Computers & Fluids 99 (2014) 1–17

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Numerical and experimental investigations of a nonslender delta wing with leading-edge vortex flap

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ARTICLE INFO

Article history:
Received 20 September 2013
Received in revised form 10 March 2014
Accepted 12 March 2014
Available online 3 April 2014

Keywords:
Nonslender delta wing
Leading-edge vortex flap
Vortex breakdown control
Modified turbulence model

ABSTRACT

The aim of this paper is to numerically and experimentally evaluate the control efficiency of a series of leading-edge vortex flaps for a nonslender delta wing at a moderate Reynolds number. Both downward and upward deflected leading-edge vortex flaps are examined by experimental measurements and numerical simulations. It has been found in the wind tunnel experiments that the upward deflected vortex flap increases the vortex lift at low angles of attack due to the enhancement of the vortex strength while at high angles of attack the aerodynamic performances are significantly deteriorated due to a premature flow stall. Meanwhile the flap deflected downward has an excellent performance at high angles of attack, especially with a flap deflection angle of $-70°$. Consequently, numerical simulations of this optimal configuration are conducted to explore the mechanism of aerodynamic performance improvement and the vortical structures. A recently modified turbulence model has been demonstrated to be suitable to capture the complex vortex structures in this type of flow. In addition, the numerical results are in good agreement with those of the PIV data. Obviously the lift enhancement is due to the fact that the stall phenomenon of the baseline wing is significantly delayed by the vortex flap. This has been proved by the comparisons of vortical topologies, mean pressure coefficients and the limiting streamlines between the experimental measurements and the numerical simulations. Besides, the drag coefficient is reduced by an additional vortex system generated at the leeside of the flap. Furthermore, our simulations are capable of discerning the classical dominant frequencies of helical mode instability, Kelvin–Helmholtz instability and vortex wandering. Correspondingly some unsteady phenomena encountered in the two cases are investigated by the distributions of high levels of turbulent kinetic energy.

1. Introduction

The nonslender delta wing is a recently topic of interest due to its recent proposed application to micro-air vehicles and unmanned combat air vehicles which are highly flexible and require extreme maneuverability [1–3]. Although both of the maximum lift coefficient and stall angle of this type of delta wing are lower than those of the traditional slender delta wings [4], its aerodynamic performance is preferable at low to moderate angles of attack. It is well known that the flow past a delta wing undergoes various unsteady phenomena, including leading edge vortex formation, vortex wandering, vortex breakdown, shear layer instability, etc. Usually, these flow phenomena will interact with each other in a complex unsteady fashion. With respect to nonslender delta wings, the leeward side is dominated by separated and vortical flows, even at very low angles of attack [1]. Unlike the slender delta wings, the Reynolds number has strong influence on the vortical flows developing over moderately swept wings [5,6] and promotes the vortex breakdown followed by the disappearance of the primary vortex. One unique feature of nonslender delta wings is that the primary reattachment is observed outboard of the symmetry plane even after breakdown reaches the apex [1]. Generally, the largest buffeting imposed on the wing is detected just prior to stall [7]. Another distinct feature is that there exits a weaker second vortex which has the same sign of vorticity as the primary vortex and emerges in the separated shear layer outboard of the primary vortex, leading to a so-called dual primary vortex system at low angles of attack [2,8–10]. The generation of this second vortex is attributed to the interaction of the secondary flow with the shear layer which is split into two same-sign primary vortices by the impingement of the secondary separation [8,10]. With the incidence raised, the inboard primary vortex becomes more and more prominent than the second primary vortex.

In order to extend the application of nonslender delta wings to post stall regime, both active and passive flow control methods are

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http://dx.doi.org/10.1016/j.compfluid.2014.03.011
0045-7930/

used in the past literature [11] to modify the vortex location, strength and structure so that the lift enhancement, drag reduction, additional forces and moments for flight control, and suppression of wing buffet can be achieved. Various flow phenomena including flow separation, vortex formation, flow reattachment, and vortex breakdown are the targets of flow control strategies. For delta wings at high angles of attack, the dominant stalled flow is responsible for lift reduction and produces large buffet excitation level on the wing, thus the unsteady aerodynamic loads will excite wing structure vibration in their natural frequencies, leading to increase of fatigue loads and maintenance costs [12]. Hence delaying the vortex breakdown and flow stall is beneficial to increasing the stall angle, and to the improvement of aerodynamic behavior in high angles of attack. More specifically, it has been demonstrated that two key parameters affecting the occurrence and movement of vortex breakdown are swirl level and pressure gradient [11]. In addition, the onset of vortex breakdown over a delta wing moves upstream towards the apex as either parameter is increased. That is to say, in order to delay the breakdown or stall, the flow control strategies are supposed to focus on the modification of these two factors. Particularly in the post-stall region, active and passive control of flow reattachment is considered to contribute to lift enhancement.

