Interaction of Thrust Vectoring Jets with Wing Vortical Flows

Submitted by Ping Jiang

for the degree of PhD

of the University of Bath

2009

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ABSTRACT

It has been widely anticipated that thrust vectoring could be an effective method of providing sufficient levels of stability and control for highly manoeuvrable and flexible Unmanned Combat Air Vehicles (UCAVs). The present project aims to understand the interactions of delta wing vortical flows and thrust vectoring, with an emphasis on unsteady aspects. Food-colouring dye flow visualization, Laser-induced fluorescent flow visualization, Particle Image Velocimetry (PIV) and force measurements were conducted in the water and wind tunnels over a range of dimensionless frequencies and jet momentum coefficients. Both slender and nonslender wings were tested with the purpose of understanding the effect of sweep angle on the aerodynamics-propulsion interaction.

The interaction of statically pitched trailing-edge jets with leading-edge vortices over stationary delta wings was studied. It was found that under-vortex blowing with rectangular nozzle at stall and post-stall regimes could yield the maximum effectiveness of trailing-edge blowing, due to the promotion of earlier reattachment and delay of vortex breakdown. The effect of nozzle geometry can be important, because the entrainment effect of the jet depends on it. Studies of the flow field reveal strong jet-vortex interactions, distortion of jet vortices, and merging of wing and jet vortices. The dynamic responses of wing vortical flows to dynamic trailing-edge blowing exhibit hysteresis and phase lag, which increases with the increasing dimensionless frequency of jet momentum. Time delay for the decelerating jet is significantly larger than that for the accelerating jet. Sweep angle has no significant influence on the effect of unsteady trailing-edge blowing. From a design aspect, hysteresis and time delay need to be considered for the flight control systems.
ACKNOWLEDGEMENT

First of all, I wish to thank my supervisor, Professor Ismet Gursul and Dr. Zhijin Wang for all the help and support from them. Professor Ismet Gursul gave me very good guidance and a great deal of valuable advices on my three years’ research. He even helped me develop good working habits in the scientific research; Dr. Zhijin instructed me on experimental methodology, and gave me a lot of help with my writing-up. I also wish to give many thanks to the technicians who helped me during my PhD study. Les, Andy, H and Roland gave me great help by producing and fixing my test models. In particular, Les and Andy helped me to clean the whole water tunnel for laser-induced fluorescent flow visualization tests. Vajay spent a lot of time designing and testing the electrical control parts for my setup. Collin and Jeff debugged the HP VEE programme for the control system of the test rig. I also wish to thank the members of Aerodynamic Group. Special thanks will go out to Dr. Eleni Vardaki, Dr. Sam Heathcote, Dr. David Marles, Dr. Panagoitis and Nathan Williams. They gave me much valuable advice on my tests and my data analysis. Thanks also go to Paul, Charbel, Anna, Nick, Pinnuta, Carl, Luke, Dario, Kunyuan and Leisheng for creating a fantastic atmosphere in the office. I also wish to thank my landlords, Anne and Peter, who treat me as one of their family members, and make me feel comfortable and cozy. Finally I would like to thank my parents Xiuling Guo and Guofu Jiang for all the emotional and economic support they have given me during the time I spent working on my PhD study.

Many thanks to all!
# TABLE OF CONTENTS

**ABSTRACT** ............................................................................................................................. I

**ACKNOWLEDGEMENT** ........................................................................................................ II

**TABLE OF CONTENTS** ........................................................................................................ III

**NOMENCLATURE** ................................................................................................................ VII

**LIST OF FIGURES** .............................................................................................................. IX

**CHAPTER 1  INTRODUCTION** .......................................................................................... 1

1.1 Background ........................................................................................................................... 1

1.2 Literature Review ................................................................................................................ 3

1.2.1 Aerodynamics of Delta Wing ....................................................................................... 3

1.2.1.1 Delta Wing ............................................................................................................. 3

1.2.1.2 Flows over Slender Delta Wings ......................................................................... 5

1.2.1.3 Flows over Nonslender Delta Wings .................................................................... 6

1.2.1.4 Vortex Breakdown ............................................................................................... 8

1.2.1.4.1 Types of vortex breakdown ......................................................................... 9

1.2.1.4.2 Mechanisms of vortex breakdown ............................................................... 10

1.2.1.4.3 Parameters affecting vortex breakdown ..................................................... 11

1.2.1.4.4 Oscillations of vortex breakdown location ............................................... 12

1.2.1.4.5 Vortex breakdown in unsteady flows ......................................................... 13

1.2.1.4.6 Mechanism of time lag ............................................................................. 15

1.2.2 Unsteady Vortical Flow Control ................................................................................. 16

1.2.3 Trailing-Edge Jet Blowing ......................................................................................... 17

1.2.3.1 Vortex Breakdown and Trailing-Edge Jets ....................................................... 17

1.2.3.2 Entrainment Effects of Trailing-Edge Jets ...................................................... 20

1.2.4 Objectives ................................................................................................................... 21

Chapter 1 Figures ..................................................................................................................... 23

**CHAPTER 2  METHODOLOGY** ......................................................................................... 35

2.1 Experimental Apparatus ............................................................................................... 35
2.1.1 Wind Tunnel Facility ........................................................................................................ 35
2.1.2 Water Tunnel Facility ........................................................................................................ 36
2.1.3 Experimental Models ......................................................................................................... 37
  2.1.3.1 Delta Wing Models ..................................................................................................... 37
  2.1.3.2 Nozzle Design of Trailing-Edge Jets ......................................................................... 38
2.1.4 Trailing-Edge Jet Setup ...................................................................................................... 38
  2.1.4.1 Static Trailing-Edge Jet Setup .................................................................................. 38
  2.1.4.2 Unsteady Pitched Trailing-Edge Jet Setup .............................................................. 39
  2.1.4.3 Unsteady Blowing Trailing-Edge Jet Setup ............................................................ 40
2.2 Experimental Methods ......................................................................................................... 41
  2.2.1 Food-Colouring Dye Flow Visualization ......................................................................... 41
    2.2.1.1 Experimental Method ......................................................................................... 41
    2.2.1.2 Data Processing ................................................................................................. 43
    2.2.1.3 Uncertainty Analysis ......................................................................................... 43
  2.2.2 Laser-Induced Fluorescent Flow Visualization ............................................................ 44
    2.2.2.1 Experimental Method ......................................................................................... 44
  2.2.3 Particle Image Velocimetry ............................................................................................ 45
    2.2.3.1 Experimental Method ......................................................................................... 45
    2.2.3.2 Data Processing ................................................................................................. 47
    2.2.3.3 Vorticity and Circulation .................................................................................... 47
    2.2.3.4 Uncertainty Analysis ......................................................................................... 49
  2.2.4 Force Measurements ....................................................................................................... 50
    2.2.4.1 Experimental Method ......................................................................................... 50
    2.2.4.2 Data Validation ................................................................................................. 51
    2.2.4.3 Uncertainty Analysis ......................................................................................... 52
Chapter 2 Figures .................................................................................................................. 54

CHAPTER 3 EFFECT OF STATIC THRUST VECTORING JETS ON DELTA WING AERODYNAMICS .............................................................. 66

3.1 Summary .............................................................................................................................. 66
5.3 Scope for Future Work ........................................................................................................186
5.4 Closing Comments ...........................................................................................................187

CHAPTER 6      REFERENCES ...................................................................................188
APPENDIX      LIST OF PUBLICATIONS PRODUCED FROM THE PROJECT .....................195
## NOMENCLATURE

### LATIN SYMBOLS

<table>
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<tr>
<th>SYMBOL</th>
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<td>Limiting angle of attack</td>
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<td>β</td>
<td>Jet pitch Angle</td>
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<td>Φ</td>
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## ABBREVIATION

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<tr>
<td>3D</td>
<td>Three-Dimensional</td>
</tr>
<tr>
<td>CCD</td>
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<td>PIV</td>
<td>Particle Image Velocimetry</td>
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<td>MAV</td>
<td>Micro Air Vehicle</td>
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<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Air Vehicle</td>
</tr>
<tr>
<td>UCAV</td>
<td>Unmanned Combat Air Vehicle</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

CHAPTER 1

Figure 1.1: Conceptual UCAV configurations [12] ...............................................................23
Figure 1.2: Schematics of thrust vectoring .............................................................................23
Figure 1.3: Leading-edge vortices over the top surface of a delta wing [31]..........................24
Figure 1.4: Schematic of the leading-edge of delta wing behind the shock wave. ...............24
Figure 1.5: The delta winged Convair F106 Delta Dart [18] ..................................................25
Figure 1.6: Schematic of the subsonic flow field over the top of a delta wing [18] ...............25
Figure 1.7: Schematic of the spanwise pressure coefficient distribution over a delta wing...26
Figure 1.8: Contribution of various effects to the total lift over delta wing [34].......................26
Figure 1.9: Schematic streamline patterns for (a) reattachment on the wing surface (b) no reattachment on the wing surface [33] ...............................................................................27
Figure 1.10: Streamline pattern and magnitude of time-averaged velocity near the wing surface in water tunnel experiments, Λ=50° [35] .................................................................28
Figure 1.11: Crossflow vorticity from PIV measurements showing dual vortex structures [36]. ........................................................................................................................................28
Figure 1.12: Dual vortex structures in a cross plane by computational simulations [37]. .......29
Figure 1.13: Variation of lift coefficient as a function of angle of attack [13] .........................29
Figure 1.14: A flow visualization of Bubble-type(above) and Spiral-type (below) vortex breakdown over a delta wing [20] ..................................................................................30
Figure 1.15: Bubble-type(above) and Spiral-type (below) vortex breakdown over a delta wing [42]. ........................................................................................................................................30
Figure 1.16: Breakdown location over delta wing of Λ=75° [53] ...........................................31
Figure 1.17: Time histories of breakdown locations for left (solid line), and right (dash line) vortices for α = 37 deg and Λ= 70 deg [60] .................................................................31
Figure 1.18: Spectrum of unsteady flow phenomena over delta wings as a function of dimensionless frequency [65] ..................................................................................32
Figure 1.19: Chordwise breakdown location as a function of angle of attack for a pitching motion wing [69] .................................................................................................32
CHAPTER 2

Figure 2.1:  Planar view of wind tunnel.................................................................54
Figure 2.2:  Overview of experimental setup in the wind tunnel............................54
Figure 2.3:  Sketch of the Eidetics model 1520 water-tunnel. .................................55
Figure 2.4:  Dimensions of delta wing models tested in the water tunnel (wind tunnel) ....55
Figure 2.5:  Sketch of delta wing model for Laser-induced fluorescent visualization.....56
Figure 2.6:  Dimensions of rectangular nozzle tested in the water tunnel (wind tunnel) ...56
Figure 2.7:  Dimensions of circular nozzle tested in the water tunnel (wind tunnel). .......57
Figure 2.8:  Dimensions of rectangular nozzle built with a 30° yaw angle for water tunnel (wind tunnel) experiments.................................................................57
Figure 2.9:  Experimental arrangement..................................................................58
Figure 2.10: Schematics of unsteady pitching jet system (for force measurements). .....59
Figure 2.11: Illustration of trailing-edge jet pitching angle in the water tunnel (Wing model was placed upside down). .................................................................60
Figure 2.12: Illustrative diagram of dynamic blowing jet system..............................61
Figure 2.13: Schematic of calculation of the vortex breakdown location..................62
Figure 2.14: Example of Laser-Induced Fluorescent flow visualization. Red (upper):
Leading-edge vortex; Yellow (lower): Jet vortex.................................................62
Figure 2.15: Experimental arrangement in the water tunnel....................................63
Figure 2.16: Sensotec Model 31 load Cells for force measurement............................64
Figure 2.17: Variation of $C_N$ as a function of angle of attack for nonslender wing ($\Lambda=50^\circ$),
$\beta=0^\circ$, $C\mu=0$...............................................................................................64
Figure 2.18: Variation of $C_N$ as a function of angle of attack for slender wing ($\Lambda=65^\circ$), $\beta=0^\circ$,
CHAPTER 3

Figure 3.1: Changes in lift coefficient for the nonslender wing ($\Lambda=50^\circ$) with trailing-edge blowing with rectangular nozzle.................................78

Figure 3.2: Laser fluorescence flow visualization pictures in a cross-flow plane for nonslender wing ($\Lambda=50^\circ$), $\beta=30^\circ$, $C_\mu=0.43$, $y_{jet}/(b/2)=-0.6$. Laser sheet was placed at $x/c=0.8$........................................................................................................79

Figure 3.3: Food-colouring dye flow visualization for nonslender wing ($\Lambda=50^\circ$), $y_{jet}/(b/2)=-0.6$, $\beta=0^\circ$............................................................................................80

Figure 3.4: Variation of the delay of vortex breakdown location as a function of the spanwise location of the jet. $\Lambda=50^\circ$, $\beta=20^\circ$, rectangular nozzle. (a)$\alpha=10^\circ$; (b)$\alpha=15^\circ$; (c)$\alpha=20^\circ$..............................................................................................................81

Figure 3.5: Time-averaged cross-flow vorticity field at $x/c=0.8$ for the nonslender wing. $\Lambda=50^\circ$, $\alpha=20^\circ$, $\beta=30^\circ$, $y_{jet}/(b/2)=-0.6$, rectangular nozzle.................................82

Figure 3.6: Magnitude of time-averaged velocity and streamline pattern near wing surface. $\Lambda=50^\circ$, $\alpha=20^\circ$, $\beta=30^\circ$, $y_{jet}/(b/2)=-0.6$, rectangular nozzle. (a) $C_\mu=0$; (b) $C_\mu=0.24$; (c) $C_\mu=0.43$; (d) $C_\mu=1$........................................................................................................83

Figure 3.7: Changes in $C_L$ under the effect of blowing with rectangular nozzle for slender wing ($\Lambda=65^\circ$). .................................................................84

Figure 3.8: Laser fluorescence flow visualization pictures for slender wing ($\Lambda=65^\circ$), $\beta=30^\circ$, $C_\mu=0.43$. Laser sheet was placed at $x/c=0.8$..................................................85

Figure 3.9: Food-colouring dye flow visualization for slender wing ($\Lambda=65^\circ$), $y_{jet}/(b/2)=-0.5$, $\beta=0^\circ$..................................................................................................86

Figure 3.10: Variation of the delay of vortex breakdown location as a function of jet pitch angle. $\Lambda=65^\circ$, $C_\mu = 0.43$, $y_{jet}/(b/2)=-0.6$, rectangular nozzle .........................88

Figure 3.11: Optimum effectiveness of trailing-edge jet as a function of wing sweep angle from various studies. .................................................................88
Figure 3.12: Changes in lift coefficient for nonslender wing ($\Lambda=50^\circ$) with trailing-edge blowing with circular nozzle. ................................................................. 89

Figure 3.13: Vorticity in a cross-flow plane at $\Delta x/c=0.25$ for circular nozzle (left column) and rectangular nozzle (right column). (a) and (b) are for jet only with no wing; (c) and (d) with wing, $C_\mu=0.24$, $\alpha=20^\circ$, $\beta=0^\circ$. ......................................................... 90

Figure 3.14: Vorticity in a cross-flow plane at $\Delta x/c=0.25$ for (a) circular nozzle (b) rectangular nozzle, $C_\mu=0.24$, $\alpha=24^\circ$, $\beta=0^\circ$. ........................................................ 91

Figure 3.15: Vorticity in a cross-flow plane at $\Delta x/c=0.25$ for rectangular nozzle, (a), $C_\mu=0.24$, (b), $C_\mu=0.43$, $\alpha=20^\circ$, $\beta=0^\circ$. ................................................................................ 92

Figure 3.16: Laser fluorescence flow visualization in a cross-flow plane at $\Delta x/c=0.25$, $\Lambda=65^\circ$, $\alpha=10^\circ$, rectangular nozzle, $y_{jet}/(b/2)=-0.6$. ................................................................. 93

Figure 3.17: Effect of jet yaw angle on changes in $C_L$ for (a), nonslender wing ($\Lambda=50^\circ$); (b), slender wing ($\Lambda=65^\circ$). $y_{jet}/(b/2)=-0.6$, rectangular nozzle. ............................................. 95

Figure 3.18: Flow visualization for three different values of jet yaw angle for $\alpha=32^\circ$, $\Lambda=65^\circ$, $C_\mu=0.24$, $\beta=0^\circ$. ..................................................................................... 96

Figure 3.19: Time-averaged cross-flow vorticity field at the trailing-edge ($x/c=1.0$) for (a) $\gamma=0^\circ$, (b) $\gamma=30^\circ$ (inboard blowing). Rectangular nozzle, $\Lambda=65^\circ$, $\alpha=10^\circ$, $\beta=0^\circ$, $C_\mu=0.24$, $y_{jet}/(b/2)=-0.6$. ..................................................................................... 97

CHAPTER 4

Figure 4.1: Food-colouring dye flow visualization over nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing at different $f^*$, $\alpha=20^\circ$. ......................................................... 118

Figure 4.2: Phase-averaged vortex breakdown location as a function of normalized time $t/T$ over nonslender delta wing ($\Lambda=50^\circ$), (a) $\alpha=20^\circ$, (b) $\alpha=25^\circ$. ................................................. 119

Figure 4.3: Phase-averaged normal force coefficient as a function of normalized time $t/T$ over nonslender delta wing ($\Lambda=50^\circ$), (a) $\alpha=20^\circ$, (b) $\alpha=25^\circ$. ................................................. 120

Figure 4.4: Variation of phase lags of the dynamic response of normal force ($\phi_N$) and vortex breakdown ($\phi_b$) as a function of dimensionless blowing frequency over nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing. ........... 121
Figure 4.5: Variation of normalized time constant $\tau_{U_\infty/c}$ of vortex breakdown ($\tau_b \bigr)$ and normal force coefficient ($\tau_N \bigr$) over nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing, at $\alpha = 20^\circ$ and $25^\circ$.................................121

Figure 4.6: Variation of peak-to-peak amplitude of vortex breakdown location $\Delta X_{bd}$ as a function of dimensionless frequency $f^*$ of nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing, at $\alpha = 20^\circ$ and $25^\circ$.................................122

Figure 4.9: Variation of mean value of normal force coefficient $C_{N,mean}$ as a function of dimensionless frequency $f^*$ of nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing, at $\alpha = 20^\circ$ and $25^\circ$.................................123

Figure 4.10: Food-colouring dye flow visualization over slender delta wing ($\Lambda=65^\circ$) with periodic trailing-edge blowing at different $f^*$, $\alpha=35^\circ$.................................124

Figure 4.11: Phase-averaged vortex breakdown location as a function of normalized time $t/T$ over slender delta wing ($\Lambda=65^\circ$), (a) $\alpha=35^\circ$, (b) $\alpha=40^\circ$. ..........................................125

Figure 4.12: Phase-averaged normal force coefficient $C_N$ as a function of normalized time $t/T$ over slender delta wing ($\Lambda=65^\circ$) at $\alpha=30^\circ$...................................................126

Figure 4.13: Variation of phase lags of the dynamic response of normal force ($\phi_N$) and vortex breakdown ($\phi_b$) as a function of dimensionless blowing frequency $f^*$ for slender delta wing ($\Lambda=65^\circ$) with periodic trailing-edge blowing. ..............................................126

Figure 4.14: Variation of peak-to-peak amplitude of vortex breakdown location $\Delta X_{bd}/c$ and normal force coefficient $\Delta C_N$ as a function of dimensionless frequency over slender delta wing ($\Lambda=65^\circ$) with periodic trailing-edge blowing. ..............................................127

Figure 4.15: Variation of normalized time constant $\tau_{U_\infty/c}$ of vortex breakdown ($\tau_b \bigr)$ and normal force coefficient ($\tau_N \bigr$) over slender delta wing ($\Lambda=65^\circ$) with periodic trailing-edge blowing. .................................................................127

Figure 4.16: Variation of mean value of phase-averaged vortex breakdown location ..........128

Figure 4.17: Dynamic response of vortex breakdown over nonslender delta wing ($\Lambda=50^\circ$) at $\alpha=25^\circ$, for (a) accelerating $C_\mu$; (b) decelerating $C_\mu$......................................................129

Figure 4.18: Dynamic response of vortex breakdown of nonslender delta wing ($\Lambda=50^\circ$) at $\alpha=20^\circ$, for (a) accelerating $C_\mu$; (b) decelerating $C_\mu$......................................................130

Figure 4.19: Dynamic response of normal force coefficient of nonslender delta wing ($\Lambda=50^\circ$)
at $\alpha=25^\circ$, for (a) accelerating $C_{\mu}$; (b) decelerating $C_{\mu}$.................................131

