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Study on longitudinal stability improvement of flying wing aircraft based on synthetic jet flow control

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ABSTRACT

This paper studies aerodynamic efficiency improvements to address the poor longitudinal stability of flying wing aircraft. The improvements use numerical simulation based on synthetic jet flow control technology to analyze the effects of typical flow control parameters and flow control mechanisms. The research results show that the periodic flow field disturbance introduced by synthetic jet control technology improves the blending of boundary layers, strengthens the momentum transport inside and outside the boundary layers, and slows down the process of flow separation. This achieves the goal to broaden the pitching moment in the linear domain. Analysis of control parameters shows that obvious effects on the flow control at the leading edge of the model. The larger fluidic momentum coefficient leads to an evident increase in the effectiveness of control of the flow field; and the optimal jet injection frequency occurs at around 1, where the control effect based on the principle of vortex interference is shown to be the most significant.

1. Introduction

For modern fighters flying at a high angle of attack, the longitudinal stability decreases as the angle of attack increases. The flying wing aircraft can also experience these conditions even at small angles of attack, i.e. the lift curve shows a nonlinear increase at small angles of attack and the nonlinear change of pitching moment has the potential to become unstable. Since as the angle of attack increases, flow separation occurs on the upper wing surface of the aircraft, causing the aerodynamic center to move forward. Additionally, since the longitudinal body size of a tailless aircraft is shorter, the moment of the force may change from static stability to static instability, greatly limiting the aerodynamic performance of the flying wing aircraft [1].

Aircrafts with a conventional configuration can be corrected by the horizontal tail, even if the longitudinal stability is poor. However, since flying wing aircrafts do not have a horizontal tail, the envelope of safe longitudinal control is much narrower than for conventional aircrafts. Therefore, in the initial design stage for flying wing aircrafts, significant consideration should be given to the question of how to broaden the available moment border as much as possible to delay the emergence of the turning point of the pitching moment, while achieving the design objectives. Traditional methods for improvement, such as airfoil design and wing sections twist, will adversely affect the overall performance of the aircraft. However, development of flow control technology provides an innovative solution for improvement.

Flow control technology uses the interaction of hydrodynamic forces between fluids to control and magnify the flow signal by changing the local flow [2,3]. Traditional aircraft flow control methods include slats, wing fence, vortex generator, boundary layer blow/suction etc., however these methods usually introduce additional resistance and need an air supply and vent line design. They also have shortcomings due to requirements for a complicated device structure and high control power. These methods are under the category of macro flow control. Although the newly emerging synthetic jet active control technology is lower energy, it essentially creates disturbances in sensitive areas of the flow field to change the local, or even the global, flow regime through coupling and amplification on a large scale, which can create a well-leveraged effect. In particular, modern synthetic jet exciters which use MEMS technology have multiple advantages including a simple and compact structure, light weight, low power consumption, and high sensitivity, while having little influence on the overall characteristics such as aerodynamic shape, structure and weight of the target aircraft, making it possible to finely control the flow.

Early studies of synthetic jet control mainly focused on aspects such as flow separation control, stall characteristics delay and analysis of the control mechanisms of two-dimensional airfoils [4–6]. Synthetic jet control studies using actual aircrafts, especially flying

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wing aircrafts, have mainly focused on wind tunnel tests and there are only a few studies existing in the literature. Boeing carried out a series of wind tunnel tests using synthetic jet control at low speeds for the "Stingray" demonstrator [7,8] and the results show that the synthetic jet control technology is effective for lift augmentation and drag reduction. Mahmood studied post-stall flow separation control under large angles of attack on a small aspect ratio flying wing configuration unmanned aerial vehicle (UAV). The wind tunnel test results show that synthetic jet control can achieve a 15% incremental lift and a 10% resistance reduction [9]. Wang Lixin carried out a vortex control study on a small aspect ratio flying wing UAV [10]. His study shows that interaction between the direct force from the vortex and the varying force from the flow field can provide the necessary roll moment for an operating aircraft; however the vortex control technique is essentially belonging to the category of macro flow control. Du Hai et al. studied the effect of plasma flow control technology on the aerodynamic moment of flying wing aircrafts and measured the control effects of parameters including excitation voltage [11].

In conclusion, due to its excellent aerodynamic properties, flow control of flying wing aircraft has become a hot research topic. However, research has mainly focused on the conventional aspects such as lift augmentation and drag reduction, while there has not been sufficient flow control research focused on improving the longitudinal stability performance of flying wing aircrafts and expanding the boundary targets of flight performance. Therefore, this paper performed a study to improve the longitudinal moment characteristics of flying wing aircraft using synthetic jet control technology, and analyzed the physical mechanism of control efficiency generated by the synthetic jet, and studied the effects of typical control parameters on the control efficiency. The purpose of this study is to verify the practical synthetic jet control simulation technology, and lay the foundation for promoting further application research.

