condition, therefore, a high-performance combat aircraft must have excellent aerodynamic at high attack angle. However, when the angle exceeds a certain value, a left–right asymmetric back vortex system will form in the leeward zone of the forebody, producing an extremely large lateral force that generates yawing and rolling moment. Besides, the magnitude and direction change roles of lateral force are unidentified for the random of back vortex system, and this phenomenon is commonly known as "phantom sideslip" [1]. Wing shapes of flying wing aircrafts with low aspect ratio are similar to delta wings, and are subjected to asymmetric flow at a moderate angle of attack.

Currently, from the perspective of the generation mechanism of the asymmetric characteristic of such flow, there are mainly two points of view. One claims that the inherent perturbation in flow field conducts shear flow through viscous boundary layer of object aircraft, resulting in asymmetry of flowfield transition and separation, which further causes the asymmetry of leeward vortices. Thus, it is believed that the inherent perturbation in boundary layer generates asymmetric flow. On the contrary, the second point of view holds that the generation of an asymmetric flow does not need the boundary layer. In fact, as long as there are perturbations in the flow, they will disrupt the relative balance of leeward vortices. As a result, the unbalanced leeward vortices will continue to develop and expand through mutual induction and extrusion, and finally turning into an asymmetric flow pattern. This point of view is also known as spatial dynamic instability of flow field [2–4].

Literature [5] analyzes the changes of yawing moment with the angle of attack of an aircraft F111 when flying at zero sideslip state. The study finds that the yawing moment at a high angle of attack has a much larger magnitude than that of the maximum control yawing moment provided by the rudder, and both the magnitude and direction change of the yawing moment are uncertain. Through experiment, Lamont and Hunt [4] find that following conditions characterize the asymmetric flow: the leeward side of the model flies along the axial direction in vortex pairs in an alternative and separated way, and the motion direction of the separation flow finally tends to accord with that of the free stream. Moreover, the alternative separated vortex structure model causes the lateral force of section to present a sinusoidal quasi-periodic distribution along the axial direction. In the flowing asymmetric state, the flow characteristics include the asymmetry of the separation point positions of object plane and the corresponding asymmetry of vortex development and shedding. Therefore, they manifest as the intense unsteady aerodynamic characteristic of aircraft on a macro level.

Due to the emergence of asymmetric vortices flowing around a body, the aircraft may go through complex or even uncontrollable

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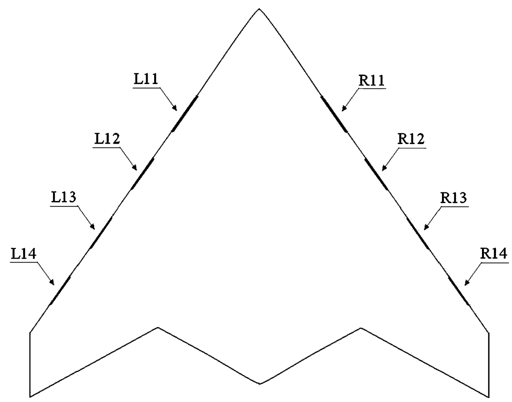


Fig. 1. Schematic diagram of the actuators layout.

flight phenomena like lateral–directional deviation, wing rock, or downward rush. At high angle of attack within the post-stall range, the control surfaces of traditional aircrafts (such as vertical tail and rudder) are caught up in the separation flow field of wings, resulting in abruptly declined efficiency and inability to provide the yawing moment and lateral force required for aircraft control. Consequently, the aircraft is in severe lack of lateral controllability within the attack angle range in maximum lift and post-stall state. To improve the aircraft maneuverability, researches on the control of lateral force and yawing moment induced by the forebody asymmetric vortex at high angle of attack are carried out. Moreover, relevant flow field structures and quantitative analyses on corresponding aerodynamic force have been investigated [6,7].

The control of asymmetric vortex consists of passive control and active control. The passive control aims to suppress the generation of asymmetric vortex or reduce their variation randomness. Active control aims to purposefully control the asymmetric state of back vortex to obtain the desired lateral force and to control the aircraft flying at a high angle of attack by replacing the functions of invalid aerodynamic control planes like empennage and so forth.