Figure 4.20: Dynamic response of normal force coefficient of nonslender delta wing ($\Lambda=50^\circ$) at $\alpha=20^\circ$, for (a) accelerating $C_{\mu}$; (b) decelerating $C_{\mu}$.................................132

Figure 4.21: Phase-averaged vorticity in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................133

Figure 4.22: Phase-averaged velocity vectors in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................134

Figure 4.23: Phase-averaged streamline pattern in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................135

Figure 4.24: Phase-averaged vorticity in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................136

Figure 4.25: Phase-averaged velocity vectors in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................137

Figure 4.26: Phase-averaged streamline pattern in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................138

Figure 4.27: Variation of normalized circulation of vortical flow in a cross-flow plane at $x/c=0.3$ over nonslender delta wing for accelerating and decelerating jet momentum coefficient, $f^*=0.09$, $\alpha=25^\circ$, $\Lambda=50^\circ$.................................139

XIV
Figure 4.28: Variation of normalized time constants $\tau/T$ of vortex breakdown, normal force coefficient and circulation over nonslender delta wing for accelerating and decelerating jet momentum coefficient, $\alpha=25^\circ$, $\Lambda=50^\circ$.....................................139

Figure 4.29: Variation of normalized time constant $\tau U_\infty/^c$ of vortex breakdown, normal force coefficient and circulation over nonslender delta wing for accelerating and decelerating jet momentum coefficient, $\alpha=25^\circ$, $\Lambda=50^\circ$.....................................140

Figure 4.30: Phase-averaged vorticity in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. ...........................................................................................141

Figure 4.31: Phase-averaged velocity vectors in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. ...........................................................................................142

Figure 4.32: Phase-averaged streamline pattern in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. ...........................................................................................143

Figure 4.33: Phase-averaged vorticity in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. ...........................................................................................144

Figure 4.34: Phase-averaged velocity vectors in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. ...........................................................................................145

Figure 4.35: Phase-averaged streamline pattern in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. ...........................................................................................146
Figure 4.36: Near-surface streamline pattern for the nonslender (Λ = 50°) wing for accelerating momentum coefficient, α=20°, f* = 0.09. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................147

Figure 4.37: Magnitude of time averaged velocity near the wing surface for the nonslender (Λ = 50°) wing for accelerating momentum coefficient, α=20°, f* = 0.09. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................148

Figure 4.38: Near-surface streamline pattern for the nonslender (Λ = 50°) wing for decelerating momentum coefficient, α=20°, f* = 0.09. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................149

Figure 4.39: Magnitude of time averaged velocity near the wing surface for the nonslender (Λ = 50°) wing for decelerating momentum coefficient, α=20°, f* = 0.09. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements. .................................................................150

Figure 4.40: Variation of normalized circulation of vortical flow in a cross-flow plane at x/c=0.3 over nonslender delta wing for accelerating and decelerating momentum coefficient, f* = 0.09, α=20°, Λ=50°.............................................151

Figure 4.41: Variation of normalized time constants τ/T of vortex breakdown, normal force coefficient and circulation over nonslender delta wing for accelerating and decelerating momentum coefficient, α=20°, Λ=50°.............................................151

Figure 4.42: Variation of normalized time constant τU∞/c of vortex breakdown, normal force coefficient and circulation over nonslender delta wing for accelerating and decelerating momentum coefficient, α=20°, Λ=50°.............................................152

Figure 4.43: Dynamic response of vortex breakdown over slender delta wing, Λ=65°, α=35°, for (a) accelerating Cμ; (b) decelerating Cμ.................................................................153

Figure 4.44: Dynamic response of vortex breakdown over slender delta wing, Λ=65°, α=40°, for (a) accelerating Cμ; (b) decelerating Cμ.................................................................154

Figure 4.45: Dynamic response of normal force coefficient over slender delta wing, Λ=65°,
$\alpha=35^\circ$, for (a) accelerating $C_\mu$; (b) decelerating $C_\mu$. 

Figure 4.46: Phase-averaged vorticity in a cross-flow plane over slender delta wing for accelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.

Figure 4.47: Phase-averaged velocity vectors in a cross-flow plane over slender delta wing for accelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.

Figure 4.48: Phase-averaged streamline pattern in a cross-flow plane over slender delta wing for accelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.

Figure 4.49: Phase-averaged vorticity in a cross-flow plane over slender delta wing for decelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.

Figure 4.50: Phase-averaged velocity vectors in a cross-flow plane over slender delta wing for decelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.

Figure 4.51: Phase-averaged streamline pattern in a cross-flow plane over slender delta wing for decelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.

Figure 4.52: Variation of normalized circulation of vortical flow in a cross-flow plane at $x/c=0.8$ over slender delta wing for accelerating and decelerating jet momentum coefficient, $f^* = 0.09$, $\alpha=35^\circ$, $\Lambda=65^\circ$.

Figure 4.53: Variation of normalized time constants $\tau/T$ of vortex breakdown and circulation over slender delta wing for accelerating and decelerating jet momentum.
coefficient, $\alpha=35^\circ$, $\Lambda=65^\circ$. .................................................................162

Figure 4.54: Variation of normalized time constant $\tau U_\infty/c$ of vortex breakdown and circulation over slender delta wing for accelerating and decelerating jet momentum coefficient, $\alpha=35^\circ$, $\Lambda=65^\circ$. .................................................................163

Figure 4.55: Variation of normalized time constants $\tau/T$ of vortex breakdown over slender delta wing for accelerating and decelerating jet momentum coefficient, $\alpha=40^\circ$, $\Lambda=65^\circ$. ................................................................................................................163

Figure 4.56: Variation of normalized time constant $\tau U_\infty/c$ of vortex breakdown over a slender delta wing for accelerating and decelerating jet momentum coefficient, $\alpha=40^\circ$, $\Lambda=65^\circ$. ................................................................................................................164

Figure 4.57: Phase-averaged variations of $X_{bd}/c$ over nonslender wing with transient trailing-edge blowing, $\Lambda=50^\circ$, (a) $\alpha=20^\circ$, (b) $\alpha=25^\circ$ ..................................................165

Figure 4.58: Variation of phase lags of the dynamic response of vortex breakdown ($\phi_b$) as a function of dimensionless blowing frequency for nonslender wing with transient trailing-edge blowing.............................................................166

Figure 4.59: Variation of peak amplitude of the dynamic response of vortex breakdown ($\Delta X_{bd}/c$) as a function of dimensionless blowing frequency for nonslender wing with transient trailing-edge blowing. ..........................................................166

Figure 4.60: Phase-averaged variations of $X_{bd}/c$ over slender wing with transient trailing-edge blowing, $\Lambda=65^\circ$, (a) $\alpha=35^\circ$, (b) $\alpha=40^\circ$. .............................................................167

Figure 4.61: Variation of phase lags of the dynamic response of vortex breakdown ($\phi_b$) as a function of dimensionless blowing frequency for slender wing with transient trailing-edge blowing. ..........................................................168

Figure 4.62: Variation of peak amplitude of the dynamic response of vortex breakdown ($\Delta X_{bd}/c$) as a function of dimensionless blowing frequency for slender wing transient trailing-edge blowing..........................................................168

Figure 4.63: Food-colouring dye flow visualization for slender wing at different dimensionless frequencies $f^*$ with a periodically pitching jet, $\alpha=20^\circ$. ..............169

Figure 4.64: Phase-averaged variations of $X_{bd}/c$ for slender wing ($\Lambda=65^\circ$) with a periodically pitching jet, $\alpha=20^\circ$. .........................................................................................170
Figure 4.65: Phase-averaged variations of $C_N$ for slender wing with a periodically pitching jet, (a) $\alpha=10^\circ$, (b) $\alpha=20^\circ$, (c) $\alpha=30^\circ$, (d) $\alpha=40^\circ$.

Figure 4.66: Hysteresis loops of phase-averaged variations of $C_N$ for slender wing with a periodically pitching jet, column (a) $\alpha=10^\circ$, (b) $\alpha=20^\circ$, (c) $\alpha=30^\circ$, (d) $\alpha=40^\circ$.

Figure 4.67: Variations of phase lags of $C_N$ ($\phi_N$) and $X_{bd}/c$ ($\phi_b$) as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet.

Figure 4.68: Variations of normalized time constant $\tau U_\infty/c$ of $C_N$ as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet.

Figure 4.69: Variations of peak-to-peak amplitude of vortex breakdown location $\Delta X_{bd}/c$ as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet, $\Lambda=65^\circ$, $\alpha=20^\circ$.

Figure 4.70: Variations of peak-to-peak amplitude of normal force coefficient $\Delta C_N$ as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet.

Figure 4.71: Mean values of normal force coefficient $C_{N,mean}$ as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet.

Figure 4.72: Phase-averaged variations of $C_N$ for nonslender wing with a periodically pitching jet, (a) $\alpha=10^\circ$, (b) $\alpha=15^\circ$, (c) $\alpha=20^\circ$, (d) $\alpha=25^\circ$.

Figure 4.74: Variations of phase lags of $C_N$ ($\phi_N$) as a function of dimensionless frequency $f^*$ for nonslender wing with a periodically pitching jet.

Figure 4.75: Variations of normalized time constant $\tau U_\infty/c$ of $C_N$ as a function of dimensionless frequency $f^*$ for nonslender wing with a periodically pitching jet.

Figure 4.76: Variations of peak-to-peak amplitude of normal force coefficient $\Delta C_N$ as a function of dimensionless frequency $f^*$ for nonslender wing with a periodically pitching jet.

Figure 4.77: Variations of mean value of $C_{N,mean}$ as a function of dimensionless frequency $f^*$ for nonslender wing with a periodically pitching jet.
CHAPTER 1 INTRODUCTION

1.1 Background

Unmanned Air Vehicles (UAVs), commonly referred to as remotely operated aircraft or unpiloted aerial vehicles, are those power driven aircraft that can be operated without a flight crewmember on board. They can be remotely guided or have autonomous flight capability based on pre-programmed flight plans using complex automation systems [1-3]. Compared with cruise missiles, UAVs can be reused and are usually capable of controlled, sustained and level flight. In contrast to other aircraft, the significant advantage of UAVs lies in that they are not constrained by human limitations and requirements. Some manoeuvres that would be beyond the 9g limit of pilots could be achieved with an unmanned vehicle [4]. UAVs can be operated in various conditions and accomplish all kinds of missions, especially those with high risk, such as military patrol and reconnaissance [5], scientific research [6], emergency and disaster monitoring [7], search and rescue [8], etc. In addition, they are more cost-effective than manned aircraft operations as well [9]. UAVs have become a major focus of research in many countries and are forming an integral part of modern air forces.

At present, with the advent of new unmanned weapon systems, the evolutionary process of UAVs has moved to the stage of Unmanned Combat Air Vehicles (UCAVs). The objective of this class of vehicles is to provide advanced capabilities for completing a variety of extreme dangerous and difficult missions that have never been considered because the safety of pilots has to be taken into consideration. In order to meet the requirements of future wars, current and future UCAVs will be highly manoeuvrable and highly flexible [10]. They will need to be
capable of providing excellent performance at both high and low speeds with better stability and control characteristics. Taking all above requirements into consideration, the current and future planforms of UCAVs are usually blended delta wing-body configuration designs [11, 12], because delta wings can generate higher lift at higher angles of attack [13-16] and are able to provide better performance at supersonic speeds [17, 18]. Figure 1.1 shows some conceptual designs, which are blended delta wing-body configurations. However, recent research [10, 12, 19] indicated that serious stability and control issues exist for these delta wing configurations because of the absence of conventional aerodynamic control surfaces, such as the fin and tailplane. Tailless designs provide a number of significant benefits but, to be successful, there is a need to explore and understand alternative methods of providing sufficient levels of stability and control.

Recently, thrust vectoring control has been widely anticipated to be an effective method for use on future UCAV configurations with tailless design [10], as sketched in Figure 1.2. The mechanism of this method is to control the vortical flows over delta wings with thrust vectoring at the trailing-edge, with the aim of improving the manoeuvrability and stability of aircraft. With the requirement for high manoeuvrability of future unmanned air vehicles, interaction of vortex flows with thrust vectoring jets becomes important. This aerodynamics-propulsion interaction may affect the characteristics of the leading-edge vortices and consequently affect aerodynamic forces and moments on the wing [10, 12]. Also, unsteady vortex flows over stationary and manoeuvring delta wings are likely to be affected by this vortex-jet interaction [11].

It is known that the flow over delta wings is dominated by two large, counter-rotating leading-edge vortices that are formed by the roll-up of vortex sheets shedding from leading-edges. At high angle of attack, the leading-edge vortices undergo a sudden expansion that is called vortex breakdown [11, 20]. Vortex breakdown has adverse aerodynamic effects on delta wing performance, i.e., the decrease of lift and pitching moment [18]. Several studies [21-29] demonstrated that thrust vectoring at the trailing-edge could delay vortex breakdown significantly,
suggesting thrust vectoring control could be an effective method to improve the UCAV wing performance. However, there are still many issues associated with thrust vectoring on UCAVs, especially unsteady aerodynamic aspects, that remain to be fully investigated.

This thesis begins with a literature review of delta wing aerodynamics and unsteady interactions of vortex flows with thrust vectoring jets, followed by the objectives of this study. Experimental apparatus and methods employed in this investigation are described in the following chapter. The results of this research are discussed in three chapters. Chapter 3 deals with the interactions of static trailing-edge jets with vortical flows over delta wings. This is continued in Chapter 4 with an emphasis on the effects of unsteady trailing-edge blowing jets. Chapter 5 presents the interactions of unsteady pitching jets with delta wing leading-edge vortices. Finally, a summary of the main conclusions from this research is given in Chapter 6.

1.2 Literature Review

Since the present investigation was based on the study of unsteady interactions of trailing-edge jet and vortical flows over delta wings, this section reviews the relevant literature of aerodynamics of delta wings, including the vortical flows over slender and nonslender wings and vortex breakdown phenomenon, which is of great importance to the stability and control of highly manoeuvrable aircraft. The literature review on the trailing-edge jet blowing and unsteady aerodynamics associated with thrust vectoring is also provided.

1.2.1 Aerodynamics of Delta Wing

1.2.1.1 Delta Wing

A delta wing is a highly swept wing with a triangular planform. Its use was first pioneered in Germany by Alexander Lippisch before the Second World War [30].
Since then the delta wing has become a favourite design in the aerospace industry. One of the primary advantages of the delta wing is its ability to generate higher lift at higher angles of attack. The leading-edges of the delta wing can generate two symmetrical vortices that remain on the top surface of the delta wing, and they are so called “leading-edge vortices”, as shown in Figure 1.3 [31]. This pair of leading-edge vortices can produce high vortex lift due to their suction effect. Another main advantage of the delta wing is that it is capable of providing better performance at supersonic speed. In contrast to traditional wing designs, the leading-edge of a delta wing can remain behind the shock wave generated by the nose of an aircraft when flying at supersonic speeds [32], as illustrated in Figure 1.4. This can reduce the wave drag dramatically [32]. In addition, the delta wing is easy to manufacture and can be made very substantial. A typical delta wing design used on the Convair F106 of the United States Air Force is shown in Figure 1.5 [18].

Delta wings are divided into two categories: slender and nonslender wings, according to sweep angle. In this thesis, a slender wing is defined as one with leading-edge sweep angle greater than 55°, while a nonslender wing is defined as one with equal to or less than 55° of sweep. Distinct differences in flow physics exist between slender and nonslender wings. Flow characteristics are strongly dependent on the wing sweep angle. These include flow separation, vortex formation, flow reattachment on the wing surface, and vortex breakdown [33].

Generally, aircraft with delta wing body configurations spend limited time in supersonic flight only, using their high speed capability for short “supersonic dashes” [18]. They usually spend a great portion of their flight time on cruising at subsonic speeds. Moreover, during their take-off and landing, they also fly at low speed. For this reason, the low-speed aerodynamic characteristics of delta wings are of great importance. The present study also considers the interactions of unsteady flows and thrust vectoring at low speed. Therefore, the aerodynamics of delta wings at low Reynolds number is introduced in the next section.
1.2.1.2 Flows over Slender Delta Wings

The flow over delta wing is dominated by two large, counter-rotating leading-edge vortices that are formed by the roll-up of vortex sheets, as sketched in Figure 1.6 [18]. The generation of these leading-edge vortices is due to the pressure difference between the top and bottom wing surface. The pressure on the bottom wing surface is higher than that on the top surface. Thus, the flow underneath the wing tries to pass the sharp leading-edges from the bottom to the top. The boundary layer will separate at the leading-edge and results in free, three dimensional shear layers. These shear layers then curl into a pair of primary vortices as sketched in Figure 1.6 [18]. In a cross plane normal to the wing surface, the leading-edge vortex appears as a nearly circular region of high vorticity surrounded by a shear layer or feeding sheet which originates from the leading-edge. This shear layer may exhibit various forms of instability, which could cause vortical sub-structures that wrap around the leading-edge vortex [19]. The flow that separates at the leading-edge (primary separation line $S_1$ shown in Figure 1.6) reattaches on the wing surface along the primary attachment line $A_1$ (shown in Figure 1.6) at small angles of attack. Underneath the primary vortex, a secondary vortex, with the opposite sign of vorticity, is formed with its own separation line $S_2$ and attachment line $A_2$[18]. The formation of the secondary vortex is due to interactions between the primary vortex and boundary layer which develop on the upper wing surface. The time-averaged axial velocity in the primary vortex core is roughly axisymmetric, and it can reach as large as four or five times of the freestream velocity. These large velocities are due to the low pressure in the vortex core [10]. Figure 1.7 [18] shows the spanwise pressure coefficient distribution across a delta wing. Being a strong and stable source of high energy and vorticity flow, the leading-edge vortices can cause significant static pressure drop near the leading-edge, and thus create a strong “suction effect” on the upper wing surface. This “suction effect” can enhance the lift up to 60% of the total lift [14] and make it possible that the delta-winged aircraft could fly at the angle of attack that the conventional wing planforms would be stalled. A theory for predicting the vortex lift due to the “suction effect” of leading-edge vortex was presented by
Polhamus [34]. The contribution of various effects to the total lift is shown in Figure 1.8 [34]. It is noted that a large increase associated with vortex induced lift occurs at higher angle of attack, suggesting a significant role of leading-edge suction effect.

For a slender wing, the primary reattachment line of leading-edge vortices locates on the upper wing surface at small angles of attack, as shown schematically in a cross-flow plane in Figure 1.9 (a) [33]. The primary reattachment line is outboard in contrast to the centerline of delta wing. The reattachment location on the wing surface is marked as Point A (shown in Figure 1.9). With the angle of attack increasing, the primary reattachment line moves inboard, that is, towards to the centerline of the wing. At a sufficiently high angle of attack $\alpha_{R}$, the reattachment line reaches the centerline. Beyond this limiting angle of attack $\alpha_{R}$, the flow reattachment to the wing surface is not possible and Point A moves away from the wing surface as shown in Figure 1.9 (b). For slender delta wings, the limiting angle of attack $\alpha_{R}$ decreases with increasing sweep angle. This means that, for highly swept delta wings, flow reattachment occurs at very small angles of attack only [33].

Extensive investigations have been undertaken for understanding the aerodynamics aspects of slender delta wings, and the flow topology over them is now reasonably well understood. A recent review article by Gursul [11], gives a detailed and thorough overview of the unsteady vortex flows over slender wings, such as shear layer instabilities, vortex wandering, vortex shedding, wing and fin buffeting and wing rock phenomenon, etc.

### 1.2.1.3 Flows over Nonslender Delta Wings

In contrast to the effort undertaken in vortical flows over slender wings, the aerodynamics associated with nonslender delta wings has only recently become a topic of increased interest in the literature. There are many similarities between slender and nonslender wings in the way that the vortical flows form over them. For example, nonslender wings also exhibit a primary vortex generated by the rollup of the shear layer separating from each leading-edge. The flow over nonslender wings
also reattaches to the wing surface and forms a primary reattachment line [11].