Although active flow control methods are effective in various flow regimes of delta wings [13–15], the required complex devices inside the wings are not easy to manufacture and are usually heavy, bring extra weight and reducing the thrust-weight ratio of the flight vehicles. On the other hand, it is well known that the passive control technique, as a simple and reliable method, has been widely used in delta wings. Yang and Gursul [16] investigated the control efficiency of a variable leading-edge extension which had the ability to vary the sweep angle and demonstrated that this strategy was suitable for feedback control due to a monotonic variation trend of breakdown with sweep angle. A drooping apex flap [17] was considered as an effective control surface and could delay vortex breakdown. In addition, a 65°/65° chinard configuration [18] delayed the development of vortex breakdown owing to the beneficial interaction between the vortices generated by the forewing and the main wing. As an attractive tool, the leading edge vortex flap (LEVF) is employed to directly modify the strength and structure of vortices originating from the separation point along the leading edge. It was found that the drag of a delta wing was reduced and the lift-to-drag ratio was increased as the LEVF deflected downward [19]. On the other hand, the upward deflected flap induces a stronger leading edge vortex at low angles of attack, and accordingly promoted the vortex breakdown [20]. In the experiment on the 70-degree-sweep delta wing with a tapered vortex flap [21], the results showed that the lift coefficient was decreased as the LEVF deflected downward. However the stall angle increased with the deflected angle of the vortex flap, while the drag coefficient was decreased. It was observed in experiments [22] that a stronger vortex lift was generated by an upward deflected flap at low to moderate angles of attack. Deng and Gursul [20] experimentally studied the effect of upward deflected flaps on the vortex breakdown and reported that the efficiency of the flaps and sensitivity of breakdown location strongly depended on the angles of attack and the flap deflection angles. Marchman [23] found that the constant chord upward deflected vortex flap with flap deflection angle of 40° could increase the lift coefficient by about 0.18 at angles of attack prior to stall.

The above-mentioned investigations concentrated primarily on the control effect at low to moderate incidences, while that at post-stall angles of attack has been seldom involved. The present paper is dedicated to extending the range of applicability of LEVF to post-stall region, and the objective is twofold: firstly, to find the wing-flap configuration with optimal aerodynamic performance at high angles of attack by conducting wind tunnel force measurements and particle image velocimetry (PIV) experiment; secondly, to numerically investigate the mechanism of lift enhancement and vortical structures on the optimal configuration. Accordingly, the paper is organized as follows. Sections 2 and 3 describe the experiment setup and numerical strategy used in our work. Section 4 provides the force coefficients and PIV results in the wind tunnel. And Section 5 is dedicated to assessing the capability of the present numerical tool to simulate this type of flow and to presenting detailed simulation of the optimal configuration.

2. Experimental setup

The experiments were conducted in a low speed wind tunnel in Department of Fluid Mechanics of Northwestern Polytechnical University. This tunnel has a square test section with a height of 500 mm, a width of 600 mm, and a length of 700 mm. The maximum free stream velocity is 30 m/s, with a corresponding turbulence intensity of less than 0.6%. A schematic of the wind tunnel setup, the delta wing model and its size are presented in Fig. 1. The wing model is mounted on a six-degree-of-freedom strain-gauge internal balance, which in turn is mounted on an angle of attack (α)/sideslip angle (β) mechanism to control the wing's attitude angles. The lift and drag coefficients are calculated by the time-averaged voltage signals from the force balance which were acquired using a 16-bit National Instrument PCI-6221 data acquisition card at a sampling frequency of 1000 Hz over a period of

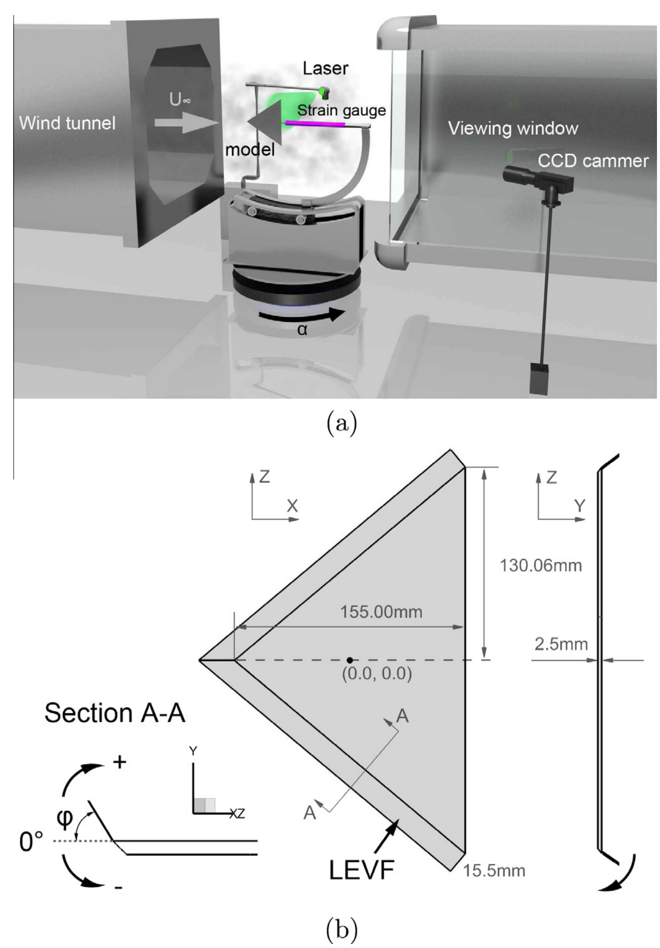

Fig. 1. The experimental setup: (a) schematic of the model in the wind tunnel test section, and (b) dimensions of the wing with a leading edge flap.