Aerospace Science and Technology 57 (2016) 103–117

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Vortical flow prediction of a diamond wing with rounded leading edges

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A R T I C L E I N F O

Article history:
Received 23 September 2015
Received in revised form 5 February 2016
Accepted 9 February 2016
Available online 18 February 2016

Keywords:
Diamond wing
Vortical flow
Validation
Swept wings with rounded leading edges

A B S T R A C T

The objective of this work is to assess the potential and limitations of current practice in computational fluid dynamic modeling in predicting vortical flowfields over a generic 53-degree swept diamond wing with rounded leading edges. This wing was designed under STO AVT Task Group 183 and has a constant NACA 64A-006 airfoil section with a leading edge radius of 0.264 percent chord. CFD simulations were run for different angles of attack at a Mach number of 0.15 and a Reynolds number of 2.7×10^6 based on the mean aerodynamic chord to match experiments. The wind tunnel experiments of the diamond wing were carried out in the Institute of Aerodynamics and Fluid Mechanics of the Technische Universität München, Germany and include aerodynamic lift, drag, and pitch moment measurements as well as span-wise pressure distributions at different chord-wise locations. This data set is used to validate the CFD results. The results presented demonstrate that the CFD compare well with the experiments at small angles of attack; the pitch moments predicted by the SARC turbulence model provide a better match to experimental results than the SA model at moderate angles of attack; and at high angles of attack, CFD predictions are not as good. The flow visualization results show that a leading-edge vortex is formed above the upper surface of the wing at an angle of attack of about eight degrees. This vortex becomes larger and stronger when the angle of attack is increased. With increasing angle of attack, the vortex formation point moves upstream and the vortex core moves inboard towards the wing center. Finally, the computational results show that the flow over the diamond wing is relatively steady throughout the range of angles of attack.

1. Introduction

Today's modern fighter aircraft typically employ a delta wing configuration to reduce the wave drag at supersonic speeds. The aerodynamic performances of these delta wings are vastly different from those known for the high-aspect ratio wings. In the latter case, the lift increases linearly with angle of attack in the attached flow region and then sharply decreases in the post-stall region [1]. The lift of a sharp delta wing has also an initial linear increase, but at an angle of attack of just few degrees there is an additional lift force to the attached flow lift which makes the lift-curve slope nonlinear. This additional lift, often called the vortex lift, is caused by the vortical flows formed above the wing [2]. The flow separation point of a sharp delta wing is fixed at the leading edge [2]. This creates a strong shear layer along the wing edges which will then roll up into a pair of counter-rotating vortices over the upper surface on the two halves of the wing [3]. These vortices are called leading-edge vortices and their structures depend on the wing's sweep angle, leading-edge geometry, wing thickness, and freestream conditions [4].

For a sharp-edged delta wing, the separation points are fixed at the leading edge for a considerable range of angle of attack [5]. The vortex strengths and vortex lift will therefore increase with the increase in the angle of attack. At higher angles, however, vortices experience an abrupt transformation called the vortex breakdown which is an asymmetric phenomenon. In a vortex breakdown, the axial velocity component suddenly decelerates and the swirl component of the mean velocity decreases due to the vortex core expansion [6]. The asymmetric vortex breakdown conditions result in additional moments in pitch, yaw, and roll with magnitudes as large or even larger than those obtained from traditional control surface deflections. The vortex breakdown may result sudden changes in pitch moment, loss of lift, and buffeting [7]. The sta-

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http://dx.doi.org/10.1016/j.ast.2016.02.011
1270-9638/Published by Elsevier Masson SAS.

Nomenclature

a	speed of sound	m/s
C_f	skin friction coefficient, $F/q_\infty S$	
C_L	lift coefficient, $L/q_\infty S$	
C_m	pitch moment coefficient, $\bar{M}/q_\infty Sc$	
C_p	pressure coefficient, $(p - p_\infty)/q_\infty$	
c	mean aerodynamic chord	m
c_r	chord length at wing root	m
F	skin friction force	N
L	lift force	N
M	Mach number, V/a	
$\bar{M}$	pitch moment	N m
p	static pressure	Pa
p_∞	freestream pressure	Pa
q_∞	dynamic pressure, $\rho V^2/2$	Pa
Re	Reynolds number, $\rho Vc/\mu$	
S	planform area	m^2
s	semi span	m
t	time	s
V	freestream velocity	m/s
x, y, z	aircraft position coordinates	

Greek

α	angle of attack	rad
β	side-slip angle	rad
ρ	air density	kg/m^3
μ	air viscosity	kg/(m s)

bility and control (S&C) and structural analysis of delta wings are therefore highly dependent on the ability to observe and accurately calculate the principle characteristics of vortical flows.