However, there exist some distinct differences in vortical flow topology between these two types of delta wings. One of the distinct features of nonslender wings is that the primary reattachment of flow separated from the leading-edge occurs outboard of the wing centerline even at higher angles of attack. Sometimes even when the vortex breakdown reaches the wing apex, the reattachment of the flow is still possible [19]. Figure 1.10 shows the streamline pattern and the magnitude of the time-averaged velocity near the wing surface for a nonslender wing (\(\Lambda=50^\circ\)) [35] (Noted that here \(\Phi\) is the angle between PIV measurement plane and freestream). At \(\alpha=10^\circ\), the primary attachment line is inboard and the secondary separation line is outboard. With increasing angle of attack, the attachment line moves towards the wing centerline. At the stall angle of \(\alpha=20^\circ\), the primary attachment line is still clear and almost reaches the wing centerlines, although the vortex breakdown moves to the wing apex in this angle of attack. As the angle of attack increases to the post-stall region (\(\alpha=25^\circ\)), the wing has stalled and the streamline takes the form of closed spiralling patterns. In contrast to slender wings, the reattachment line of nonslender wing is more outboard.

Another unique characteristic of nonslender wing is the appearance of a second vortical structure with the same sign of vorticity as the primary one observed outboard of the primary vortex, resulting in the appearance of a dual vortex structure. This phenomenon, that was only observed at low angle of attack and low Reynolds number, has been identified by both experimental investigations [36] and computational simulations [37]. Taylor et al. [36] observed the dual vortex structure in PIV measurements for a nonslender wing (\(\Lambda=50^\circ\)) at \(\alpha=7.5^\circ\) and a Reynolds number \(Re=8700\), as shown in Figure 1.11. The computational simulations by Gordnier and Visbal [37] also showed a dual vortex structure over a 50° sweep delta wing at \(\alpha=5^\circ\), as shown in Figure 1.12. The appearance of the second vortex is due to the interactions between the secondary flow and the primary shear layer. When the secondary flow separates from the wing surface, it impinges on the primary shear layer and is split into the two same sign vortices. The second vortex is slightly weaker.
and smaller than the original vortex. At locations on the aft portion of the wing, the
dual vortex structure weakens and becomes less distinct, which is due to the
unsteadiness [19].

Compared with slender wings, nonslender wings have a lower maximum lift
coefficient \( C_{L,MAX} \) and a smaller stall angle [13]. For delta wings with lower sweep
angle, \( C_{L,MAX} \) decreases considerably. Figure 1.13 shows the variation of lift
coefficient of delta wings with different sweep angles as a function of angle of attack
[34]. For a 65° sweep slender wing, \( C_{L,MAX} \approx 1.55 \) at the stall angle of \( \alpha \approx 32° \); for a
nonslender wing with a sweep angle \( \Lambda=45° \), \( C_{L,MAX} \) drops to 0.9 at a much lower stall
angle of \( \alpha \approx 20° \).

According to Polhamus’ leading-edge suction theory [34], the vortex lift
contribution becomes a smaller proportion as the sweep angle decreases. For
nonslender wings, vortex breakdown even occurs at a very small angle of attack.
However, there is no obvious relationship between the onset of vortex breakdown and
the change of lift coefficient [19]. The effect of sweep angle on the normal force
coefficient \( C_N \) is even larger. For nonslender wings, \( C_N \) may become larger again after
the initial drop on the stall angle [19].

1.2.1.4 Vortex Breakdown

At a sufficiently high angle of attack, leading-edge vortices undergo a sudden
expansion, which is called vortex breakdown or vortex bursting. Vortex breakdown is
characterized by the abrupt structural change of the vortex core, which is followed by
a deceleration and reversal of the axial flow, divergence of the stream surfaces,
instabilities and finally turbulent flow. This phenomenon was first observed by Werle
in 1954 [38] in a water tunnel facility. Vortex breakdown has adverse effects on wing
performance. For example, the lift and pitching moment for slender wings decreases
after vortex breakdown, which is due to the disappearance of the “suction effect” of
leading-edge vortices. Besides, Mabey [39] reported that vortex breakdown over a
slender wing can increase wing and fin buffeting, which could cause fatigue damage
of the aircraft structure. Vortex breakdown was also demonstrated to be responsible for the stability and control of aircraft [10].

Efforts have been made by researchers to improve our understanding of the vortex breakdown phenomenon, including types of vortex breakdown, vortex breakdown mechanisms, parameters affecting vortex breakdown, oscillations of vortex breakdown and the response of vortex breakdown in unsteady flows, etc. The following sections will present a review of these aspects.

### 1.2.1.4.1 Types of vortex breakdown

It is commonly accepted that vortex breakdown has two major types, that is, so called spiral-type and bubble-type [11, 40, 41]. Flow visualization by Lambourne and Bryer [20] revealed these two different types of vortex breakdown on the wing surface at the same time, as shown in Figure 1.14. A spiral-type vortex breakdown is characterized by a rapid deceleration of the core flow, followed by an abrupt kink, at which point the flow takes the form of a spiral. A typical spiral-type vortex breakdown is shown in Figure 1.15 [42]. The bubble-type vortex breakdown is characterized by a stagnation point on the swirl axis, followed by an oval shaped recirculation bubble. The bubble is nearly symmetric over its length, but in the rear it becomes open and asymmetric [40]. A typical bubble-type vortex breakdown is shown in Figure 1.15 [42]. Leibovich [41] and Payne [40] also found the flow downstream of vortex breakdown is wakelike, while the flow upstream is jetlike.

Previous research [11, 20, 43] suggested that the spiral-type vortex breakdown is more common over delta wings. In fact, in experiments even the bubble-type vortex breakdown switches to spiral form from time to time [11]. Escudier [44] suggested that bubble-type is the basic form of vortex breakdown, while the spiral-type is the consequence of the instability of the bubble form. This was supported by flow visualization studies performed by Jumper etc. [45], which indicated that even in the case where vortex breakdown looks like the bubble-type, a spiral-type breakdown can be observed in instantaneous pictures with a short exposure time. However, the
visualization of both types of vortex breakdown by Payne [40] indicated that these two types of vortex breakdown seem to transform randomly from one to another.

1.2.1.4.2 Mechanisms of vortex breakdown

A number of researchers have examined the vortex breakdown phenomenon, and have tried to present an interpretation of its mechanism. Reviews of these works were presented by Hall [46], Leibovich [41], Escudier [44], Delery [47] and Lucca-Negro and O’Doherty [48].

Benjamin [49] introduced the concept of subcritical and supercritical states of a swirling flow. His analysis of a given perturbation to a given columnar flow showed that a small perturbation to the flow field may propagate to the upstream only if the swirl level reaches to a certain value. If the swirl level is higher than this critical value, the state is referred to as “subcritical state”; otherwise, it is “supercritical state”. The perturbation is stable in the subcritical state, which will lead to a vortex breakdown. There is a transition in the state of the flow, from supercritical upstream of vortex breakdown to subcritical downstream. By increasing swirl level, the breakdown location moves upstream until the entire flow becomes subcritical. Based on the quasi-cylindrical Navier-Stokes equations, vortex breakdown of viscous swirling flow was also numerically analyzed by Gyllenram et al. [50]. Their numerical quasi-cylindrical analysis suggests that there exists a critical swirl level that may determine the point of vortex breakdown, where the quasi-cylindrical approximation fails to give a solution.

At present, it is generally accepted that vortex breakdown is a wave propagation phenomenon, with a strong analogy to shocks in gas dynamics [11]. The waves in the flow may travel along the vortex core, and the waves could propagate upstream (against the freestream) if the flow is subcritical. The collision of the freestream and upstream waves propagating in the opposite direction may be responsible for vortex breakdown. The waves can move upstream in the subcritical section, but are unable to propagate further at a location where critical conditions exist.
This location can be taken as an estimate of the location of vortex breakdown [51]. A vortex breakdown can be considered as a superposition of an upstream moving wave and a uniform freestream velocity that makes the wave stationary [11].

Other interpretations of vortex breakdown based on flow stagnation, hydrodynamic instability and a combination of different theories were also presented. Since these interpretations are beyond the scope of this dissertation, the reader is directed to the relevant review articles [41, 44, 46-48].

1.2.1.4.3 Parameters affecting vortex breakdown

Both experimental and theoretical investigations showed that there are two important parameters affecting the onset and movement of vortex breakdown: swirl level and the external pressure gradient outside the vortex core [11]. An increase in either of them could lead to the earlier onset of vortex breakdown. For leading-edge vortices, these parameters strongly depend on the wing geometry [52], such as angle of attack, sweep angle, roll or yaw angle and leading-edge profile, etc.

An increase in the angle of attack can promote the onset of vortex breakdown, and the vortex breakdown position will move closer to the wing apex. A summarized plot of vortex breakdown locations reported from previous literature over delta wings for $\Lambda = 75^\circ$ as a function of angle of attack was presented by Gursul and Xie [53], as shown in Figure 1.16. It can be seen that results reported by different researchers are in good agreement. Vortex breakdown location moves to the apex when the angle of attack increases to approximately $58^\circ$. In contrast, an increase in the sweep angle can delay the occurrence of vortex breakdown. Hummel and Srinivasan [54], Lambourne and Bryer [20] observed the same breakdown downstream move when the sweep angle was increased. This is because an increase in the angle of attack or decrease in sweep angle can cause a corresponding increase in the swirl level of the vortex core. The pressure gradient distribution on the suction surface of delta wing is also related to the change in the angle of attack and sweep angle [52].

For unsteady wings, both the swirl level and the pressure gradient are expected
to vary during a wing manoeuvre, such as the variation in the roll angle. Pelletier and Nelson [55] reported that a rolling wing can create a sideslip angle, which changes the effective sweep angle for both sides of the wing. As the wing rolls, the vortex breakdown for the leeward side (the side rolling upwards) of the wing will move downstream towards the trailing-edge, while the vortex breakdown for the windward side will propagate upstream to the wing apex. Gresham et al. [56] also reported similar observations in their study on the roll oscillations of nonslender wing.

Another parameter that contributes to the variation of vortex breakdown location is the leading-edge profile. The leading-edge vortex for the wings with sharp windward leading-edges showed an earlier onset of breakdown, and the primary reattachment location is more inboard [19]. Although the flow separation and vortex breakdown location were strongly affected by leading-edge shape, Kegelman and Roos [57] showed that, for slender wings, lift was weakly influenced. Since the separation point of shear layer is not steady for round leading-edge configurations, the interactions of leading-edge vortex and trailing-edge jet could be more complex. Therefore, sharp leading-edge was tested in most previous research [21-29], for the purpose of simplifying the experiments.

1.2.1.4.4 Oscillations of vortex breakdown location

It has been observed that the vortex breakdown location over stationary delta wings is not steady and oscillates along the axial direction [40, 58]. Fluctuations of up to 10% of chord length were first observed by Lowson [58] in 1964. In subsequent research, more significant oscillations of vortex breakdown, up to 40-50% of the chord length, were observed by Ol & Gharib [59], and Taylor & Gursul [35] in their flow visualization. It was found that the oscillations of vortex breakdown become larger when the angle of attack or sweep angle was increased [19]. In addition, Menke and Gursul [60] suggested that these oscillations are in the form of asymmetric motion of breakdown locations for the left and right vortices. An example of time histories of vortex breakdown locations for left and right vortices was presented by
Menke and Gursul, as shown in Figure 1.17 [60]. It can be seen that two vortex breakdowns, oscillating in asymmetric motion, are almost mirror images. It is also noted that time history of vortex breakdown location consists of low-frequency, large-amplitude fluctuations and high-frequency, low-amplitude fluctuations [11]. The sources of these fluctuations are not clear.

Another interesting aspect is that the oscillations of vortex breakdown locations are quasi periodic. It was reported that these quasi periodic oscillations exist at both low and high Reynolds numbers [61-63]. Gursul and Yang [64] investigated the possibility that these quasi periodic fluctuations might be related to the hydrodynamic instability of vortex breakdown, that is, helical mode instability. However, this possibility was discarded since the dominant frequencies of vortex breakdown location occur at much lower frequencies than the frequency of helical mode instability, suggesting that the helical mode instability has no effect on the oscillations of vortex breakdown. Figure 1.18 shows the spectrum of unsteady flow phenomena over delta wings as a function of the dimensionless frequency [65]. It can be seen that the frequency range of the oscillations of vortex breakdown is much closer to that of aerodynamic manoeuvres, compared with the frequencies of other phenomena, suggesting that the vortex interactions over delta wings may become more complex for manoeuvring aircraft. The response of vortex breakdown and a possible coupling between the wing manoeuvre and vortex breakdown in this frequency range are very important [11].

These vortex breakdown oscillations may be very important for the stability and control of highly manoeuvrable aircraft, such as UCAVs, and also can lead to severe problems to wing and fin buffeting. Hence, it is necessary to find an effective method to control these oscillations, thus ensuring a successful highly manoeuvrable aircraft.

1.2.1.4.5 Vortex breakdown in unsteady flows

Experimental studies suggested that time lag exists in the dynamic response of
vortex breakdown due to the wing motion with respect to its variation with respect to pitching motion [11]. Lowson first reported a time lag of vortex breakdown location in 1964 [58]. More detailed observations of time lag were recently made by Wolffelt [66], Atta and Rockwell [67, 68], and LeMay et al. [69]. These investigations suggested a similar trend: for a periodic pitching motion wing, the vortex breakdown location forms a hysteresis loop with the variation of angle of attack, as shown in Figure 1.19 [11]. This hysteresis loop becomes wider with the increasing oscillatory frequency of pitching wing, indicating that the phase lag increases with the increasing frequency. Similar phase lag has also been observed for other types of wing motions, such as plunging and rolling. Furthermore, time lags for different wing shapes, such as diamond, cropped, delta and double delta wings, were observed to be similar.

The studies relevant to time lags for different wing motion and shapes were summarized by Gursul in his review article [11]. Recent investigations of vortex breakdown control techniques revealed similar time lags. A summarized plot of phase lags for different types of unsteady motions as a function of reduced frequency \( K = \frac{\alpha c}{2U_c} \) was given by Gursul [51], as shown in Figure 1.20. These unsteady motions include pitching motion (filled square—LeMay et al. [69]; filled delta—Gursul and Yang [70]), leading-edge extensions (blank circle—Yang and Gursul [71]), oscillating leading-edge flaps (blank square—Deg and Gursul [72]) and oscillating fin at the trailing-edge (blank delta—Xie [73]). Figure 1.20 suggests that these results show a consistent trend of increasing phase lag with increasing frequency no matter what type of unsteady motion is tested. Even for the unsteady motion of oscillating fin at the trailing-edge, which is expected to be different from other unsteady motions in which the wings are not stationary, the measured phase lags were in close agreement with other results [11]. Therefore, Gursul [11] proposed that the mechanism of time lag with respect to the quasi-unsteady case is universal regardless of the type of unsteady motion.

Greenwell and Wood [74] simulated the dynamic response of vortex breakdown location by a first-order system, since the response of vortex breakdown is
very similar to that of a first-order system. With this idealization, the time constant $\tau$ can be estimated from the time history of vortex breakdown location in response to a given unsteady motion. Greenwell and Wood [74] obtained the normalized time constant $\tau U_\infty / c = 1.67$ associated with the variation of vortex breakdown location for pitching wing motions. The time constants of different types of unsteady motion were given by Gursul et al. [75]. The normalized time constant $\tau U_\infty / c$ was found to be dependent on the type and amplitude of unsteady motion, the breakdown location in the static case, and wing sweep angle. For delta wings with sweep angle not less than 70°, the normalized time constant $\tau U_\infty / c$ is between 1-2. For delta wings with lower sweep angle, time constant is larger.

Time lag is of great importance for the stability and control of aircraft. Significant differences exist between the effects of static and dynamic blowing trailing-edge jets with regard to the hysteresis and large phase lags associated with the wing vortical flows. The presence of large time-constants of these complex trailing-edge jets-vortex interactions is important for the dynamic aspects of thrust vectoring. In particular, the consequences of this behaviour are serious for the stability and control issues of the vehicle if the control system is based on static characteristics. A thorough understanding of the dynamic jet-vortex interactions and unsteady development of vortex breakdown, is therefore of paramount importance to flight control system designers.

1.2.1.4.6 Mechanism of time lag

Mechanisms of time lag of vortex breakdown location associated with unsteady motion have been proposed. Initially, the possibility of time lag of vortex breakdown was related to the development of vortex flow. However, this possibility was discarded, since Greenwell and Wood [74] found that the time lag of vortex development is very small compared to that of vortex breakdown location. Another possible mechanism [11], based on wing motion, can not be universally accepted,
since it failed to explain the time lag of vortex breakdown when the wing is stationary. For example, the time lag of vortex breakdown associated with unsteady oscillating fin at the trailing-edge over a stationary wing [73] cannot be explained by this theory. A thorough review on these mechanisms was given by Gursul [11].

Based on the theory of vortex breakdown as a wave propagation phenomenon, Gursul [51] proposed an explanation of the time lag which is universally applicable for the vortex flows over slender wings. As mentioned earlier, a stationary vortex breakdown can be considered as the superposition of an upstream propagating wave and a uniform downstream freestream velocity. In the dynamic case, the speed of the waves moving upstream is dependent on the axial wave number, that is, wave frequency. For example, for a cylindrical vortex with Rankine velocity distribution and no axial velocity, the exact dispersion relation is given by Kelvin and the speed of the waves travelling upstream can be found numerically [11]. According to this numerical model, the wave speed travelling upstream decreases with the increasing wave frequency. Consequently, vortex breakdown location in the dynamic case is different from that in the quasi-static case. For example, for pitching wing motion (see Figure 1.19) [69], vortex breakdown location in the dynamic case is aft compared to that in the quasi-static case under the pitch-up motion (for a given angle of attack), while farther forward under the pitch-down motion. As a result, the time lag of vortex breakdown location is formed.

1.2.2 Unsteady Vortical Flow Control

Controlling vortical flow over delta wings could bring many benefits, such as lift enhancement, generation of lift and moment for flight control, and attenuation of fin buffeting, etc [33]. The modifications of vortex location, strength and structure, can be utilized by various active flow control methods.

During the past four decades, great effort has been undertaken to control the vortical flows over delta wings, such as leading-edge suction and blowing [76, 77],
small aspect ratio jets [78-80] and trailing-edge jets blowing [21-29], etc. The two
main goals of these flow control methods were 1) to control the leading-edge vortices
to generate the forces and moments for flight control; 2) to delay the vortex
breakdown so as to improve the stability of aircraft and reduce wing and fin buffeting
[11]. Steady leading-edge suction and blowing could effectively delay the vortex
breakdown by influencing the swirl level in the vortex [33]. This is because the
vorticity of the leading-edge vortices originates from the separation line along the
leading-edge, that the control of separation characteristics or shear layer can influence
the strength and location of the vortices as well as the location of vortex breakdown.
The blowing from small aspect ratio jets can add momentum to the flow from various
positions on the wing surface, such as near the wing apex in the symmetry plane [78],
along the vortex core underneath the vortex axis [79], and in the spanwise position
underneath the vortex axis [80]. This can accelerate the axial flow in the core, and
modifies the pressure gradient favorably. Trailing-edge jets blowing can also modify
the external pressure gradient and delay the vortex breakdown. This flow control
method will be discussed in detail in the following section.

1.2.3 Trailing-Edge Jet Blowing

As mentioned earlier, trailing-edge jet blowing could be an effective method to
control the leading-edge vortices. Moreover, in practice, trailing-edge blowing is also
an economical method, since it can take advantage of the existing propulsion system,
providing powerful blowing effects to maneuver the vortex flow upstream.

1.2.3.1 Vortex Breakdown and Trailing-Edge Jets

Several investigators have examined the effects of trailing-edge jets on the
vortical flows over delta wings [21-29]. The earliest investigation on the trailing-edge
jet blowing was reported by Helin and Watry [21] in 1994. They examined the effect
of a trailing-edge blowing jet on flows over a 60° sweep delta wing. Flow
visualization showed that the burst position of vortex breakdown was moved downstream up to 18% of chord length by increasing the velocity ratio $U_r$ of jet to 8.0 (where $U_r=U_{jet}/U_\infty$, $U_{jet}$ is the velocity of jet fluid, and $U_\infty$ is the freestream velocity). Force measurements were absent in Helin’s investigation, although he speculated that the delay of vortex breakdown by the trailing-edge blowing could possibly result in higher lift. Subsequently, Nawrocki [23] and Shih & Ding [22] made similar observations on a slender wing with the same sweep angle [21]. They further found that trailing-edge jet blowing is more effective by pointing the jet downward in the pitching direction. The largest delay of vortex breakdown was 50% of chord length with the jet pointed downward 45° at the angle of attack $\alpha = 20°$ [22]. Furthermore, Shih and Ding found that an upper limit for the downward jet angle exists such that any increase beyond that angle may not further delay the vortex breakdown. On the other hand, Wang et al. [26] reported that the delay of vortex breakdown increases with the increasing yaw angle between the trailing-edge jet and wing centerline. Wang et al. [26] performed flow visualization on a 65° sweep delta wing. The delay of vortex breakdown could be 25% of chord length by a vectored trailing-edge jet with a 60° yaw angle. Flow visualization by Phillips et al. [27] showed that the vortex breakdown due to the presence of a fin can be completely eliminated by a trailing-edge jet even at high angles of attack, as shown in Figure 1.21. This observation indicated that the adverse pressure gradient due to the fin can be overcome by trailing-edge jet blowing.

