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Interaction of multiple vortices over a double delta wing

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ABSTRACT

Interaction of strake and wing vortices over a 70°/50° double delta wing were studied experimentally in a wind tunnel using particle image velocimetry (PIV) measurements. The upstream effect of the wing vortex on the formation of the strake vortex was identified. A dual-vortex structure of the strake vortices was observed before the wing vortex developed. Further downstream, wing and strake vortices rotated around each other slowly initially, and then faster with downstream distance, at an increasing rate with increasing incidence. Prior to vortex breakdown, both wing and strake vortices were found meandering in relatively small regions. The correlation between the instantaneous locations of the vortices increases if the vortices become sufficiently close to each other. The proper orthogonal decomposition (POD) analysis of the instantaneous velocity fields suggested that, for both wing and strake vortices, the most energetic mode was displacement in the first helical mode. The most energetic mode reveals out-of-phase displacements when the vortices are close to each other.

1. Introduction

Leading edge vortices play an important role in the aerodynamics of delta wings. A great deal of effort has been focused on the study of these vortices, vortex breakdown phenomenon, and aerodynamics of delta wings, as summarized in several review articles [1,2]. Gursul [3] has noted the lack of emphasis on the unsteady aspects of these flows. There have been very few studies on multiple vortices over aircraft type configurations. The main characteristics of the flow over aircraft configurations are the existence and interaction of multiple vortices that originate from forebodies, wings, strakes, and canards. These interactions are the most challenging aspect of the simulation of flows around aircraft configurations. A recent example of this is the flow simulations [4] of F-16XL aircraft (NATO AVT-113 research activity), where the inner and outer wing vortices interact. While the inner wing vortex was predicted well, the outboard vortex was not. It is believed that this may be due to the interaction of the two vortices and, in particular, the unsteady aspects of the interaction. Vortex interactions also exist on Unmanned Air Vehicles, such as X47-B. However, little is known about the interactions of these multiple vortices. The main objective of this study is to investigate vortex interactions over generic (and simple) wings, and ultimately to enable control of multiple vortices to improve aerodynamic performance and flight control.

Double delta wings [5] have been studied as generic configurations that have multiple vortices and vortex interactions. The main feature of the flow is the presence of both strake and wing vortices. At low angles of attack the vortices remain separate, whereas for flows at higher angles of attack the two vortices interact, coil-up, merge, and vortex breakdown develops. The interaction process and breakdown of the vortices depend on the angle of attack and leading edge sweep angles of the strake and wing [5,6]. Previous studies showed intensified interactions between strake and wing vortices as angle of attack increased, due to the increasing sizes and strengths of the vortices. Similar observations were also reported by Gai et al. [7] and Sohn and Chung [8]. Two adjacent co-rotating vortices with unequal strengths revolve around a center located on the connecting line between the two vortices. When the strengths of the two vortices are about the same, they tend to spiral around each other but still maintain their identities until merging occurs. It is known from the two-dimensional simulations and experiments that the merging process strongly depends on the strength of the vortices and the separation distance between them [9]. Vortices of comparable strength undergo a symmetric merger, whereas for large differences in strength, catastrophic merger occurs very rapidly as the weaker vortex is split and wrapped around the dominant vortex [10].

Surprisingly, for the interaction of multiple vortices over delta wings, there are no experimental studies that focus on the unsteady aspects. Turbulence kinetic energy and unsteady flow data could be invaluable for the validation of numerical simulations and various turbulence models. Previous simulations have used

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Nomenclature

a_M	Vortex meandering amplitude	z_i	The coordinate of instantaneous vortex location in the normal direction
c	Wing root-chord length	$\bar{z}$	The coordinate of time averaged vortex location in the normal direction
Re	Reynolds number, $\rho U_\infty c/\mu$	α	Angle of attack
t	Wing thickness	μ	Dynamic viscosity
U_{std}	Standard deviation of velocity fluctuations	ν	Kinematic viscosity
U_∞	Freestream velocity	ρ	Density
s	Local semi-span	ω	Vorticity
x	Chordwise distance	Λ	Sweep angle
y	Spanwise distance	N	Number of snapshots
y_i	The coordinate of instantaneous vortex location in the spanwise direction	r	Distance to the wing centerline
$\bar{y}$	The coordinate of time averaged vortex location in the spanwise direction	PIV	Particle image velocimetry
z	Distance from wing surface in the normal direction in the measurement plane	POD	Proper orthogonal decomposition
		UAV	Unmanned air vehicle