2. Numerical model

2.1. Computational method

Synthetic jet calculation code developed by our research group is used in this study [12]. Synthetic jet flow control simulations require time-accurate solutions of the governing equations. The incompressible Navier–Stokes equations are used for the numerical simulations. Space discretization of the convective fluxes is performed using upwinding and Roe's approximate Riemann solver. Third order accurate, upwind biased formulas with high grid resolution are used to minimize the diffusion in the numerical solution and evaluate the convective flux derivatives. The viscous terms are computed using second-order accurate central differences. The eddy viscosity is computed using the two-equation turbulence model of Menter's SST k–ω model. The unsteady cases are performed with second order time accuracy and dual time stepping.

In the actual calculations, the flow control model is simplified and the internal flow field of the fluidic actuator is not included. Instead, the jet boundary condition is set at the exit of the actuator and thus the flow control parameters within the boundary condition are used to describe the jet characteristics. The synthetic jet disturbance is defined as:

$$u_{jet} = \sqrt{\frac{c}{2H}} U_\infty \left[\sqrt{c_{\mu 0}} + \sqrt{c_\mu} \sin\left(2\pi \frac{F^+ U_\infty}{x_{te}} t \right) \right] f(\zeta)\, d_{jet}$$

$$c_\mu = 2 \cdot \frac{\sum_{i=1}^{K} A_i}{A_{wing}} \cdot \left(\frac{u_{jet}}{U_\infty} \right)^2$$

$$F^+ = \frac{f \cdot c}{U_\infty}$$

The steady momentum blowing coefficient $c_{\mu 0}$ and the oscillatory momentum blowing coefficient c_μ determine the amplitude of synthetic jet, different actuator types can be modeled through appropriate combinations of $c_{\mu 0}$ and c_μ. Only the synthetic jets are considered in this study with $c_{\mu 0} = 0$. The non-dimensional frequency F^+ relates the period of the jet cycle to the convection time of the flow over the surface. Where u_{jet} is the instantaneous jet speed at the actuator nozzle, U_∞ is the free inflow velocity, A_i is the nozzle area of the i actuator, K is the number of actuators, A_{wing} is the model reference area, f is the actuator jet frequency, and c is the mean aerodynamic chord of the model. H determines an effective jet width, x_{te} is distance from actuator to trailing edge of model, where d_{jet} is a vector of unit length representing the direction of the jet outlet, θ_{jet} being the angle between d_{jet} and the wall. $f(\xi)$ is the tangential distribution of the velocity. The spatial variation of the jet in the tangential direction is supposed to have a negligible influence on the flow, therefore, a "top hat" tangential distribution is adopted, corresponding to $f(\xi) = 1$.

If multiple actuators are working simultaneously, it can be assumed that there is no phase difference between each actuator jet and their characteristics such as jet velocity, frequency and drift angle are consistent.

2.2. Numerical method validation

In order to verify whether the developed numerical simulation technology and established flow control model can accurately capture the subtle characteristics of the jet flow field, a Seifert TAU0015 airfoil flow control experiment [5,6,13] is selected for the numerical validation. Four sub-iteration steps are used in the calculation (four complete multigrid cycles) and a complete flow cycle is divided into 80 pieces. Generally, after 25∼35 cycles of calculation, a stable periodic flow solution after control can be achieved.

Fig. 1 shows the calculation results of the TAU0015 airfoil synthetic jet control, which are compared to the experimental data from Seifert and the OSC2D program results [14], wherein (a) shows the control effect of the airfoil under different angles of attack; (b) is the influence of the jet momentum coefficient on the control efficiency; and C_L is obtained based on calculation of a complete jet circle time-averaged C_p integral. As shown in the figure, when the airfoil angle of attack is greater than 12°, results of OSC2D and calculation in this paper sharply over-predict the experimental data even though there are consistent general variations. This is due to the fact that in the experiment, the sensors could not be installed near the flow actuator, and thereby the influence of the pressure peak at the leading edge on the aerodynamic characteristics could not be included. Calculations from Joslin and Viken also show that the experiment conducted by Seifert underestimated the lift characteristics of the airfoil [15]. Therefore, the selected numerical method and the established flow control model in this paper can effectively capture the flow field characteristics of the synthetic jet with good reliability and accuracy.

3. Calculation model

In theory, the larger the size of the jet nozzle, the greater the energy disturbance injected into the aircraft flow field, and the more significant the impact on the aircraft flow field. However, the size of jet actuator is restricted by factors such as the aircraft structure, aerodynamic shape, and actuator design, and thus cannot be very large. Also, if the size of the actuator is too small, the disturbance energy provided will be quickly extinguished, not being able to produce a sufficiently effective disturbance to the main flow field. Therefore, in practice, multiple actuators are generally