The studies above demonstrated that trailing-edge jet blowing could delay the leading-edge vortex breakdown significantly; by up to 50% of wing chord. It was also shown that the downward jet pitch angle and vectored jet yaw angle are important parameters that may exert influence on the blowing effect of the trailing-edge jet. However, most knowledge of trailing-edge blowing effect was from slender wings, whereas the effect over nonslender wings is still unknown.

Velocity ratio $U_r$ tested in the literature was in the range from 0 to 15. Previous research showed that distinct differences exist between the blowing and no blowing cases in the delay of vortex breakdown. A dimensionless parameter jet momentum
coefficient $C_\mu$ was introduced in order to represent the strength of the jet with various nozzles geometries and different wing configurations. The definition of $C_\mu$ is:

$$
C_\mu = \frac{\rho U_{jet}^2 A_{jet}}{\frac{1}{2} \rho U_x^2 S_w}
$$

(1.1),

where $A_{jet}$ is the exit area of the jet nozzle, and $S_w$ is the wing area. The maximum value of $C_\mu$ reported from the literature was 1.1 [22]. Mitchell et al. [24] reported that the effectiveness of a trailing-edge jet was highly dependent on the jet velocity applied, however, there was an upper limit on the effective velocity ratio that can provide positive vortex breakdown control.

The previous investigations also demonstrated that strong asymmetric breakdown of the leading-edge vortices can be induced by arranging an asymmetric vectored trailing-edge jet. Shih and Ding [22] mounted twin jets at the trailing-edge asymmetrically in order to control the vortex on either side, independently. They directed the left side jet 30° downward and the right side jet 30° upward. A strong asymmetrical control effect was observed. The vortex breakdown on the left side was moved downstream to 35% of chord length, whereas the vortex breakdown on the right side was only moved downstream to 12.5% of the chord length. Mitchell et al. [24] also examined the blowing effects of asymmetric trailing-edge jets over a 75° sweep delta wing. They mounted two identical rectangular nozzles at the trailing-edge with an independent jet fluid injection circuit, which allows for asymmetric control configuration. They found that the asymmetric jet blowing was consistent in delaying the vortex breakdown location for the controlled vortex. However, it has an adverse effect on the uncontrolled vortex, which initiated an early vortex breakdown for all velocity ratios tested. The vortex breakdown for the uncontrolled side shifted upstream up to 31% of the chord length. This not only indicated the adverse control affect of asymmetric trailing-edge blowing, but also demonstrated its ability to influence the vortex breakdown of the uncontrolled vortex.

The geometry of jet nozzles tested in previous research was reported to be rectangular, although these nozzles had different configurations. Helin [21] and
Nawrocki [23], and Shih and Ding [22] mounted two symmetrical rectangular jets with high aspect ratio (8:1) and (9:1), respectively. Wang et al. [26] also used one single rectangular jet placed at the centerline of the wing. The geometry of the trailing-edge jet could be another important parameter that may have significant influence on the blowing effect. However, only rectangular nozzles have been tested so far, and the effect of other geometries is still unclear.

The effects of intermittent trailing-edge blowing on the leading-edge vortex breakdown over a dynamically pitching wing have also been studied by Vorobieff and Rockwell [25]. It was found that the blowing effect persists throughout the entire pitching cycle due to the phase lag of vortex breakdown relative to the pitching motion of the wing. They also found that trailing-edge blowing during the upstroke part of the periodic wing pitching motion was the most energetically efficient way to delay vortex breakdown. However, the effect of unsteady trailing-edge blowing over a stationary or manoeuvrable wing has not yet been studied. For example, the dynamic response of vortex breakdown and lift force associated with the unsteady blowing, are still unknown. Besides, time lag for dynamically trailing-edge jet blowing needs to be further investigated. The unsteady aspect of trailing-edge thrust vectoring, which is very important to the stability and control of highly manoeuvrable aircraft, is in great need of further exploration.

### 1.2.3.2 Entrainment Effects of Trailing-Edge Jets

Entrainment effects and the interaction between the jet and the wing vortices were suggested in previous research [27, 29, 81, 82]. As the jet exhausts into a crossflow, a counter rotating vortex pair is generated. This was observed by Zhang [81] and Milanovic & Zaman [83]. Wang et al. [82] found strong interactions between jet and wing vortices. On the one hand, the wing vortices were drawn toward the jet center by the induced velocity of the jet vortices. On the other hand, the jet vortices were also significantly affected by the wing vortices, even being immersed into the
wing vortices downstream, but imposed only mild influence on jet vortex structures. Further evidence of strong interactions of the jet-wing vortex was provided by Phillips et al. [27]. Figure 1.22 shows flow visualization images for (a) jet off, (b) jet on (static blowing), and (c) just after the jet was turned off. It can be observed that the leading-edge vortex was drawn towards and parallel to the jet after the jet was turned on, as shown in Figure 1.22(b). When the jet was turned off, the wing vortex realigned itself to become nearly parallel to the freestream. Vortex breakdown then slowly propagated upstream, and eventually came back nearly to its original position similar to that shown in Figure 1.22 (a). Figure 1.22 (c) also illustrates the hysteresis and large phase lag associated with the wing vortical flow. Just after the jet was turned on, it is obvious that the vortex breakdown location was significantly moved downstream, but the leading-edge vortex was still nearly parallel to the freestream, not being drawn downward towards the jet. This observation suggests the presence of a large time lag associated with complex jet-vortex interaction. The near-surface flow structure and topology over a nonslender wing (\(\Lambda=35^\circ\)), which was subjected to trailing-edge jets, was investigated by Yavuz and Rockwell [29]. Their PIV measurements showed that trailing-edge jet blowing had a remarkable, global influence on the surface patterns located upstream. The role of jet entrainment and jet-vortex interactions deserves further study.

1.2.4 Objectives

The above literature survey indicates that jet blowing at the trailing-edge could delay vortex breakdown significantly, suggesting thrust vectoring control could be an effective method to improve the manoeuvrability of UCAVs. Previous studies have greatly improved our understanding of the effect of the trailing-edge jets on delta wing vortical flows. However, many of the aerodynamic issues associated with thrust vectoring, especially those unsteady aspects, remain to be explored. For example, force measurements that quantify the effect of thrust vectoring jets on wing
aerodynamics were absent from the literature. One of the main objectives of this study is to understand the effect of trailing-edge jets on wing aerodynamic forces.

A second objective is to understand the effect of wing sweep angle. Important differences exist between the aerodynamics of slender and nonslender wings with regard to the structure of vortical flows, vortex breakdown, and reattachment. One of the distinct features of nonslender wings is the location of the primary attachment zone outboard of the symmetry plane. Reattachment location correlates with the wing stall process and increased buffeting. The effect of trailing-edge jets on nonslender wing vortical flows is largely unexplored. The two exceptions are Reference 28, which studied a wing with $\Lambda=50^\circ$ and Reference 29, which studied the wing near-surface flow patterns for a wing with $\Lambda=35^\circ$.

Another aspect that remains to be studied is the effect of nozzle geometry, which affects the entrainment process and the interaction between jet and wing vortices. As the jet exhausts into crossflow, a counter-rotating vortex pair is generated [81]. One of the objectives of this study is to understand the scale of these effects, and its effects on the wing aerodynamic performance.

There has been a lack of study of the effects of dynamic thrust vectoring, which is important for the flight control of UCAVs. For the dynamic thrust vectoring in which the jet pitch angle or the momentum flux varies as a function of time, significant time delays and hysteresis of the vortical flows and aerodynamic forces are expected. The response of wing vortical flow is expected to be similar, at least qualitatively, to that of unsteady wings. Hysteresis and the time lag of vortical flows and vortex breakdown over pitching or plunging wings are well known [11]. One of the objectives of the present work is therefore to understand the effects of the dynamically varying pitch angle and momentum coefficient of the trailing-edge jet on delta wing aerodynamics, with an emphasis on quantifying hysteresis and phase lags.
Chapter 1 Figures

Figure 1.1:  Conceptual UCAV configurations [12].

Figure 1.2:  Schematics of thrust vectoring
Figure 1.3: Leading-edge vortices over the top surface of a delta wing [31].

Figure 1.4: Schematic of the leading-edge of delta wing behind the shock wave.
Figure 1.5:  The delta winged Convair F106 Delta Dart [18].

Figure 1.6:  Schematic of the subsonic flow field over the top of a delta wing [18].
Figure 1.7: Schematic of the spanwise pressure coefficient distribution over a delta wing [18].

Figure 1.8: Contribution of various effects to the total lift over delta wing [34].
Figure 1.9: Schematic streamline patterns for (a) reattachment on the wing surface (b) no reattachment on the wing surface [33].
Figure 1.10: Streamline pattern and magnitude of time-averaged velocity near the wing surface in water tunnel experiments, $\Lambda = 50^\circ$ [35].

Figure 1.11: Crossflow vorticity from PIV measurements showing dual vortex structures [36].
Figure 1.12: Dual vortex structures in a cross plane by computational simulations [37].

Figure 1.13: Variation of lift coefficient as a function of angle of attack [13].
Figure 1.14: A flow visualization of Bubble-type (above) and Spiral-type (below) vortex breakdown over a delta wing [20].

Figure 1.15: Bubble-type (above) and Spiral-type (below) vortex breakdown over a delta wing [42].
Figure 1.16: Breakdown location over delta wing of $\Lambda = 75^\circ$ [53].

Figure 1.17: Time histories of breakdown locations for left (solid line), and right (dash line) vortices for $\alpha = 37\ deg$ and $\Lambda = 70\ deg$ [60].
Figure 1.18: Spectrum of unsteady flow phenomena over delta wings as a function of dimensionless frequency [65].

Figure 1.19: Chordwise breakdown location as a function of angle of attack for a pitching motion wing [69].
Figure 1.20: Phase lag of vortex breakdown location for different types of unsteady motion [51].
Figure 1.21: Flow visualization of trailing-edge jet/vortex breakdown interaction [27].

Figure 1.22: Flow visualization for (a) jet off, (b) jet on, (c) just after the jet is turned off, at the trailing-edge [27].
CHAPTER 2       METHODOLOGY

2.1 Experimental Apparatus

In the present investigation, experiments were conducted in the wind tunnel as well as the water tunnel. In the wind tunnel, it is convenient to set up six-component strain-gauged internal force balance so that lift over delta wing models can be easily measured. However, higher jet momentum in the air is hard to achieve because of the limit of wind tunnel, so the experiments related to unsteady pitched and blowing trailing-edge jet with higher jet momentum were carried out in the water tunnel. Also, high quality images of flow visualization can be obtained from the water tunnel testing. Another aspect need to be emphasized, the characteristics of aerodynamics over delta wings with sharp leading-edges, such as the formation of leading-edge vortex [43], vortex breakdown location [20] and interactions of leading-edge vortex & trailing-edge jet vortex [19], are insensitive to Reynolds number changes, it is therefore reasonable to expect the results obtained from water-tunnel investigations of delta wings are in good agreement with those of air.

2.1.1 Wind Tunnel Facility

The wind tunnel experiments were performed in the high-speed working section, with a cross-section of $2.13 \times 1.52 \times 2.7$ m (width, height, length), of a closed circuit wind tunnel. A planar view of this wind tunnel is shown in Figure 2.1. This wind tunnel consists of a high speed section (1) and a low speed section (2) as seen in the diagram. A single turbine (3) behind the high speed test section was used to drive the air flow inside the tunnel. Several cascaded vanes were assembled at
each corner (4) and upstream, to help redirect the flow back around the tunnel and reduce the turbulence and flow losses. This wind tunnel provides a free stream velocity range from 2 m/s to 50 m/s. The viewing windows surrounding the working section are made of optical glass which achieves more than 90% of transmittance. The illumination lights and laser can pass through them without significant energy loss, thus providing an ideal background for flow visualization and PIV measurements. An overview of the general experimental setup in the wind tunnel is shown in Figure 2.2.

2.1.2 Water Tunnel Facility

The water tunnel experiments were performed in a free-surface water tunnel facility located in the Mechanical Engineering Department at the University of Bath. This water tunnel facility is an Eidetics Model 1520 close-loop water tunnel with a 0.381×0.508×1.52m working section, as illustrated in Figure 2.3. The tunnel can provide a free stream velocity range from 0 to 0.45m/s with a turbulence intensity of less than 1% U∞, through a horizontal, closed-loop continuous flow system. A fine filter assembled in the water inlet guarantees that no particles bigger than 100µm can enter the test section. Three layers of honeycomb screens are placed between the settling water tank and test section in order to reduce the turbulence. The tunnel has four viewing windows: three surrounding the test section and one downstream allowing axial viewing. The height of the test section above the floor allows flow visualization from below as well as from the sides. All these windows are made of optical glass, providing ideal transmittance for flow observations and PIV measurements. The tunnel also incorporates a pressurized dye system with six available dye tubes to enable flow visualization with different colours. Control of the dye velocity is achieved by gate valves and is equalized to that of the freestream. As the interactions of vortex flow over delta wings with trailing-edge jet blowing are not dependent on Reynolds number,
2.1.3 Experimental Models

2.1.3.1 Delta Wing Models

Two models with sweep angles $\Lambda = 50^\circ$ and $65^\circ$, representing nonslender and slender delta wings respectively, were tested. Both wings had a thickness of 4.1mm/12.7mm and a chord length of 100mm/310mm (models tested in the water tunnel/ models tested in the wind tunnel), giving a thickness-to-chord ratio of 4.1%. All models incorporated a sharp leading-edge formed by beveling the pressure surface by 45°; the trailing-edge was square. The design of wing models The dimensions of delta wing models are shown in Figure 2.4.

For the wind tunnel experiments, the delta wing models were made of aluminum and used for force measurements. Models were mounted on the high-incidence rig through a six-component strain-gauged internal balance, as shown in Figure 2.2. For the water tunnel experiments, the models for flow visualization and PIV measurements were constructed from an aluminum alloy. Identical models constructed from ABS (Acrylonitrile-Butadiene-Styrene copolymers) were used for force measurements conducted in the water in order to reduce the pre-loading of load cells. During the water tunnel experiments, the wings were mounted upside down on a streamlined strut projecting from the rear of the model. This streamlined strut was also constructed from ABS. The total weight of model with the strut is less than 150 grams. Rapid prototyping (RP) machine, which can produce small and accurately dimensioned plastic pieces, was used to make ABS models.

For the laser-induced fluorescent flow visualization (performed in the water), wing models were made hollow inside so that the laser fluorescent dye could be fed to the delta wings from two thin stainless tubes (diameter=2mm) embedded in the streamlined strut. The laser dye was released to the water from the slots (of 0.5mm thickness) in the leading-edge of delta wing models. The models for laser-induced flow visualization are shown in Figure 2.5. In the laser-induced fluorescent flow visualization and PIV experiments, the models were painted black in order to minimize the reflection of laser sheet. In the food-colouring dye flow visualization...
experiments, the models were painted white in order to achieve an ideal contrast for locating vortex breakdown locations;

2.1.3.2 Nozzle Design of Trailing-Edge Jets

In order to investigate the effect of nozzle geometry on the wing aerodynamics, two jet geometries, rectangular and circular, were tested. The rectangular jet was generated by a convergent rectangular nozzle with a 2 ×12mm / 6×36 mm exit (for water tunnel/ wind tunnel experiments), as shown in Figure 2.6; the circular jet was generated by a convergent round nozzle with a 3mm/10mm diameter exit (for water tunnel/ wind tunnel experiments), as shown in Figure 2.7. In order to investigate the effect of jet yaw direction on the wing flows, one of the rectangular nozzles was built with a ±30° yaw angle, as shown in Figure 2.8. The exit area of all nozzles was designed with the consideration of keeping the same Cµ for different nozzle geometries. For all the jets, the water flow (air flow) was supplied through two pipelines connected with the two ends of the jet. In order to minimize the influence of collision of the flows from each side and achieve a uniform flow pattern of the jet, a very thin wallboard was placed inside the nozzle to separate the two flows. The outer diameter of the pipeline was the same as the wing’s thickness, so that the jet and its pipelines could fit behind the trailing-edge without extruding.

2.1.4 Trailing-Edge Jet Setup

2.1.4.1 Static Trailing-Edge Jet Setup

A statically pitched and yawed jet system was fitted at the trailing-edge of the wing models. The experimental arrangement is shown in Figure 2.9. The jet fluid (air or water) is pumped into the pipes and then fed into the nozzle through the two ends. In order to achieve a uniform flow from each side, two high quality flow meters were arranged at the inlet of jet fluid to adjust the flow rate precisely. Nozzles were
designed to be movable parallel to the wing trailing-edge for the purpose of studying the blowing effect at different spanwise positions. This design allows an easy change of the jet pitching angle $\beta$ by rotating the pipe-nozzle assembly for both static and dynamic variations. During the experiments, there is no contact between the jet system and the wing, thus ensuring that any changes in the force measurements are solely from the blowing effects. The gap between the pipe feeding the nozzle and the wing was 0.02c. The effect of gap on the aerodynamic forces was investigated and it was found that no noticeable effect existed for up to 0.08c.

2.1.4.2 Unsteady Pitched Trailing-Edge Jet Setup

As it is easy to achieve a higher jet momentum in the water, the experiments related to unsteady pitched and blowing trailing-edge jet were carried out in the water tunnel. The corresponding experimental setup introduced in the following two sections is for water tunnel tests only.

In order to understand the effects of an unsteady pitched trailing-edge jet on the wing aerodynamics, a jet system, which is capable of making the jet dynamically oscillate in the pitching direction, was constructed. The schematics of this jet system are presented in Figure 2.10. This system consists of a steel support board, two fixture clamps, several streamlined struts, a trailing-edge jet, some jet fluid feeding pipes, a stepping motor with a stainless steel chain, an A/D signal converter, a desktop PC plus data acquisition card and some other accessories.

The steel board provided the support to delta wing models and other components. Two fixture clamps were used to clamp the whole experimental setup on the top of water tunnel. They allowed the rotation of the whole setup in the pitching direction. The changes of incidence $\alpha$ were achieved by swinging the whole experimental system, including the wing and jet system, backwards or forwards. During the force measurements, the delta wing was mounted upside down on a streamlined strut jointed with an aluminum cross bar. This cross bar was screwed onto a pair of load cells attached on the steel board via fixed brackets (shown in...
Figure 2.10). For other experiments, the struts of delta wings were directly fixed onto the assembly plane of the steel board. The strut was fabricated as an aerofoil shape.

A jet nozzle was arranged at the trailing-edge of the wing models with a gap of 0.02c (the same as static case). The two ends of jet nozzle were connected with two jet fluid feeding pipes screwed into the support struts of the jet system. One of the feeding pipes was jointed with a stainless steel chain that was hidden inside a hollow streamlined strut (right one). This chain was connected to a stepping motor mounted on the top of the steel board. The stepping motor provided a precise control of the movement of the chain, by receiving the command from a PC via an A/D converter (not plotted in Figure 2.10). A VEE program was developed to generate the commands with different waveforms, amplitudes and frequencies for the stepping motor. The jet nozzle was then pitched to any expecting pitching angle β by the movement of the chain, thus generating a dynamic pitching jet. Since the wing model was mounted upside down in the water tunnel, the jet pitching angle β was set to be positive when it moved upward away from the wing suction surface, as illustrated in Figure 2.11.

2.1.4.3 Unsteady Blowing Trailing-Edge Jet Setup

The effect of dynamically varying jet velocity (jet momentum coefficient) of trailing-edge jets on the wing aerodynamics is another main topic of this investigation. A dynamically blowing jet system was thus designed to fulfill this aim. The experimental setup of a blowing jet system is generally the same as that of the dynamic pitched jet system except adding an independent jet flow control circuit. An illustrative diagram of this jet blowing system is shown in Figure 2.12. This blowing jet system consists of a water pressure regulator with a pressure meter, a high precision stepping motor valve, a desktop PC plus a data translation card, two flow meters and other accessories.