the time-averaged velocity or surface pressure for comparison. The study of Boelens et al. [4] showed that unsteady data are needed to improve the predictions. Little is known about the unsteady aspects of the interaction of multiple vortices. However, based on our knowledge of vortices on simple delta wings [3], we may expect vortex meandering, helical mode instability of vortex breakdown, quasi-periodic oscillations of breakdown location, and vortex shedding. Some of these unsteady flow phenomena may play a role in the unsteady interactions of multiple vortices. For example, oscillations of strake vortex breakdown may influence the wing vortex breakdown. Alternatively, unsteady features of the wing vortex (due to vortex meandering or helical mode instability) may influence the unsteadiness of the strake vortex. A coupling between the motions of breakdowns is a strong possibility. Additional complexity arises as the main wing has a lower sweep angle and vortex forms closer to the wing surface for nonslender wings [11]. This results in strong interactions of the vortex with the surface boundary layer and sometimes in a dual-vortex structure at low angles of attack. These features of the nonslender vortices may also have an effect on the unsteady aspects and the interaction of multiple vortices.

This paper reports an experimental study of the interactions of multiple vortices over a 70°/50° double delta wing with the kink at mid-chord. These sweep angles were chosen because simple delta wings with these sweep angles were extensively studied and reported in the literature. Particle Image Velocimetry (PIV) flow measurements over the double delta wing were conducted in a wind tunnel and compared to the flow over a simple slender delta wing with a sweep angle of 70°. Unsteady aspects such as vortex meandering and dominant flow features were analyzed and discussed.

2. Experimental apparatus and methods

2.1. Experimental setup

The experiments were conducted in a closed-loop wind tunnel with a test section of 2.13 × 1.52 × 2.70 m, located in the Department of Mechanical Engineering at the University of Bath. The tunnel has a maximum speed of 50 m/s and a freestream turbulence level of around 0.1% of the freestream velocity. Fig. 1 shows the experimental arrangement which includes the layout of the working section and the high-alpha rig. The wing models are attached to the high-alpha rig which allows the angle of attack to be varied with an accuracy of ±0.25 degrees as the wind tunnel is running.

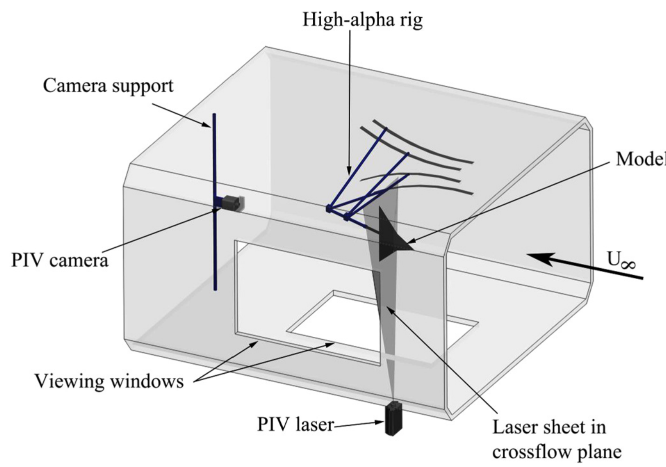

Fig. 1. Schematic of experimental setup.

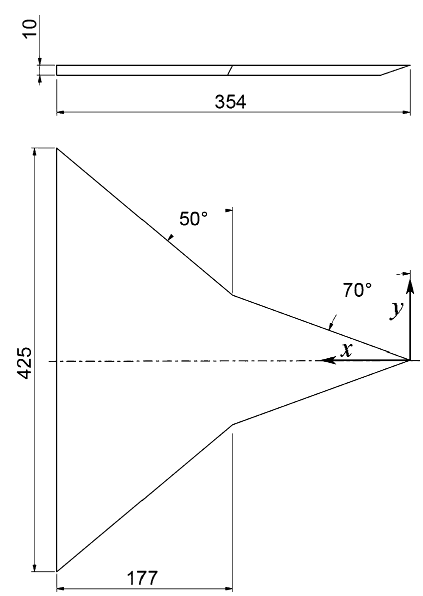

Fig. 2. The double delta wing model.

A double delta wing model with sweep angles of $\Lambda = 70°$ and 50° (with the kink at mid-chord, as shown in Fig. 2), and a simple slender delta wing model of $\Lambda = 70°$ were tested. Both models had a chord length of $c = 354$ mm and a thickness-to-