To control the asymmetry of flow, many solutions have been developed including model spanwise blowing, strake winglet, transition zone, slotting, and placing perturbation block at nose [2,3]. However, in practical applications, besides the excellent control efficacy, any solution control technique should not affect the aircraft original performance, or involve too much auxiliary equipment. Therefore, the synthetic jet device based on Micro Electro-Mechanical Systems (MEMS) technology has a great application potential in the future flow control of aircraft in this perspective.

Synthetic jet technology is one of the existing active flow control technologies, based on local flow field changes due to the interaction between synthetic jet flow and main flow, and its essence lies in that designing micro perturbation in the sensitive zones of flow field can change local or even the whole flow state by coupling and amplifying with macro large-scale flow. Compared with traditional flow control techniques like slat, fence or vortex generator, the synthetic jet actuator based on MEMS technology has simpler and compact structure, is lighter, lower power consumption, and higher sensitivity. Moreover, the slight influence on the overall features of target aircraft, such as aerodynamic configuration, structure, and weight makes fine control of flow possible.

This paper investigates the active control of asymmetric flow of flying wing aircraft based on synthetic jet technology. The study evaluates the application of synthetic jet technology to the asymmetric flow control of flying wing aircraft, analyzes its control efficacy, and carries out an analysis on the influence of typical flow control parameters. On one hand, flow control aims to restrain the development of asymmetric separated vortices and improve the influence of asymmetric vortex on lateral–directional aerodynamic characteristic of the model in zero sideslip state. On the other hand, it aims to actively utilize the asymmetric vortex and explore the ways of employing asymmetric flow to achieve the goal of the lateral–directional aerodynamic control of the model through synthetic jet and asymmetric vortex interactions.

2. Numerical simulation

2.1. Numerical analysis method

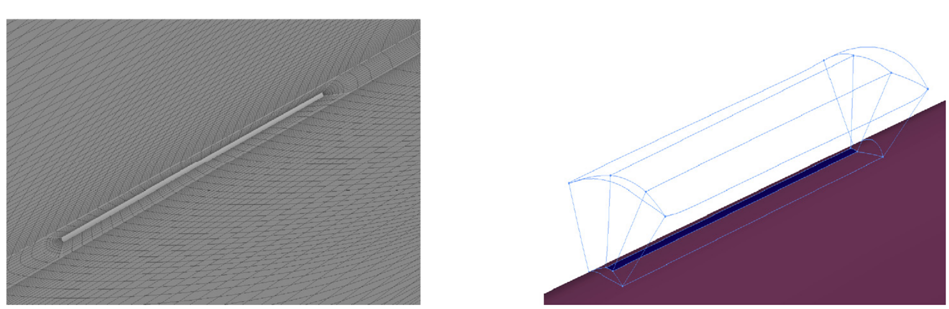
Synthetic jet calculation code developed by our research group is used in this study. The unsteady Reynolds averaged Navier–Stokes equations describe flow control equations, turbulence model is described through the shear stress transport (SST) two-equation model, and spatial discretization scheme introduces the Roe scheme based on preconditioning technology. The sub-iteration is fixed at four steps (four complete multi-grid cycles), and a complete jet flow period is set to include 80 portions. Generally a steady periodic flow state of control model can be achieved through the calculation of 30 ∼ 45 periods.

A Seifert TAU0015 airfoil flow control experiment [8,9] and Flow control over a Hump Model (Computational Fluid Dynamics Validation 2004, CFDVAL2004) [10–12] are selected for the numerical simulation verification and validation.

The simulation results [13,14] show that the developed numerical simulation technology and established flow control model can accurately capture subtle characteristics of jet flow field, the data have good reliability and accuracy compared to wind tunnel experimental data and program results.

2.2. Flow control model

Synthetic jet perturbations are generated through the nozzle of actuator, and a complete control model should include the cavity of actuator. The calculation simplifies the flow control model,



(a) enlarge view of surface grid near the actuator nozzle (b) grid topologies design for the jet actuator

Fig. 2. Schematic diagram of surface grid and grid topology design near the actuator nozzle (every fourth point in i-direction and every second point in j-direction is shown for clarity).