The water pressure regulator was installed in front of the valve in order to
reduce the pressure of water to 20PSI (1.5bar), thus ensuring that the stepping motor valve was not over pressurized and its performance was optimized. In order to generate the dynamic blowing jets as expected, a high precision two-way metering solenoid valve was used to control the flow rate of jet fluid. This valve can operate continuously without overheating by eliminating the coil heating problems associated with solenoid designs. The needle of the valve is driven by a high precision linear stepping motor, giving a resolution of 0.000125” per step. The stepping motor was controlled via a desktop PC using DT2112 Data Translation card with 12 bit D/A conversion; analog output from the card was taken to the stepping motor, utilizing feedback control to position the valve needle accurately. Prior to every single test, the relationship of the voltage of command signal from PC and flow rate was calibrated. By converting flow rate to jet momentum coefficient $C_\mu$, the relationship of voltage $V$ and $C_\mu$ was obtained. Based on this relationship, a Labview program was developed to generate different waveforms (periodic and transient) of commands enabling the valve to operate dynamically, thus simulating dynamic thrust vectoring of a periodically varying $C_\mu$ and transiently varying $C_\mu$. After passing through the valve, the jet fluid was separated into two flows and then fed into the two ends of the nozzle. Two flow meters were used to adjust the flow rate of each side accurately, thus ensuring a uniform flow pattern from each side of the jet nozzle.

### 2.2 Experimental Methods

#### 2.2.1 Food-Colouring Dye Flow Visualization

**2.2.1.1 Experimental Method**

In the experimental fluid dynamics realm, it is critically important to see the flow patterns produced by the flow fluid. Food-colouring dye flow visualization is a widely used experimental technique to make the flow patterns visible. This method
is to mark the trajectories of flow by injecting the food-colouring dye into the fluid.

In the present investigation, in order to detect the variations of vortex breakdown locations, food-colouring dye flow visualization was carried out in the water tunnel. The food-colouring dye, diluted 1:4 with water, was released near the apex of delta wing models. A JVC NV-DS99B digital camera with a high-resolution of 1,920,000 pixels and a capture rate of 25 frames per second was mounted on a tripod beneath the test section. This camera was used to capture images from the dye flow visualization, and was interfaced to a desktop PC via the commercial software package PINNACLE STUDIO DV, v7.15.1 (Pinnacle Systems Inc.), thus enabling real time viewing of the wing, capture of camera images and video recordings. The wing surface was illuminated by two floodlamps from the proper distance, ensuring a good background contrast. During the tests, the side windows of the test section was covered with a semitransparent plastic board in order to diffuse the illuminating light, which makes the bright floodlamp work as a shadowless lamp. Unwanted shadows which could have occurred on the wing surfaces were therefore avoided.

All the flow visualizations were performed at a constant free-stream velocity of $U_\infty=0.3\text{m/s}$, giving Reynolds numbers ($\text{Re} = \frac{U_\infty c}{\nu}$, where $U_\infty$ is the freestream velocity and $\nu$ is the fluid kinematic viscosity) $\text{Re} = 3.0 \times 10^4$ for both wings. For the purpose of comparison with previous data, experiments were carried out at the same range of jet momentum coefficient ($C_{\mu} = \frac{\rho U_{\text{jet}}^2 A_{\text{jet}}}{\frac{1}{2} \rho U_\infty^2 S_w}$, where $A_{\text{jet}}$ and $S_w$ denote the cross-sectional area of the nozzle exit and surface area of the wing) from 0 to 0.43 for both wings. The values of the momentum coefficient used in the experiments are realistic for thrust vectoring applications and also have been used by previous investigators [21-29].

In static tests, the trailing-edge jet was arranged at a fixed pitch angle $\beta$ and blew at a static $C_{\mu}$. For this case, the time required for flowfield to be established was usually a few seconds, thus 20 seconds video recording in this investigation were enough to provide sufficient information to describe the flowfield. The dynamic case was more complicated, as the jet oscillated periodically in the pitching
direction or blew at a dynamic $C_\mu$ during the tests. An average of 30 cycles was captured each time. For the static case, individual frames were captured from the recorded video as still images for further analysis by using PINNACLE STUDIO DV software. For dynamic cases, a series of frames were captured at constant time intervals with a MATLAB program. Processing of the images and data analysis was performed with MATLAB as well, which is described in the following section.

2.2.1.2 Data Processing

In this investigation, detecting the variation of vortex breakdown location is the main aim of food-colouring dye flow visualization. It is therefore necessary to explain how to identify the location of vortex breakdown first. The position of vortex breakdown is defined as, the location where the streakline marking the core makes an abrupt kink to form a spiral [19]. Figure 2.13 shows a typical measurement of vortex breakdown location.

A MATLAB program was developed to process the images captured from flow visualization in order to calculate the location of the vortex breakdown. The images were amplified first to minimize the uncertainty in identifying vortex breakdown locations. For each image, wing apex, trailing-edge and vortex breakdown location were identified manually. Then the pixel values of these three positions were imported into MATLAB code, and calculation of the vortex breakdown location was made by using the following equation:

$$X_{bd} \cdot c = \frac{\text{Pixel}_{\text{vortexbreakdown}} - \text{Pixel}_{\text{wingapex}}}{\text{Pixel}_{\text{trailingedge}} - \text{Pixel}_{\text{wingapex}}} \quad (2.1)$$

2.2.1.3 Uncertainty Analysis

The uncertainty in identifying vortex breakdown positions depends on three main factors: the uncertainty in locating the breakdown, the reading uncertainty of scale on video images, and the magnification of the lens. In order to minimize the
influence of the first factor, the calculation included as many images as possible and then averaged them. For the static case, at least 20 images were analyzed; for the dynamic case, at least 10 cycles (about 200 images) were analyzed. The camera used has a high resolution of 1600×1200 pixel, so the reading uncertainty of scale in this investigation is about 0.3% of the chord length. As for the magnification of the lens, the camera position and zoom range were kept the same for each test. The uncertainty of this factor can be neglected. Therefore, in this investigation, the overall uncertainty in locating breakdown position was estimated to be 1% of the chord length.

2.2.2 Laser-Induced Fluorescent Flow Visualization

2.2.2.1 Experimental Method

Laser-induced fluorescent flow visualization is another effective technique to investigate the fluid flows, especially in water. The method is to introduce a fluorescent compound to the flows being visualized and use a planar laser light to illuminate it. Because of the density of the fluorescent compound and its interaction with laser light to produce highly visible illumination, the flow can be easily visualized. This method allows for the visualization of phenomena such as waves, wakes, vortex shedding, vortex wandering, vortex merging and the dispersion of vortex, etc.

In this investigation, measurements in a cross plane were taken in order to obtain qualitative information about the leading-edge vortex and small vortical structures. A pure planar green laser sheet was generated from a water-cooled Coherent 12 Watt Argon-Ion continuous laser beam through a combination of cylindrical and spherical lens. The position of the laser sheet in the freestream direction can be adjusted using a trolley. A Panasonic NV-DS99B digital camera with a resolution of 570,000 pixels was mounted at the axial viewing window of the water tunnel to record the cross flow with a capture rate of 25 frames per second.
The delta wing models for laser-induced fluorescent flow visualization were painted black to remove unwanted reflections. In order to distinguish the leading-edge vortices and jet vortices, two different kinds of fluorescent dyes were used. The fluorescent dye of Rhodamine 6G presenting yellow colour in the laser illumination was fed into the jet nozzle from its water pipelines. Rhodamine B500% presenting red colour was pumped into the tubes embedded in the streamlined strut, and it was released to the water from the slots in the leading-edges of models. Figure 2.14 presents an example of a laser-induced fluorescent flow visualization picture captured in this investigation. The red vortex (upper) is the leading-edge vortex, and the yellow (lower) one is the jet vortex.

During the experiments, the laser sheet was set normal to the freestream in order to obtain the cross flow pattern. For some tests, the laser sheet was placed at 25% of the chord length downstream from the jet exit, providing an ideal visualization of interactions between jet and leading-edge vortices. In some tests, the laser sheet was placed at 80% of the chord length, thus obtaining an observation of the variation of leading-edge vortices. In order to investigate the effect of nozzle geometry, both rectangular and circular jets were tested. The experimental arrangement for laser-induced fluorescent flow visualization experiments is shown in Figure 2.15. All the recordings were made using Mini DV tapes. The images were processed with PINNACLE STUDIO DV software.

2.2.3 Particle Image Velocimetry

2.2.3.1 Experimental Method

Particle Image Velocimetry (PIV) is an advanced optical laser measuring technique for instantaneous and non-intrusive measuring of flow fields. This technique is of high importance in aerodynamics and fluid mechanics research, as it can provide precise quantitative information from the flows. The principle of this technique is to measure the velocity field by measuring the displacement of selected
micro-sized particles in the flow. The flow field seeded with particles is illuminated using a planar laser sheet. A CCD camera captures two images of the illuminated flow field at a short time interval $\Delta t$, so that the same particles are captured in two images. Then the images are divided into small interrogation cells. Cross correlation methods are applied into these interrogation cells to determine the exact displacement of each particle in the flow, $\Delta x$ and $\Delta y$. The velocity of each particle can be calculated as,

$$u = \frac{\Delta x}{\Delta t}, \quad v = \frac{\Delta y}{\Delta t} \quad (2.2)$$

Assuming that the particles are small enough to follow the flow, the velocity of the flow field can be therefore obtained.

In this investigation, a low frame rate TSI PIV system was used to investigate the interactions between the trailing-edge jet vortex and the vortical flows over delta wings. This system can generate a pair of pulsed mini Nd.YAG (Neodymium: Yttrium Aluminium Garnet) lasers giving the maximum pulse energy of 120 mJ. A combination of spherical and cylindrical lenses was used to produce the required laser sheet and adjust its divergence and focus. An 8-bit grayscale TSI CCD camera with a resolution of 2048×2048 pixels was used to capture the images at a maximum data rate of 7.5 frames per second. Synchronization of the camera and the laser was accomplished through a synchronizer unit. The laser unit of PIV was fixed on a supporting cart next to the side window of test section. This allowed the alteration of horizontal and vertical positions of the laser unit. The experimental arrangement for PIV measurements is shown in Figure 2.15.

The experimental conditions of PIV measurements were the same as those of flow visualization tests (Section 2.2.1.1). The flow was seeded with commercially available hollow glass particles with mean diameter of 4 µm, provided by TSI. Clogging of the particles was prevented by mixing them with water and adding a small portion of detergent, before pouring them into the water tunnel. The PIV camera was placed near the downstream viewing window to measure the velocity field in a cross flow plane. In additional experiments, the camera was placed
underneath the tunnel working section and the light sheet was placed parallel and close to the wing surface (1mm) to reveal the near-surface flow pattern. The arrangement of laser sheet for PIV measurements was shown in Figure 2.9. Prior to the tests, the focus of CCD camera was adjusted to exactly lie in the investigated cross plane in order to obtain better data quality.

For the static $C_\mu$ measurements, the PIV camera captured the images at the maximum rate of 7.5 Hz. For the dynamic $C_\mu$ measurements, in order to capture the variation of flow field due to the unsteady blowing jet, the PIV system was externally triggered at a specific time by a desktop PC so that a sequence of velocity field at a specific $C_\mu$ can be obtained.

### 2.2.3.2 Data Processing

For static $C_\mu$ measurements, a sequence of 100 pairs of images was captured for each case so that a time-averaged velocity field can be calculated. The time interval of each pair of images was 0.375s. For dynamic $C_\mu$ measurements, every single test was repeated 100 times, thus also providing 100 pairs of images for each specific $C_\mu$. Then the phase-averaged velocity field can be calculated. The number of images was found sufficient enough for an averaged velocity field.

Processing of the captured images was performed by the commercial software INSIGHT 6 (TSI). A Hart cross-correlation algorithm was applied to analyze the images, with an interrogation cell size of 32 by 32 pixels. The interrogation cells from each image frame were cross-correlated with each other, pixel by pixel. In each interrogation cell, the cross-correlation produced a signal peak, statistically identifying the average displacement of the particles. An accurate measurement of the displacement, and then the velocity vectors, was achieved. The vorticity and circulation of the flow field were therefore calculated.

### 2.2.3.3 Vorticity and Circulation

Vorticity and circulation are two closely related parameters in aerodynamics,
which are of great importance for the analysis of rotational flows. Vorticity, denoted as $\xi$, in most text books [18], describes the rotation of the flows at each point. Circulation, denoted as $\Gamma$, describes the rotation of the flows within a finite area. Vorticity is a ‘microscopic’ measure of rotation. In contrast, circulation is a ‘macroscopic’ measure of rotation. Mathematically, vorticity is a vector quantity, and it is simply twice the angular velocity of a fluid element, as defined in Equation 2.3.

$$\xi = 2\omega$$

(2.3)

where, in Cartesian coordinates:

$$\omega = \frac{1}{2} \left[ \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) i + \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) j + \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) k \right]$$

(2.4)

Since $u$, $v$ and $w$ denote the $x$, $y$ and $z$ components of velocity respectively, vorticity can be also described as the following equation,

$$\xi = \nabla \times V$$

(2.5)

Equation 2.5 indicates that “In a velocity field, the curl of the velocity is equal to the vorticity.” [18] In the present investigation, the vorticity is normalized by the chord length and the freestream velocity. Normalized vorticity is denoted as:

$$\frac{\omega \cdot c}{U_\infty}$$

(Note that the symbol $\omega$ denotes vorticity and not angular velocity in the Chapter 3 and 4).

Circulation is the line integral of velocity around a closed curve in the field. It is a scalar quantity. In Reference 18, circulation is defined as:

$$\Gamma = \oint_C V \cdot ds$$

(2.6)

Circulation is also related to vorticity as follows,

$$\Gamma = -\oint_C V \cdot ds = -\iint_S (\nabla \times V) \cdot ds$$

(2.7)

This equation indicates that circulation can be seen as vorticity integrated in an open surface. In this investigation, the circulation is normalized by the chord length and free stream velocity, denoted as follows:
\[
\frac{\Gamma}{U_c e}
\]

Circulation was calculated by using a MATLAB (2007) code, this is explained in more detail in Chapter 4.

2.2.3.4 Uncertainty Analysis

The uncertainty of PIV velocity measurements depends on three main factors: the seeding particle size, the density of seeding particles in the flow, and the resolution and quality of images [84]. The size of seeding particles was found to be one of the major sources of uncertainty in the data collected from PIV. Bigger particles can not follow the flow perfectly and also possibly influence the flow. Thus the particles should be small enough to track the flow. In this investigation, neutrally buoyant TSI hollow glass spheres with a 4µm mean diameter were selected.

The density of seeding particles was another major source of uncertainty. The number of particles per interrogation cell is of high importance in the PIV data processing. Insufficient particles in the interrogation cell could cause spurious or “bad” vectors. Kean and Adrian [84] demonstrated that the possibility of obtaining an accurate measure of the displacement of a set series of particles increases as the number of particles increases. However, there is a limit of seeding density due to finite intensity and spatial resolution capabilities of current imaging technology. Furthermore, very high seeding density could alter the characteristics of the flow being measured [84]. In the present study, approximately 1 cm\(^3\) of powdered glass particles was added to 3 litres of water and then poured into the water tunnel. The water tunnel would run without test rig for 5 minutes, thus ensuring the particles could be homogeneously distributed in the tunnel. The preliminary data analysis indicated that approximately three particle pairs were found in each interrogation cell, which can provide better data quality.

The resolution and quality of images is another main factor that could influence the data quality. Blur images and the reflection of laser light can greatly
influence the cross-correlation of image pairs. In this investigation, the focus of CCD camera was adjusted carefully prior to tests and the model was painted black in order to minimize these influences. An interrogation cell size of 32 by 32 pixels was applied for producing the velocity vectors. The effective grid size was varied from 1.8 mm in cross-flow planes to 3.0 mm in a plane near the wing surface.

The uncertainty of PIV velocity measurements was estimated to be around 2% of the freestream velocity.

### 2.2.4 Force Measurements

#### 2.2.4.1 Experimental Method

For force measurements conducted in the wind tunnel, wing models were mounted on the high-incidence rig through a six-component strain-gauged internal balance. Experimental arrangement is shown in Figure 2.2. Experiments were conducted at a constant free-stream velocity of $U_\infty = 15$ m/s, giving Reynolds numbers $Re = 3.1 \times 10^5$ for both slender and nonslender wings. For the purpose of comparison, experiments were carried out at the same jet momentum coefficient $C_{\mu}$ of 0.24 for both wings. Force measurements were carried out for wing incidences of $\alpha = 3^\circ - 40^\circ$. A total of five values of jet pitch angle were tested, i.e., $\beta = 0^\circ, 10^\circ, 20^\circ, 30^\circ$ and $40^\circ$. The jet yaw angle effects at $\gamma = -30^\circ$ (outboard) and $30^\circ$ (inboard) were also investigated (see Figure 2.9).

Signals from the force balance were simultaneously digitized using a 12bit A/D board and a personal computer at a sampling frequency of 1 KHz per channel. The duration of each record was about 10 seconds. This has been verified to be sufficiently long for the root mean square (rms) value of the measured signals to reach a steady value (variation less than 1.0%). The measured forces were then normalized by $qS_w$, where $q = \frac{1}{2} \rho U_\infty^2$ is the freestream dynamic pressure.

For force measurements in the water tunnel, the aerodynamic forces were
measured using a pair of load cells attached on the assembly board of the jet pitching system, as shown in Figure 2.10. Experiments were conducted at a constant free-stream velocity of $U_\infty = 0.3$ m/s, giving Reynolds numbers $Re = 3.0 \times 10^4$ for both wings. As the lift acting on the delta wing models is quite small (less than 0.5N), The Sensotec Model 31 load cell (shown in Figure 2.16) with the maximum load 250 gram was selected. This load cell, which achieves a combined non-linearity and hysteresis of 0.5% full scale, can offer quick response and high accuracies of measurements. The streamlined support strut of delta wing was mounted on the load cells by a cross bar.

Signals from the force balance were simultaneously digitized and amplified using a 12bit A/D board and a PC at a sampling frequency of 100Hz per channel. For the static tests, the duration of each record was 30 seconds; for the dynamic case, 30 cycles was captured for each test. This was found long enough to get sufficient data points. The measured forces were then normalized by $qS_w$.

2.2.4.2 Data Validation

In this investigation, the force measurements were conducted both in the wind tunnel and water tunnel. The force results obtained in the wind tunnel were compared to the data from the literature. When there is no trailing-edge blowing, $C_{\mu}= 0$, the measurement of lift coefficient demonstrated that the maximum $C_L$ was about 1.1 for the nonslender wing ($\Lambda=50^\circ$), which occurred near the stall angle of $\alpha \approx 20^\circ$. For the slender wing ($\Lambda=65^\circ$), however, the stall angle shifts to $\alpha \approx 32^\circ$ and its maximum $C_L$ is about 1.5. These results are in agreement with those reported in literature [13, 29, 83, 85].

The results obtained in the water tunnel were then compared to the data obtained in the wind tunnel. For both nonslender and slender delta wings, it was found the results obtained in water tunnel are in good agreement with those obtained in the wind tunnel, as shown in Figures 2.17 and 2.18.
2.2.4.3 Uncertainty Analysis

Uncertainty in the force measurements was calculated using the Kline-McClintock [86] method of analyzing error propagation. The effects of a number of sources of error may be combined to give the uncertainty in the result. If the output variable, \( R \) is a linear function of \( n \) independent variables: \( v_1, v_2, \ldots, v_n \),

\[
W = R(v_1, v_2, \ldots v_n)
\]  

Then the total uncertainty in \( W \), is calculated as the following way:

\[
W_r = \sqrt{\left(\frac{\partial R}{\partial v_1} w_1\right)^2 + \left(\frac{\partial R}{\partial v_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial v_n} w_n\right)^2}
\]  

The uncertainty of lift coefficient \( C_L \) measured in the wind tunnel mainly depends on two factors: freestream dynamic pressure and force balance reading. In this investigation, the freestream dynamic pressure was directly measured from digitron 2020P manometer connected to a pitot-static tube with an uncertainty of 2.1%. The accuracy of force balance reading was estimated to be 2% based on previous research conducted with this balance [87]. Applying to Equation 2.9 yields:

\[
W_r = \sqrt{\left(\frac{\partial C_L}{\partial L} \Delta L\right)^2 + \left(\frac{\partial C_L}{\partial q} \Delta q\right)^2}
\]  

where \( \Delta L \) and \( \Delta q \) are the uncertainties from force balance reading and freestream dynamic pressure. Hence, the uncertainty of lift coefficient \( C_L \) is calculated at 3%.