While the vortical flow behavior over slender wings with sharp leading edges has been studied extensively for over last few decades [8–10], much less is known about the formation of vortices over wings with lower sweep angles and blunt leading edges. These types of wings are often incorporated in the designs of unmanned combat aircraft vehicles (UCAV) [11]. For these wings, the vortex flow structure is very complicated and depends heavily on the leading edge bluntness and the wing sweep angle. For delta wings with blunt tips, the leading edge separation point is also very sensitive to the boundary layer changes [12]. The blunt tip vortices can also have significant effects on the stability and control characteristics of a maneuvering aircraft at high angles of attack. The objective of this work is to assess the potential and limitations of current practice in computational fluid dynamics (CFD) modeling for predicting vortical flowfields over a generic 53-degree swept diamond wing with blunt tips.

The diamond wing considered in this work was designed under STO AVT Task Group 183. The wing planform is based on the SACCON UCAV geometry. The SACCON wing trailing-edge was swept forward by 26.5°to form a diamond-shaped planform. The new wing has a constant airfoil section of NACA 64A-006 with a leading edge radius of 0.264 in percent chord. The wind tunnel experiments of the diamond wing were carried out in the Institute of Aerodynamics and Fluid Mechanics of Technische Universität München, Germany and include aerodynamic lift, drag, and pitch moment measurements as well as span-wise pressure distributions at different chord-wise locations. This data set is used to validate CFD results.

This work is organized into four major categories. First a survey of the literature and theories pertaining to the delta wing vortical flows is provided. The flow solvers are then briefly described. Next, the test case is presented and the experimental setup is detailed. Finally, the simulation results will be discussed.

2. Vortical flows

The vortical flow behavior over delta wings is extremely complex and differs substantially from sharp to blunt tipped wings and from nonslender to slender wings. Over the past few decades, most research on vortical flows was done on the vortices over slender sharp-edged delta wings [13]. Some early works in this field were reviewed by Sun [14] and most recently by Mitchell et al. [4]. In one of the earliest studies, Jensen (1948) [15] studied the low-speed flowfields and the lift and moment characteristics of a sweptback wing and a delta wing, both with a 65° sweptback

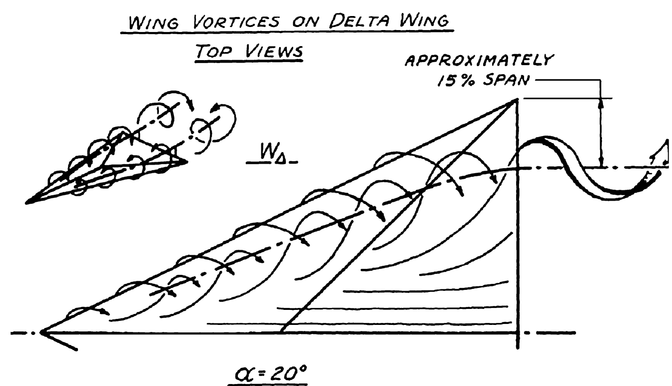

Fig. 1. Jensen's sketch of leading edge vortices over a delta wing at $\alpha = 20°$ [15].

leading edge and a double wedge symmetrical airfoil section. His results showed that two strong vortices are formed over the upper surfaces of both wings for angles of attack as low as 10°. A sketch of these vortices is shown in Fig. 1 for the delta wing case. Jensen's work also showed that the lift curve slope increases for angles of attack above ten degrees.

It is well known that a sharp leading edge causes the boundary layer to separate at the leading edge resulting a free shear layer. For a slender wing, the separated shear layers roll up into a pair of counter-rotating vortices over the upper surface on the two halves of the wing. The shear layer may exhibit instabilities that increase the vortical substructures and, therefore, the primary vortex increases in both size and strength as it extends downstream. Ornberg [16] in 1954 showed that these leading edge vortices are stationary and form a low pressure region over the upper surface that will increase the lift. Notice that this additional lift comes at the expense of a drag penalty due to loss of leading-edge suction [17]. The leading edge vortices allow the onset of stall to be delayed to higher angles as well. For steady and inviscid flow, the vortex lift can be approximated to some extent by the leading edge suction analogy [18], linear slender wing theory [19], or detached flow methods [20]. The Polhamus's leading edge suction analogy is probably the most widely applicable method to estimate the vortex lift of different planforms at different flight speeds. This analogy assumes that the vortex lift has the same magnitude as the potential-flow force which is lost because of the separation at the sharp leading edge [21]. The method has provided good results for attached vortices [18].

As the angle of attack increases, the cores of leading edge vortices will move inboard and secondary vortices can be formed below the main vortices [22]. Ornberg [16] in 1954 and Marsden et al. [23] in 1958 found the existence of these secondary