The uncertainty of normal force coefficient \( C_N \) measured in the water tunnel mainly depends on two factors: the error associated with the load cells and the uncertainty of flow speed. Applying to Equation 2.9 yields:

\[
W_r = \sqrt{\left(\frac{\partial C_N}{\partial Q_1} \Delta N_{Q1}\right)^2 + \left(\frac{\partial C_N}{\partial Q_2} \Delta N_{Q2}\right)^2 + \left(\frac{\partial C_N}{\partial U_{\infty}} \Delta U_{\infty}\right)^2}
\]  

where \( \Delta N_{Q1} \) and \( \Delta N_{Q2} \) are the uncertainties from load cell 1 and load cell 2. \( \Delta U_{\infty} \) is the uncertainty from the freestream velocity.

The measuring range of load cells used in the present investigation was 250 gram, that is, 2.45N. The output voltage of load cells is proportional to the applied load. The signal from the load cells was processed by a PC via a DT9112 Data
Translation card and HP-Vee program, and it was possible to resolve the voltage from the load cells to an accuracy of $1 \times 10^{-3}$ V. Converting this into the two load cells, yields: $\Delta N_{Q1} = 1.767 \times 10^{-6}$ V, $\Delta N_{Q2} = 1.929 \times 10^{-6}$ V. Based on the previous calibration, the freestream velocity can be controlled to an accuracy of approximately $\Delta U_\infty = 0.088$ cm/s, Hence, the uncertainty of normal force coefficient could be estimated by applying $\Delta N_{Q1}$, $\Delta N_{Q2}$, $\Delta U_\infty$ to Equation (2.11). Figure 2.19 shows the uncertainty as a function of angle of attack for both nonslender and slender wings. It can be seen that the error is less than 1% in the whole test range. Hence, the estimate uncertainty in force measurements was estimated 1%.
Figure 2.1: Planar view of wind tunnel.

Figure 2.2: Overview of experimental setup in the wind tunnel.
Figure 2.3: Sketch of the Eidetics model 1520 water-tunnel.

Figure 2.4: Dimensions of delta wing models tested in the water tunnel (wind tunnel).
Figure 2.5: Sketch of delta wing model for Laser-induced fluorescent visualization.

Figure 2.6: Dimensions of rectangular nozzle tested in the water tunnel (wind tunnel).
Figure 2.7: Dimensions of circular nozzle tested in the water tunnel (wind tunnel).

Figure 2.8: Dimensions of rectangular nozzle built with a 30° yaw angle for water tunnel (wind tunnel) experiments.
Figure 2.9: Experimental arrangement.
Figure 2.10: Schematics of unsteady pitching jet system (for force measurements).
Figure 2.11: Illustration of trailing-edge jet pitching angle in the water tunnel (Wing model was placed upside down).
Figure 2.12: Illustrative diagram of dynamic blowing jet system.
Figure 2.13: Schematic of calculation of the vortex breakdown location.

Figure 2.14: Example of Laser-Induced Fluorescent flow visualization. Red (upper): Leading-edge vortex; Yellow (lower): Jet vortex.
Figure 2.15: Experimental arrangement in the water tunnel.
Figure 2.16: Sensotec Model 31 load Cells for force measurement.

Figure 2.17: Variation of $C_N$ as a function of angle of attack for nonslender wing ($\Lambda=50^\circ$, $\beta=0^\circ$, $C_\mu=0$).
Figure 2.18: Variation of $C_N$ as a function of angle of attack for slender wing ($\Lambda=65^\circ$), $\beta=0^\circ$, $C_\mu=0$.

Figure 2.19: Uncertainty of $C_N$ as a function of angle of attack, $\beta=0^\circ$, $C_\mu=0$. 
CHAPTER 3  EFFECT OF STATIC THRUST VECTORING JETS ON DELTA WING AERODYNAMICS

3.1 Summary

In this chapter, the interaction of static thrust vectoring jets with leading-edge vortices over stationary delta wings and its effects on the wing aerodynamics were investigated experimentally. Two models with sweep angles of \( \Lambda = 50^\circ \) and \( 65^\circ \), representing nonslender and slender wings respectively, were tested with rectangular and circular nozzles. Force, velocity measurements and flow visualization were performed. It was found that under-vortex blowing can significantly affect the aerodynamic forces on both nonslender and slender wings. The maximum lift change occurred near the stall angle due to the earlier reattachment of shear layer and delay of vortex breakdown. Force measurements revealed that the effect of nozzle geometry can be important, as the entrainment effect of the jet depends on it. The jet-vortex interaction, distortion of jet vortices, and merging of wing and jet vortices are more pronounced for the rectangular nozzle and have a larger influence on the delta wing aerodynamics. The effect of jet yaw angle is small for the nonslender wing, whereas the aerodynamics of the slender wing is very sensitive to the jet yaw angle.
3.2 Aims

This chapter presents an experimental investigation of the interaction of statically pitched trailing-edge jets with leading-edge vortices over stationary delta wings and its effects on the wing aerodynamics. Wind tunnel and water tunnel experiments were performed to simulate thrust vectoring and quantify the aerodynamic effects by means of force measurements, flow visualization, and velocity measurements. Effects of jet location, pitch angle, yaw angle, nozzle geometry, and wing sweep angle on aerodynamic forces and vortex-jet interaction were investigated.

3.3 Results

3.3.1 Nonslender Wing

When there is no trailing-edge blowing, $C_\mu = 0$, the measurement of lift coefficient (not shown here) demonstrated that the maximum $C_L$ was about 1.1 for the nonslender wing ($\Lambda=50^\circ$), which occurred near the stall angle of $\alpha = 20^\circ$. These results are in agreement with those reported in the literature [13, 35]. Figure 3.1 presents the changes in $C_L$ for the nonslender wing ($\Lambda=50^\circ$) under the effect of trailing-edge blowing of $C_\mu=0.24$ with rectangular nozzle, here $\Delta C_L = (C_L)_\text{jet on} - (C_L)_\text{jet off}$. Since there is no contact between the jet system and the wing, the measured $\Delta C_L$ is due to the jet/vortex interaction only. Two observations can be made from Figure 3.1. First, the blowing effect on $C_L$ depends on the jet spanwise position $y_{jet}(b/2)$, where $y_{jet}$ is the distance between nozzle and model centerline and $b$ is the wing span (see Figure 2.9). When the jet was located at the center of the wing, $y_{jet}(b/2) = 0$, the blowing effect on $C_L$ is relatively small. It is noted that $\Delta C_L$ appears to decrease slightly, which is more evident near the stall angle, $\alpha = 20^\circ$. In contrast, when the jet was located at $(y_{jet}(b/2) = 0.6)$, which is the
approximate position of leading-edge vortex axis, the blowing resulted in much
greater changes in $C_L$. The $\Delta C_L$ appears to increase with increasing wing incidence $\alpha$. The $\Delta C_L$ reaches its maximum values, i.e., $\Delta C_{L,\text{MAX}} \approx 0.15$, near wing stall angle, $\alpha = 20^\circ$. Secondly, for under-vortex blowing, $y_{\text{jet}}/(b/2)=0.6$, the variations of $\Delta C_L$ associated with the jet pitch angle $\beta = 0^\circ$ and $30^\circ$, are similar to each other. This observation suggests that the effect of jet pitch angle on delta wing aerodynamics was relatively small in this case. Variation of pitching moment (not shown here) is very similar to that the lift coefficient, and will not be discussed here.

These force measurements can be interpreted in relation to the cross-flow
visualization pictures shown in Figure 3.2. The jet is located at $y_{\text{jet}}/(b/2) = -0.6$ (left hand side in the picture) and the light sheet is located at $x/c=0.8$. It is seen that, for incidences $\alpha=10^\circ$ and $\alpha=15^\circ$, the effect of the trailing-edge blowing is small, although the reattachment location is more outboard for the left vortex. (The vertical dashed line shows the wing centerline). For the stall angle ($\alpha=20^\circ$), the left vortex appears somewhat smaller and reattaches much earlier. Note that the right vortex reattaches just near the wing centerline. For the largest angle of attack $\alpha=25^\circ$ (post-stall region), separated flows on both sides appear to merge. The vertical extent of the left vortex is smaller due to the jet blowing.

For a different value of pitch angle $\beta$, food-colouring dye visualization pictures are shown in Figure 3.3. It is seen that in the pre-stall regime ($\alpha=15^\circ$), the change in the breakdown location with blowing is small. For $\alpha=20^\circ$ (stall angle), when there is no blowing ($C_\mu=0$), vortex breakdown occurred at the wing apex. With the trailing-edge blowing on the left side and under the vortex ($y_{\text{jet}}/(b/2) = -0.6$), however, breakdown of the leading-edge vortex on the jet side is delayed. This observation is consistent with the observed lift enhancement with under vortex blowing (see Figure 3.1). Even for $\alpha=25^\circ$ in the post-stall region, the flow appears to be more organized with blowing. This is again consistent with the increased lift shown in Figure 3.1 in the post-stall region.

Figure 3.4 presents the variation of changes in vortex breakdown location
over the nonslender wing ($\Lambda=50^\circ$) as a function of jet location under the effect of
rectangular jet blowing for various incidences. Here
\[ \Delta X_{bd} / c = (X_{bd} / c)_{jet\ on} - (X_{bd} / c)_{jet\ off}, \]
where \( X_{bd} \), identified from flow visualization images, is the distance from the wing apex to vortex breakdown location (see Figure 2.9 and 2.13). Several observations can be made based on Figure 3.4. Firstly, for all incidences tested, the maximum \( \Delta X_{bd} / c \) occurs at or near \( (Y_{jet}(b/2) = 0.6) \), the approximate position of the leading-edge vortex in the spanwise direction [35], thus suggesting a much larger effect of under-vortex blowing on the vortex characteristics over the wings. Secondly, for under vortex blowing, the blowing effect appears to increase with increasing wing incidence \( \alpha \). The maximum \( \Delta X_{bd} / c \) is about 0.02 at \( \alpha = 10^\circ \) (Figure 3.4a). This value increases to \( \Delta X_{bd} / c \approx 0.05 \) at \( \alpha = 15^\circ \) (Figure 3.4b), and further to \( \Delta X_{bd} / c \approx 0.13 \) for \( \alpha = 20^\circ \) (Figure 3.4c), which corresponds to the stall angle. This observation is in good agreement with the results of Helin [21] and Shih & Ding [22]. It suggests that the effectiveness of trailing-edge blowing is higher near the stall angle. Thirdly, the blowing effect at or near the wing centerline is relatively small, especially for small wing incidences. The blowing has no obvious effect on the vortex breakdown location until the jet spanwise position \( y_{jet} / (b/2) \geq 0.5 \), 0.4 and 0.3, corresponding to \( \alpha = 10^\circ \), 15\(^\circ\) and 20\(^\circ\), respectively. This indicates that only under vortex blowing \((y_{jet}(b/2)=0.6)\) can yield maximum blowing effect. Fourthly, no significant differences in the variations of \( \Delta X_{bd} / c \) were observed for \( C_\mu = 0.24 \) and 0.43, suggesting that there is a saturation effect with respect to the momentum coefficient \( C_\mu \). This is consistent with the observation of Mitchell et al. [24] which also showed the existence of upper limit on the effective velocity ratio (corresponding to \( C_\mu \)). It is likely due to that the influence on the adverse pressure gradient induced by trailing-edge jet become very small as the jet velocity ratio is above this upper limit.

The effects of under-vortex blowing on vortex characteristics were further studied with PIV measurements. Figure 3.5 presents the time-averaged vorticity field measured in a cross-flow plane at \( x/c = 0.8 \) for the nonslender wing at \( \alpha = 20^\circ \) with
rectangular nozzle at \( y_{jet}/(b/2) = -0.6 \) and \( \beta = 30^\circ \). When there is no blowing (\( C_\mu = 0 \)), the leading-edge vortex pair is fairly symmetric about the wing centerline. Furthermore, the magnitude of \( \omega x s / U_\infty \) values is also symmetrically distributed, i.e., with a maximum \( \omega x s / U_\infty \) of about \( \pm 6.0 \) for both left and right sides. When there is under-vortex blowing (\( y_{jet}/(b/2) = -0.6 \)) of \( C_\mu = 1 \), the maximum magnitude of \( \omega x s / U_\infty \) (\( \approx 12 \)) on the jet side is higher than that on the other side and also those associated with \( C_\mu = 0 \), apparently due to the delay of vortex breakdown, as a well-organized vortex core with strong vorticity formed when vortex breakdown moving downstream. In addition, the separation distance between the leading-edge vortex pair increased. This observation suggests an earlier reattachment of the leading-edge vortex on the jet side.

The effects of trailing-edge jets on wing flow characteristics were further clarified by PIV measurements near the wing surface. Figure 3.6 shows the magnitude of time averaged velocity, \( u/U_\infty \), and streamline pattern near the wing surface at \( \alpha = 20^\circ \). At \( C_\mu = 0 \) (Figure 3.6a), the flow pattern is fairly symmetric about the wing centerline. Furthermore, closed spiralling streamline patterns corresponding to two nodes can be observed on both sides near wing apex. Note that leading-edge vortex breakdown occurred near the wing apex in this case (see Figure 3.3). When there is under-vortex jet blowing of \( C_\mu = 0.24 \), however, it can be seen that the reattachment occurs earlier on the jet (left) side. As a result, the closed spiralling streamline pattern near the wing apex persists only at the right side (Figure 3.6b), though its scale is much smaller than that associated with \( C_\mu = 0 \) (Figure 3.6a). These observations are consistent with the flow visualization results (Figures 3.2 and 3.3). In addition, the flow field appears asymmetric about \( y = 0 \) for \( C_\mu = 0.24 \) (Figure 3.6b). The maximum \( u/U_\infty \) region appears shifting away from the wing centerline towards the jet (left) side, which is more evident for higher momentum coefficients, i.e., \( C_\mu = 0.43 \) (Figure 3.6c) and 1.0 (Figure 3.6d). It is seen in Figure 3.6 that the flow pattern near the stall for \( C_\mu = 0 \) exhibits a single reattachment near the wing.
symmetry plane, whereas two separate reattachment lines can be identified for jet blowing.

### 3.3.2 Slender Wing

Figure 3.7 presents the changes in $C_L$ under the effect of trailing-edge blowing with the rectangular nozzle for the slender wing ($\Lambda=65^\circ$). Note that the stall angle shifts to $\alpha = 32^\circ$ and the maximum $C_L$ is about 1.5. These results are in agreement with those reported in the literature [14, 15]. It is observed that the centerline blowing causes $C_L$ to decrease up to about 0.07 for $C_\mu=0.43$, while the under-vortex blowing tends to increase $C_L$, which persists even after the slender wing stall angle, $\alpha = 32^\circ$. Comparison with the case of the nonslender wing (see Figure 3.1) indicates that the effect of centerline blowing near the stall angle is relatively larger for the slender wing. This is reasonable as the relative span of the slender wing is smaller.

The force measurements shown in Figure 3.7 can be interpreted in relation to the cross-flow visualization pictures shown in Figure 3.8. The jet is located at $y_{jet}/(b/2)=-0.6$ (left hand side in the picture) and the light sheet is located at $x/c=0.8$. It is seen that, for the smallest incidence ($\alpha=10^\circ$), the effect of blowing is small. In this picture, the dark region in the vortex core suggests the absence of vortex breakdown. For $\alpha=20^\circ$, the blowing delays vortex breakdown on the jet side (with the dark region in the core) whereas the other side exhibits a broken down vortex at that station. Again, the largest effects appear at $\alpha=30^\circ$, which is near the stall angle. The vortex on the jet side appears to be smaller in size for large angles of attack.

The overall effect of blowing is best illustrated in Figure 3.9 as a function of incidence. The largest changes in the location of breakdown occur on the jet side near the stall angle ($\alpha=32^\circ$), and even at the post-stall incidences such as $\alpha=40^\circ$. The other side shows small movement of breakdown upstream as the vortex on the jet side is delayed as a result of blowing. Figure 3.10 shows the variation of the delay of vortex breakdown location as a function of jet pitch angle for $y_{jet}/(b/2)=-0.6$.
at various angles of attack. It is seen that the effect of the jet pitch angle is small in general. With increasing incidence, the delay of breakdown increases for up to $\alpha=35^\circ$ (which is slightly larger than the stall angle), and then decreases for $\alpha=40^\circ$. The largest delays achieved for this slender wing ($\Lambda=65^\circ$) are slightly larger than those for the nonslender wing ($\Lambda=50^\circ$).

It is interesting to examine the effectiveness of a trailing-edge jet as a function of wing sweep angle, as blowing at the trailing-edge modifies the external pressure gradient and delays vortex breakdown. Figure 3.11 shows the optimum effectiveness values, defined as $(\Delta X_{bd}/c)/C_\mu$, collected from various studies reported in References 21, 22, 24, 25, 27 and 28 together with the present study, as a function of wing sweep angle. It appears that it becomes more difficult to delay vortex breakdown with decreasing sweep angle. This is likely to be due to the fact that the external pressure gradient is more adverse for nonslender wings than for slender wings [19]. As a result, the effectiveness of breakdown control is much less. Even though the delay of breakdown is more difficult for nonslender wings, the effect of trailing-edge jets on reattachment of flow is substantial as shown near the stall angle (see Figures 3.3 and 3.6).

### 3.3.3 Effect of Nozzle Geometry

In this section, effects of nozzle geometry on lift force and jet/vortex interaction details are discussed. Figure 3.12 presents the changes in $C_L$ for the nonslender wing with trailing-edge jet blowing ($C_\mu = 0.24$) with the circular nozzle. It is seen that the $\Delta C_L$ exhibits similar trends with those of jet blowing with the rectangular nozzle (see Figure 3.1). The effect of centerline blowing is small, and there is lift enhancement, which reaches its maximum values near the wing stall angle, for under-vortex blowing. However, the magnitude of $C_L$ changes is smaller for the circular nozzle. With under-vortex blowing at $y_{jet}/(b/2) = -0.6$, the maximum $\Delta C_L$ associated with the circular nozzle is about 0.075, considerably smaller than that
of the rectangular nozzle (\( \Delta C_{L,\text{MAX}} \approx 0.15 \)) (see Figure 3.1).

In order to understand the differences between the effects of circular and rectangular nozzles on \( \Delta C_L \), PIV measurements of the time-averaged vorticity field in a cross-flow plane in the near wake (at 25% chord from the nozzle exit) for the nonslender wing were carried out. In addition, in order to understand better the effect of vortex, similar measurements were performed without the wing (and vortex) and compared with the wing (and vortex) case. Figure 3.13 compares the results for the circular nozzle (left column) and rectangular nozzle (right column), and without the wing (parts (a) and (b)) and with the wing (parts (c) and (d)). It is seen that both nozzles produce a pair of counter-rotating vortices as the jets exhaust into the cross-flow when there is no vortex (parts (a) and (b)), and the distance between the pair of vortices is larger for the rectangular wing as expected. Part (c) shows that when there is vortical flow due to the wing at \( \alpha = 20^\circ \), the jet vortex with the counter-clockwise vorticity is distorted under the effect of the induced velocity of the wing vortical flow (wing vortex is not very concentrated at the stall incidence and exhibits weak vorticity). The interaction and distortion appear to be stronger for the rectangular nozzle (part (d)). The jet vortex with the counter-clockwise vorticity seems to be split into two, and a small secondary vortex is visible. The jet vortex with clockwise vorticity appears to be much weaker as a result of this vortex-jet interaction. It is interesting to note that, for highly yawed jets in crossflow, similar observations [83] were made. Only one-sign of vorticity becomes dominant for the highly yawed jets, and the magnitude of the maximum vorticity is much larger than that of the vortices for the case of zero yaw. Even the two regions of concentrated vorticity (with the same sign) were observed in Reference 83. All these features are similar to our observations.

Figure 3.14 shows a similar comparison for a larger angle of attack, \( \alpha = 24^\circ \), in the post-stall region. In this case, the wing vortical flow is even more disorganized and appears as weak vorticity patches above the nozzle. Nevertheless, the results are similar to those for \( \alpha = 20^\circ \). Distortion of the jet vortices is visible for the circular nozzle, with the counter-clockwise jet vortex becoming elongated. The shape of the
deformed jet vortex is entirely different for the rectangular nozzle. Although the counter-clockwise vortex is not split into two like the previous case ($\alpha=20^\circ$), there is strong similarity between the two cases. Again the clockwise jet vortex is weak and there might be merging with the wing vortical flow, although this is not clear.

Figure 3.15 shows the effect of increasing momentum coefficient for the rectangular nozzle for $\alpha=20^\circ$. It is seen that vortex merging takes place for the larger momentum coefficient. The wing vortex (even though it is weak at the stall angle) merges with the clockwise jet vortex. We have found evidence of vortex merging for the slender wing as well. In this case, the wing vortex is expected to be more concentrated (compare Figures 3.2 and 3.8). Figure 3.16 shows flow visualization pictures in a cross-flow plane in the near wake ($\Delta x/c=0.25$) for $\Lambda=65^\circ$ and $\alpha=10^\circ$. The left column shows images when the jet is marked only and the right column shows corresponding images when both the jet and vortex are marked with different colour dyes. Flow visualization images are shown as a function of increasing jet pitch angle $\beta$. In all cases, the wing vortex appears to merge with the jet fluid on the left side (where the clockwise jet vortex is expected to be). As the jet pitch angle increases, the distortion of the jet and generation of the jet vortices are clear. Also, with increasing jet pitch angle, the jet vortices move away from the trailing-edge and downward while the wing vortex becomes stretched.

Returning to the discussion of vorticity fields in Figures 3.13 and 3.14, the jet-vortex interaction is much stronger for the rectangular nozzle. This is partly due to the larger separation distance of the vortex pair for the rectangular nozzle. Correspondingly, vortex-induced velocity over a larger distance generates a larger mass entrainment and even pulls the leading-edge vortex downward. Wang et al [82] showed that wing vortices may be drawn toward the jet center by the induced velocity created by the jet vortices. As a result, the rectangular nozzle has a larger influence on the delta wing aerodynamics, as evidenced by the force measurements shown in Figure 3.12.
3.3.4 Effect of Jet Yaw Angle

Figure 3.17 presents the effect of jet yaw angle $\gamma$ on changes in $C_L$ for the nonslender wing ($\Lambda=50^\circ$) and the slender wing ($\Lambda=65^\circ$) for $y_{jet}/(b/2) = -0.6$, $\beta=0^\circ$, and $C_\mu=0.24$. For the nonslender wing, as the jet yaw direction changed from outboard ($\gamma = -30^\circ$) to inboard ($\gamma = 30^\circ$), the increment in the lift coefficient $\Delta C_L$ displays similar trends, which is also similar to that of the no-yaw case ($\gamma = 0^\circ$), in particular for the pre-stall incidences. In the post-stall region, there are some differences, but the overall trend is similar. For all values of $\gamma$, $\Delta C_L$ increases with $\alpha$ and reaches its maximum value near the wing stall angle ($\alpha = 20^\circ$).

In contrast with this observation, jet yaw angle has an entirely different effect on the aerodynamics associated with the slender wing. Figure 3.17(b) demonstrates that the outboard and inboard blowing produce different trends of lift increment. For outboard yaw ($\gamma = -30^\circ$), $\Delta C_L$ appears to increase gradually with increasing $\alpha$, which persists even after the stall angle of $\alpha = 32^\circ$. When the jet is yawed inboard ($\gamma = 30^\circ$), however, the changes in $C_L$ are quite different from those associated with $\gamma = -30^\circ$ and $\gamma = 0^\circ$. The maximum $\Delta C_L (\approx 0.18)$ can be observed at small wing incidence, i.e., $\alpha = 3^\circ$. As wing incidence increases, $\Delta C_L$ keeps decreasing and reaches about zero near the stall angle. The substantial effect of yaw angle is a result of relatively smaller span. Also, relative contribution of vortical flows for the slender wing is larger. Unlike nonslender wings, vortex lift makes up a large proportion of the total lift for slender wings.

In order to understand better why the slender wing is so sensitive to jet yaw angle, both small incidences and near-stall incidences were examined in detail. Flow visualization pictures for $\gamma=-30^\circ$, $0^\circ$, $30^\circ$ are shown in Figure 3.18 for the stall angle $\alpha=32^\circ$. It is seen that vortex breakdown is delayed most for $\gamma=-30^\circ$, followed by $\gamma=0^\circ$ and $30^\circ$. This is the same order for the observed lift increment shown in Figure 3.17(b).

For the case of small incidences, flow visualization and PIV measurements
were conducted for $\alpha=10^\circ$, where the force increments are very different for $\gamma=0^\circ$ and $30^\circ$. Flow visualization (not shown here) revealed that there is no breakdown at this incidence regardless of the jet yaw angle. PIV measurements of the time-averaged vorticity in a cross-flow plane at $x/c=1.0$ are shown in Figure 3.19 for these two values of yaw angle. Both the location of the leading-edge vortex and its structure are almost the same. The strength of the vortex was found as $\Gamma/U_\infty c=0.147$ and 0.152 for $\gamma=0^\circ$ and $30^\circ$, respectively. Velocity profiles (not shown here) also appear very similar. It is concluded that the observed differences in the lift coefficient for the two jet yaw angles cannot be explained with any changes in the vortical flow properties. As this implies that observed changes in the lift force are not related to the vortex lift, which suggests that the potential lift contribution might be responsible. Further studies are needed to understand the yaw sensitivity of slender wings at small incidences.

### 3.4 Conclusions

The interaction of statically pitched trailing-edge jets with leading-edge vortices over stationary delta wings and its effects on the wing aerodynamics were investigated. For the nonslender wing ($\Lambda=50^\circ$), the effect of the jet strongly depends on the spanwise location of the nozzle. For centerline blowing ($y_{jet}/(b/2) = 0$), the effect is small, while for under-vortex blowing, the maximum lift enhancement reaches $\Delta C_{L,MAX} \approx 0.15$ near the stall angle of $\alpha = 20^\circ$. The effect of jet pitch angle $\beta$ is relatively small. Flow visualization confirmed that the largest effect of blowing is observed near the stall incidence and post-stall region, where earlier reattachment of the shear layer occurs and vortex breakdown is delayed. PIV measurements at the stall angle $\alpha = 20^\circ$ also confirmed the earlier reattachment and delay of vortex breakdown.

For the slender wing, the effect of trailing-edge blowing on the lift force is generally similar, with the lift force increasing substantially with the under-vortex
blowing near the stall angle and in the post-stall region. However, the effect of the centerline blowing is larger due to the relatively shorter span of the wing. Flow visualization confirmed that the effect of blowing on the reattachment and breakdown location is small at low incidences, and the largest effects appear near the stall and in the post-stall region. The jet pitch angle $\beta$ has a relatively small effect on vortex breakdown, which is consistent with the force measurements. Delay of vortex breakdown with blowing is somewhat larger for the slender wing ($\Lambda=65^\circ$), and there is evidence that the effectiveness of trailing-edge blowing increases with the wing sweep angle.

Force measurements revealed that the effect of nozzle geometry can be important, as the entrainment effect of the jet depends on it. PIV measurements showed that wing vortical flow interacts with the jet-induced vortices in the near-wake. Large distortion of the jet vortices and formation of multiple vortices in some cases are revealed from these measurements. Merging of wing vortices with jet vortices is also observed. Overall, the jet-vortex interaction is much stronger for the rectangular nozzle and has a larger influence on the delta wing aerodynamics.

The effect of jet yaw angle is small for the nonslender wing ($\Lambda=50^\circ$), whereas the aerodynamics of the slender wing ($\Lambda=65^\circ$) is very sensitive to the jet yaw angle. Near the stall angle, this sensitivity is due to the effect on vortex breakdown and vortex lift, which makes up a large proportion of the total lift for slender wings. On the other hand, at small incidences, no noticeable effect was found on the vortical flow and the observed changes in the forces might be due to the potential lift contribution.
Figure 3.1: Changes in lift coefficient for the nonslender wing ($\Lambda=50^\circ$) with trailing-edge blowing with rectangular nozzle.
Figure 3.2: Laser fluorescence flow visualization pictures in a cross-flow plane for nonslender wing (Λ=50°), β=30°, C_μ=0.43, y_{jet}/(b/2)=−0.6. Laser sheet was placed at x/c=0.8.
Figure 3.3: Food-colouring dye flow visualization for nonslender wing ($\Lambda=50^\circ$), $y_e/(b/2)=-0.6$, $\beta=0^\circ$. 

$C_\mu=0$  

$C_\mu=0.43$  

$\alpha=15^\circ$  

$\alpha=20^\circ$  

$\alpha=25^\circ$
Figure 3.4: Variation of the delay of vortex breakdown location as a function of the spanwise location of the jet. $\Lambda=50^\circ$, $\beta=20^\circ$, rectangular nozzle. (a)$\alpha=10^\circ$; (b)$\alpha=15^\circ$; (c)$\alpha=20^\circ$. 
Figure 3.5: Time-averaged cross-flow vorticity field at $x/c=0.8$ for the nonslender wing. $\Lambda=50^\circ$, $\alpha=20^\circ$, $\beta=30^\circ$, $y_{jet}/(b/2)=-0.6$, rectangular nozzle.
Figure 3.6: Magnitude of time-averaged velocity and streamline pattern near wing surface. $\Lambda=50^\circ$, $\alpha=20^\circ$, $\beta=30^\circ$, $y_{\text{jet}}/(b/2)=-0.6$, rectangular nozzle. (a) $C_\mu=0$; (b) $C_\mu=0.24$; (c) $C_\mu=0.43$; (d) $C_\mu=1$. 
Figure 3.7: Changes in $C_L$ under the effect of blowing with rectangular nozzle for slender wing ($\Lambda=65^\circ$).
Figure 3.8: Laser fluorescence flow visualization pictures for slender wing ($\Lambda=65^\circ$), $\beta=30^\circ$, $C_\mu=0.43$. Laser sheet was placed at $x/c=0.8$. 
Figure 3.9: Food-colouring dye flow visualization for slender wing ($\Lambda=65^\circ$), $y_{jet}/(b/2)=-0.5$, $\beta=0^\circ$. 

$C_\mu=0$  

$C_\mu=0.43$
Figure 3.9: Continued
Figure 3.10: Variation of the delay of vortex breakdown location as a function of jet pitch angle. \( \Lambda=65^\circ \), \( C_{\mu} = 0.43 \), \( y_{\text{jet}}/(b/2) = -0.6 \), rectangular nozzle.

Figure 3.11: Optimum effectiveness of trailing-edge jet as a function of wing sweep angle from various studies.
Figure 3.12: Changes in lift coefficient for nonslender wing ($\Lambda=50^\circ$) with trailing-edge blowing with circular nozzle.
Figure 3.13: Vorticity in a cross-flow plane at $\Delta x/c=0.25$ for circular nozzle (left column) and rectangular nozzle (right column). (a) and (b) are for jet only with no wing; (c) and (d) with wing, $C_\mu=0.24$, $\alpha=20^\circ$, $\beta=0^\circ$. 

Chapter 3  Static Thrust Vectoring Jets
Figure 3.14: Vorticity in a cross-flow plane at $\Delta x/c = 0.25$ for (a) circular nozzle $C_\mu = 0.24$, $\alpha = 24^\circ$, $\beta = 0^\circ$.

(b) rectangular nozzle, $C_\mu = 0.24$, $\alpha = 24^\circ$, $\beta = 0^\circ$. 

91
Figure 3.15: Vorticity in a cross-flow plane at $\Delta x/c=0.25$ for rectangular nozzle, (a), $C_\mu=0.24$, (b), $C_\mu=0.43$, $\alpha=20^\circ$, $\beta=0^\circ$. 
Figure 3.16: Laser fluorescence flow visualization in a cross-flow plane at $\Delta x/c=0.25$, $\Lambda=65^\circ$, $\alpha=10^\circ$, rectangular nozzle, $y_{jet}(b/2)=-0.6$. 
Figure 3.16: Continued
Figure 3.17: Effect of jet yaw angle on changes in $C_L$ for (a), nonslender wing ($\Lambda=50^\circ$); (b), slender wing ($\Lambda=65^\circ$). $y_{\text{jet}}/(b/2) = -0.6$, rectangular nozzle.
Figure 3.18: Flow visualization for three different values of jet yaw angle for $\alpha=32^\circ$, $\Lambda=65^\circ$, $C_\mu=0.24$, $\beta=0^\circ$.
Figure 3.19: Time-averaged cross-flow vorticity field at the trailing-edge \((x/c=1.0)\) for (a) \(\gamma=0^\circ\), (b) \(\gamma=30^\circ\) (inboard blowing). Rectangular nozzle, \(\Lambda=65^\circ\), \(\alpha=10^\circ\), \(\beta=0^\circ\), \(C_\mu=0.24\), \(y_{jet/(b/2)}=-0.6\).
CHAPTER 4 EFFECTS OF UNSTEADY TRAILING-EDGE JET ON DELTA WING AERODYNAMICS

4.1 Summary

The effects of unsteady blowing and pitching trailing-edge jet on delta wing aerodynamics were investigated experimentally in order to understand the aerodynamics-propulsion interaction for dynamic thrust vectoring. Two models with sweep angles of $\Lambda=50^\circ$ and $65^\circ$, representing nonslender and slender delta wings respectively, were tested in a water tunnel. Flow visualization, velocity and force measurements were conducted at stall and post-stall incidences. For the periodic trailing-edge blowing, it was found that the dynamic response of leading-edge vortex breakdown and wing normal force coefficient exhibit phase lags for both nonslender and slender delta wings. The estimated time constant is larger than those reported in the literature for unsteady wings undergoing pitching or plunging. For the accelerating and decelerating blowing, time delay for the decelerating jet is significantly larger than that of the accelerating jet. Variations of the circulation and reattachment process near the wing surface were studied by means of velocity measurements. The range of the estimated time constants is similar at the stall and post-stall incidences for both the slender and nonslender wings. For the periodic pitching trailing-edge jet, it was found that the dynamic responses of leading-edge vortex breakdown and wing normal force exhibit similar trends of periodic blowing case for both nonslender and slender delta wing configurations. The phase lag $\phi$
increases with increasing frequency $f^*$ of the periodically pitching jet. The estimated time constants $\tau_{U_\infty}/c$ of $C_N$ are comparable to those of previous results.

### 4.2 Aim

For the dynamic thrust vectoring in which the momentum flux or the jet pitch angle varies as a function of time, significant time delays and hysteresis of the vortical flows and aerodynamic forces of delta wings are expected. The response of wing vortical flow is expected to be similar, at least qualitatively, to that of unsteady wings [11]. Hysteresis and time-lag of vortical flows and vortex breakdown over pitching or plunging wings are well known [11, 67-69, 74]. In this chapter, in order to simulate the dynamic thrust vectoring for a manoeuvre, the jet velocity (hence, momentum coefficient) or jet pitch angle was varied as a function of time. One of the objectives of this chapter is therefore to understand the effects of dynamically varying momentum coefficient or jet pitch angle of the trailing-edge jet on delta wing aerodynamics, with an emphasis on quantifying hysteresis and phase lags. Both periodic and transient variations of the momentum coefficient $C_\mu$ or jet pitch angle were investigated. In order to study the effect of sweep angle on the dynamic response characteristics of wing flow to unsteady trailing-edge blowing, both nonslender ($\Lambda=50^\circ$) and slender wings ($\Lambda=65^\circ$) were tested.

### 4.3 Results

#### 4.3.1 Periodic Trailing-Edge Blowing

**4.3.1.1 Nonslender Wing**

As discussed earlier, the effect of trailing-edge jets is thought to be more important for nonslender wings, in particular near the stall and in the post-stall
regimes. Hence, the experiments with unsteady blowing for a nonslender wing were conducted at $\alpha=20^\circ$ (approximate stall angle) and $25^\circ$.

The jet momentum coefficient $C_\mu$ of periodic trailing-edge blowing follows a cosine wave, $C_\mu = 0.215 + 0.215\cos(2\pi f t + \pi)$, with a peak-to-peak amplitude of 0.43 and a time-averaged value of 0.215, and $f$ is the oscillatory frequency of $C_\mu$. Figure 4.1 presents the typical food-colouring dye flow visualization images of leading-edge vortices over nonslender delta wing ($\Lambda=50^\circ$) at an incidence of $\alpha=20^\circ$ with different dimensionless frequencies $f^*=0.009$, $0.045$ and $0.09$, here $f^*=f/c/U_\infty$, and $c$ is the maximum chord length of delta wing models. For $f^*=0.009$, initially at $t/T = 0$ and $C_\mu = 0$, the breakdown of leading-edge vortices occurs near the wing apex. At $t/T = 0.5$ and $C_\mu = 0.43$, it can be observed that the vortex breakdown of the jet (left) side was delayed to $x/c \approx 0.15$ while the vortex breakdown at the right-hand side occurs closer to the wing apex. This observation is consistent with the steady trailing-edge blowing for the same configuration (see Chapter 3). Similar observations were also made in the post-stall incidence of $\alpha=25^\circ$ (not shown here).

The phase-averaged variations of vortex breakdown location $X_{bd}/c$ over the nonslender wing ($\Lambda=50^\circ$) at $\alpha=20^\circ$ and $25^\circ$, are presented in Figure 4.2. For each $f^*$ tested, the response of $X_{bd}/c$ to the periodically varying $C_\mu$ exhibits a periodic variation with a phase lag. The phase lag tends to increase with increasing $f^*$, while the amplitude of $X_{bd}/c$ tends to be decreasing with increasing $f^*$. Figure 4.3 presents the variation of the phase-averaged normal force coefficient $C_N$ for the nonslender wing ($\Lambda=50^\circ$) at $\alpha=20^\circ$ and $25^\circ$. Similar to the variations of the breakdown location $X_{bd}/c$, the normal force coefficient $C_N$ also follows a periodic cosine wave, with increasing phase lag and decreasing amplitude as $f^*$ is increased.

The dependence of phase lag $\phi$ of $X_{bd}/c$ and $C_N$ on the dimensionless blowing frequency $f^*$ are presented in Figure 4.4 for $\alpha=20^\circ$ and $25^\circ$. The phase lags were calculated from the Fourier series analysis of the phase-averaged variation of the quantities. It can be observed that $X_{bd}/c$ and $C_N$ exhibit similar trends of increasing $\phi$ with increasing $f^*$. This observation is similar to the findings of previous investigations.
for unsteady wings [11, 67-69, 74]. This is reasonable if vortex breakdown is considered as a wave propagation phenomenon. Based on the explanation of time lag proposed by Gursul [51] (see Section 1.2.1.4.6), time lag is dependent on the speed of waves travelling upstream. The wave speed decreases with the increasing frequency in the unsteady cases. As a result, time lag of vortex breakdown increases with frequency. Because the mechanism of time lag is universal regardless of the type of unsteady motion [11], similar trends of phase lags have been found for different unsteady cases.

However, the phase lag $\phi_N$ of $C_N$ is smaller than the phase lag $\phi_b$ of $X_{bd}/c$. For example, at $f^*=0.09$ and $\alpha=25^\circ$, $\phi_N=92^\circ$, while $\phi_b$ is larger than $\phi_N$, approximately $145^\circ$. This observation suggests that the development of vortex breakdown lags behind wing aerodynamic forces. Polhamus’ theory [34] predicts that the vortex lift is only a part of total lift over delta wings. The present observation suggests that potential lift also contributes to the dynamic response of wing aerodynamics.

If it is assumed that the response of $X_{bd}$ and $C_N$ to periodic trailing-edge blowing is similar to that of a first-order system to a sinusoidal input [11, 74], the time constant $\tau$ of the dynamic response can be estimated from the measured phase lags. Figure 4.5 presents the variation of normalized time constant $\tau U_\infty/c$ of vortex breakdown ($\tau_{bd}$) and normal force coefficient ($\tau_N$) over a nonslender delta wing at $\alpha=20^\circ$ and $25^\circ$. The estimated $\tau U_\infty/c$ for the breakdown location $X_{bd}$ is 5.6 and 4.6 for $\alpha=20^\circ$ and $25^\circ$, respectively, at $f^*=0.009$. These estimated time constants are somewhat larger than those reported in the literature ($\tau U_\infty/c = 1$ to 2) [11, 74, 88]. The normalized time constant $\tau U_\infty/c$ is estimated from $C_N$ in the range of 1.7 to 3.3, smaller than $\tau U_\infty/c$ of $X_{bd}$, suggesting a significant role played by the potential lift contribution.

Figure 4.6 and Figure 4.7 present the dependence of peak-to-peak amplitude $\Delta X_{bd}/c$ of phase-averaged breakdown location and $\Delta C_N$ of normal force coefficient on dimensionless frequency $f^*$. In both stall ($\alpha=20^\circ$) and post-stall ($\alpha=25^\circ$) regimes, $\Delta X_{bd}/c$ and $\Delta C_N$ exhibit similar trends. When the periodic trailing-edge blowing is applied, $\Delta X_{bd}/c$ and $\Delta C_N$ tend to decrease. This observation is similar to previous
investigations of unsteady wings [11, 67-69, 74].

Figure 4.8 and Figure 4.9 show the variations of mean value of breakdown location $X_{bd}/c$ and normal force coefficient $C_N$ as a function of dimensionless frequency $f^*$ of nonslender wing. It can be observed that there is no significant change in the mean value of vortex breakdown $X_{bd,mean}/c$ and normal force coefficient $C_{N,mean}$ at different $f^*$. The difference between static blowing ($f^*=0$) and continuous periodic blowing is quite small, indicating that $X_{bd,mean}/c$ and $C_{N,mean}$ are independent of the frequency of periodically varying $C\mu$.

### 4.3.1.2 Slender Wing

In order to investigate the effects of sweep angle on the dynamic response of wing flow to periodic trailing-edge blowing, food-colouring dye flow visualization and force measurements were also performed over a slender delta wing ($\Lambda=65^\circ$). Similar to the nonslender wing ($\Lambda=50^\circ$), the experiments were conducted at the stall (stall angle $\alpha\approx32^\circ$) and post-stall regimes.

Figure 4.10 presents the typical flow visualization images of the leading-edge vortices over the slender wing in the wing incidence of $\alpha=35^\circ$ at different $f^*$. For $f^*=0.009$, initially, at $t/T =0$ and $C\mu = 0$, the breakdown of the leading-edge vortices appears symmetric and occurs at $x/c \approx 0.15$. At $t/T = 0.5$ and $C\mu = 0.43$, it can be observed that the vortex breakdown of the jet (left) side was delayed to $x/c \approx 0.3$ while the vortex breakdown at the right-hand side occurs closer to the wing apex. This observation is also consistent with the steady case for the same configuration (see Chapter 3).

Figure 4.11 presents the phase-averaged variations of vortex breakdown location $X_{bd}/c$ over the slender wing ($\Lambda=65^\circ$) at $\alpha=35^\circ$ and $40^\circ$. Similar to the nonslender wing, the response of vortex breakdown location $X_{bd}/c$ of the slender wing to the periodically varying $C\mu$ also follows a periodic cosine wave with phase lag. When the frequency $f^*$ increases, the phase lag $\phi$ tends to increase, while the amplitude of $X_{bd}/c$ tends to decrease. Force measurements conducted near the stall
angle also show similar trends. Figure 4.12 presents the phase-averaged variations of normal force coefficient $C_N$ as a function of $f^*$ at $\alpha=30^\circ$. It can be observed that $C_N$ also exhibits periodic variation with phase lag.

Variations of phase lag $\phi$ of $X_{bd}/c$ and $C_N$ as a function of the dimensionless blowing frequency $f^*$ are shown in Figure 4.13. Similar to the variations of the nonslender wing, the phase lags $\phi$ of $X_{bd}/c$ and $C_N$ increase with increasing $f^*$, and the phase lag $\phi_N$ of $C_N$ is smaller than the phase lag $\phi_b$ of $X_{bd}/c$, suggesting that potential lift also contributes to the dynamic response of wing aerodynamics. The phase lag $\phi_b$ of $X_{bd}/c$ for the slender delta wing is comparable to those of the nonslender delta wing.

The dependence of peak-to-peak amplitude $\Delta X_{bd}/c$ of phase-averaged breakdown location and $\Delta C_N$ of normal force coefficient over the slender wing on the dimensionless blowing frequency $f^*$, are presented in Figure 4.14. $\Delta X_{bd}/c$ and $\Delta C_N$ tend to decline with increasing frequency $f^*$. This observation is similar for both slender and nonslender wings. However, at $\alpha=35^\circ$, $\Delta X_{bd}/c$ of $f^*=0.045$ and 0.09 are quite similar. Similar trend is also observed for $\Delta C_N$ at $\alpha=30^\circ$. Also, the phase lags $\phi_N$ of $C_N$ at $f^*=0.045$ and 0.09 for the same angle of attack are also similar, as shown in Figure 4.13. This observation indicates that the variations of phase lag and peak-to-peak amplitude with the increasing frequency $f^*$ are somehow reaching “saturation” near the stall angle.

The time constant $\tau$ of the dynamic response can be estimated from the measured phase lags of $X_{bd}$ and $C_N$ based on the same assumption as for the nonslender wing (Section 4.3.1.1). Figure 4.15 presents the variations of normalized time constant $\tau U_\infty/c$ as a function of dimensionless frequency $f^*$. The estimated $\tau U_\infty/c$ of $X_{bd}$ varied in the same range as the nonslender wing, 4.5 and 4.7, at $\alpha=35^\circ$ and $40^\circ$, respectively, which is also somewhat larger than those reported in literature ($\tau U_\infty/c = 1$ to 2) [11, 74, 88]. $\tau U_\infty/c$ estimated from $C_N$ is in the range of 0.5 to 1, smaller than $\tau U_\infty/c$ of $X_{bd}$. The mean values of vortex breakdown location $X_{bd}/c$ and normal force coefficient $C_N$ over the slender delta wing did not change much with increasing $f^*$, as shown in Figure 4.16.
In summary, the dynamic response of wing flows over the slender wing to periodically varying $C_\mu$ is generally similar to that of the nonslender wing.

### 4.3.2 Accelerating and Decelerating Jet Momentum Flux

#### 4.3.2.1 Nonslender Wing

Figure 4.17 presents the dynamic response of $X_{bd}/c$ to an accelerating jet momentum coefficient (Figure 4.17(a)) and also to a decelerating jet momentum coefficient (Figure 4.17(b)) for the nonslender delta wing at a post-stall incidence of $\alpha = 25^\circ$. The time histories of $C_\mu$ are also included in Figure 4.17. The transient $C_\mu$ followed half cosine/sine wave, i.e., from $t=0$ to $0.5T$, with the same corresponding dimensionless frequencies $f^*$ as periodic blowing configurations (Section 4.3.1), (i.e., $f^*=0.009, 0.045$ and $0.09$). For this angle of attack, steady-state locations of vortex breakdown are $X_{bd}/c = 0$ at $C_\mu = 0$ and $0.16$ at $C_\mu = 0.43$. Figure 4.17(a) indicates that, as $C_\mu$ was increased from 0 to 0.43 as a half cosine wave, $X_{bd}/c$ gradually increased to its steady value with a time delay. This observation is similar to the response of vortex breakdown over transient pitch-up and pitch-down motions of delta wings [89]. It is seen in Figure 4.17(a) that the time delay (normalized with the period) increases with increasing frequency.

Similar trends were also found for the decelerating blowing cases (Figure 4.17(b)). However, time delays are significantly larger than those of the accelerating case (note that the scales of the horizontal axis are different in parts (a) and (b)). Hence, the characteristic response times for accelerating and decelerating jets appear to be different. It is interesting that this is similar to the different flow structures reported at the same angle of attack during the pitch-up and pitch-down motions of a delta wing [90]. Also, different time constants for the upstream and downstream motion of the breakdowns were reported in response to an oscillating fin over a delta wing [91]. The effects of accelerating and decelerating trailing-edge blowing on wing flow characteristics were also studied for an angle of attack at the stall incidence of $\alpha$.
Chapter 4

Unsteady Trailing-Edge Jet

= 20°. At α = 20°, the dynamic response of X_{bd}/c to transiently varying jet momentum coefficient C_{μ} is similar to that of α = 25°, as shown in Figure 4.18.

The normal force coefficient C_{N} exhibits similar trends to X_{bd}/c. The dynamic responses of C_{N} to an accelerating jet for the nonslender delta wing at the angle of attack in the post-stall (α = 25°) and near the stall (α = 20°) are shown in Figure 4.19 and Figure 4.20, respectively. Similar to the variation of X_{bd}/c (Figure 4.17 and 4.18), C_{N} also gradually increased to its final steady value with a time delay for the accelerating jet. For the decelerating jet, the time delays are larger than those of the accelerating case.

PIV measurements were conducted to further investigate the effects of accelerating and decelerating jet momentum flux on vortical flow characteristics over the nonslender delta wing. Figure 4.21 presents the phase-averaged vorticity field in a cross-flow plane at x/c= 0.3 and α = 25° with an accelerating momentum coefficient of f^{*} = 0.09. Initially (t=0, C_{μ}=0), the flow pattern was symmetric and the separated shear layers were in contact with each other near the wing centerline. In this stalled flow, the shear layers were symmetrically placed and had low vorticity values. The corresponding velocity vectors and streamline pattern in the cross-flow plane (see Figure 4.22 and 4.23) confirmed that there is no reattachment on both sides of the wing. At t = 0.25T, the vorticity on the jet (left) side became stronger and the shear layer started moving outboard (see Figure 4.21), due to the jet entrainment effect. When C_{μ} reached the maximum value of 0.43 at t=0.5T, the shear layer on the jet side started to form a vortical structure (Figure 4.21) and the high velocity region becomes closer to the wing surface (Figure 4.22 and 4.23). At t = 1T and thereafter, the phase-averaged flow patterns did not change much. Maximum value of the magnitude of normalized vorticity \( \omega_{c}/U_{∞} \) is larger on the jet side, and corresponding vortical flow is more axisymmetric.

Similarly, the crossflow PIV measurements for the decelerating trailing-edge blowing are shown in Figures 4.24, 4.25 and 4.26. Initially (t=0, C_{μ}=0.43), the more axisymmetric vortical structure is seen at the jet side, with larger values of vorticity.
As $C_{\mu}$ decreased to 0 at $t = 0.5T$, the flow pattern remained similar to that at $t = 0$, but with slightly reduced magnitude of $\omega_c/U_\infty$. At $t = 1T$ and later, the magnitude of $\omega_c/U_\infty$ at the jet side was reduced considerably, and strong leading-edge vortical structure disappeared, suggesting that the flow eventually stalls. The corresponding velocity vectors and streamline pattern in Figure 4.25 and Figure 4.26 confirmed the same observations, and also revealed the inboard movement of the vortical structure. Further quantitative information, such as the circulation, was also obtained from these measurements as discussed below.

Figure 4.27 presents the variations of circulation $\Gamma/U_\infty c$ as a function of $t/T$ for $f^* = 0.09$. The circulation was calculated as the line integral of velocity around a rectangle that encloses the vortex on the jet (left) side. It can be observed that the trends of $\Gamma/U_\infty c$ resemble those of $C_N$ (see Figures 4.19 and 4.20). For the accelerating jet, the normalized circulation $\Gamma/U_\infty c$ reached the steady-state value at around $t/T=1.5$. However, the normalized circulation did not appear to reach the steady-state value even at $t/T=4$ for the decelerating jet. The effects of acceleration and deceleration of the jet momentum coefficient are all similar for the variations of breakdown location (Figure 4.17), normal force coefficient (Figure 4.19), and the circulation (Figure 4.27).

Time constant was estimated from these data by assuming that the response is similar to that of a first-order system to a step function input [11, 74]. The time required for the variable to reach 95% of the steady-state value was estimated as $3\tau$, where $\tau$ is the time constant of the first order system. Figure 4.28 presents the normalized time constant $\tau/T$ obtained from $X_{bd}$, $C_N$ and $\Gamma/U_\infty c$ as a function of $f^*$. It is seen that, for both accelerating and decelerating jet blowing cases, the time constant normalized by the period $\tau/T$ increases with $f^*$, and the time constant is several times larger for the decelerating jet case. The time constant of $C_N$ is smaller than that of $X_{bd}/c$, suggesting that vortex lift as well as potential lift contributions is important. The time constant of circulation is close to that of breakdown.

The corresponding variation of the time constant normalized by the
convective time unit, $\tau U_\infty / c$, is presented in Figure 4.29. Note that the estimates for the highest frequency parameter are the most reliable because of the assumption of the step function input in the calculations. The estimated $\tau U_\infty / c$ for the decelerating case varied in the range of 6 to 9, whereas it is around 2 to 3 for the accelerating case.

In order to investigate the effects of accelerating and decelerating trailing-edge blowing on wing flow characteristics near the stall, PIV measurements were also conducted at $\alpha = 20^\circ$. Figure 4.30 presents the phase-averaged vorticity field in a cross-flow plane at $x/c = 0.3$ and $\alpha = 20^\circ$ with an accelerating $C_\mu$ at $f^* = 0.09$. Initially (t=0, $C_\mu$=0), two vortical structures were fairly symmetrically placed about the wing centerline, with low vorticity values. The corresponding velocity vectors and streamline pattern in the crossflow plane (see Figures 4.31 and 4.32) showed that reattachment occurred on both sides of the wing. At t=0.25T, the vorticity on the jet (left) side became stronger and the reattachment location started moving outboard (see Figures 4.31 and 4.32), suggesting the occurrence of earlier reattachment. At t=0.5T ($C_\mu$=0.43), the vortical structure on the jet (left) side became smaller and closer to the wing surface, suggesting the delay of vortex breakdown. After t=1T, the phase-averaged flow patterns did not change much. These observations showed similar trends of flow patterns in the post-stall regime ($\alpha = 25^\circ$).

The crossflow PIV measurements for the decelerating jet at the same angle of attack are shown in Figures 4.33, 4.34 and 4.35. Initially (t=0, $C_\mu$=0.43), the vortical structure on the jet side has smaller size and larger values of vorticity. As $C_\mu$ decreased to 0 at t = 0.5T, the flow patterns did not change much. At t = 1T and later, the magnitude of $\omega x c / U_\infty$ on the jet side was reduced considerably. Moreover, the corresponding velocity vectors and streamline pattern in Figures 4.34 and 4.35 reveal that the reattachment location starts moving towards the wing centerline, suggesting the earlier occurrence of vortex breakdown. Further quantitative information, such as the circulation, was also obtained from these measurements as discussed later.
PIV measurements were also performed near the wing surface. Figures 4.36 show the phase-averaged streamline patterns near the wing surface at $\alpha = 20^\circ$. For the accelerating jet case of $f^* = 0.09$, at $t = 0$ ($C_\mu = 0$), the flow pattern is fairly symmetric about the wing centerline with closed spiraling streamline patterns (nodes) on both sides near the wing apex. Note that the leading-edge vortex breakdown occurred near the wing apex at $\alpha = 20^\circ$, which is the stall angle of the $\Lambda = 50^\circ$ wing (see Chapter 3). The corresponding time-averaged velocity field (Figure 4.37) is also fairly symmetric about the wing centerline with low magnitude of $u/U_\infty$. As $C_\mu$ increased to 0.43 at $t = 0.5T$, the reattachment occurs earlier on the jet (left) side and the closed spiraling streamline pattern near the wing apex persists only at the right side with a much smaller scale than that at $t = 0$. Also, the magnitude of $u/U_\infty$ becomes larger, the maximum $u/U_\infty$ region appears to shift away from the wing centerline towards the jet (left) side (see Figure 4.37). After $t=1T$, two separate reattachments occur on the wing surface, and the reattachment on the jet side is more outboard. As a result, the flow field appears asymmetric about the wing centerline. It is seen in Figure 4.36 that the flow pattern for $C_\mu = 0$ exhibits a single reattachment near the wing symmetry plane, whereas two separate reattachment lines can be identified with jet blowing.

The case of decelerating trailing-edge blowing is shown in Figure 4.38. At $t=0$ ($C_\mu = 0.43$), the flow pattern appears similar to that of steady trailing-edge blowing (see Chapter 3), i.e., two separate asymmetric reattachment lines. The flow field appears asymmetric about the wing centerline, with higher velocity magnitude (Figure 4.39). As the jet momentum decreases for $t = 0.5T$ and $1T$, the reattachment lines moves towards the wing centerline and the flow becomes more symmetric. After $t=2T$, the flow becomes fairly symmetric and the closed spiraling streamline patterns recovered on both sides near the wing apex.

The variations of circulation $\Gamma/U_\infty c$ as a function of $t/T$ for $f^* = 0.09$ and at $\alpha = 20^\circ$, is presented in Figure 4.40. It can be observed that $\Gamma/U_\infty c$ reached its final steady state value with time delay, and the time delay for the decelerating jet is significantly larger than that for the accelerating jet. These observations are similar
to those obtained at $\alpha = 25^\circ$ (see in Figure 4.27).

Figure 4.41 presents the normalized time constant $\tau/T$ obtained from $X_{bd}/c$, $C_N$ and $\Gamma/U_\infty c$ as a function of $f^*$ at $\alpha = 20^\circ$. It can be seen that, for both accelerating and decelerating jet blowing cases, the time constant normalized by the period $\tau/T$ increases with $f^*$, and the time constant is several times larger for the decelerating jet case. This is consistent with the observations for vortex breakdown (Figure 4.18), normal force (Figure 4.20) and circulation (Figure 4.40). The time constants of $C_N$ are also smaller than that of $X_{bd}/c$, which is similar to those of $\alpha = 25^\circ$. The corresponding variation of the time constant normalized by the convective time unit, $\tau U_\infty /c$, is presented in Figure 4.42. At $f^*=0.09$, the estimated $\tau U_\infty /c$ for the decelerating case varied in the range of 6 to 9, whereas it is around 1 to 3 for the accelerating case. The range of estimated time constant for accelerating and decelerating jets is similar to those of the post-stall angle of attack.

### 4.3.2.2 Slender Wing

Sweep angle is an important parameter, which possibly has influence on the dynamic response of wing flow to accelerating and decelerating trailing-edge blowing. Hence, experiments were also carried out on the slender wing ($\Lambda=65^\circ$) at the incidence near the stall and post-stall regions. Figure 4.43 presents the dynamic response of $X_{bd}/c$ to an accelerating $C_\mu$ (Figure 4.43(a)) and decelerating $C_\mu$ (Figure 4.43(b)) for the slender delta wing at a near stall incidence of $\alpha = 35^\circ$. For this angle of attack, steady-state locations of vortex breakdown are $X_{bd}/c = 0.13$ at $C_\mu = 0$ and 0.3 at $C_\mu = 0.43$. It can be seen that the trend of dynamic response of $X_{bd}/c$ to transient varying $C_\mu$ is similar to those of the nonslender wing. $X_{bd}/c$ gradually increased or decreased to its steady-state value with a time delay which increases with increasing frequency. Time delays of the decelerating case are significantly larger than those of the accelerating cases. Similar observations were also made for the post-stall incidence of $\alpha = 40^\circ$, as shown in Figure 4.44.

The normal force coefficient $C_N$ exhibits similar trends to $X_{bd}/c$. The dynamic
responses of $C_N$ to accelerating and decelerating jet for the slender delta wing at $\alpha = 30^\circ$ is shown in Figure 4.45. Similar to the variation of $X_{bd}/c$ (Figures 4.43 and 4.44), $C_N$ also gradually increased to its final steady value with a time delay for the accelerating jet. For the decelerating jet, the time delays are larger than those of the accelerating cases.

PIV measurements in a cross-flow plane at $x/c=0.8$ confirmed the above observations. Figure 4.46 presents the phase-averaged vorticity field in a cross-flow plane at $x/c=0.8$ and $\alpha = 35^\circ$ with an accelerating $C_\mu$ of $f^* = 0.09$. Initially ($t=0$, $C_\mu=0$), the flow pattern was symmetrically placed and had low vorticity values. When $C_\mu$ reached the maximum value of 0.43 at $t=0.5T$, the vorticity on the jet (left) side became stronger and the shear layer started moving outboard, suggesting a delay of vortex breakdown. Also, the size of vortical structure on the jet side became smaller. The corresponding velocity vectors and streamline pattern in the cross-flow plane (see Figures 4.47 and 4.48) indicate that the vortex core moved slightly closer to the wing surface. At $t = 1T$ and later, the phase-averaged flow patterns did not change much. Maximum value of the magnitude of normalized vorticity $\omega_x c / U_\infty$ is larger on the jet side.

The crossflow PIV measurements for the decelerating trailing-edge blowing are shown in Figures 4.49, 4.50 and 4.51. Initially ($t=0$, $C_\mu=0.43$), the strong vortical structure was seen on the jet side, with larger values of vorticity. As $C_\mu$ decreased to 0 at $t = 0.5T$, the flow pattern remained similar to that of $t = 0$, but with slightly reduced vorticity. At $t = 1T$ and later, the magnitude of $\omega_x c / U_\infty$ on the jet side was reduced considerably, and the shear layer started moving towards the wing centerline, suggesting earlier vortex breakdown. The corresponding velocity vectors and streamline pattern in Figures 4.50 and 4.51 confirm the observations, and also reveal the inboard movement of the vortex.

The circulation from PIV measurements is presented in Figure 4.52. It can be observed that the trends of $\Gamma/U_\infty c$ resemble those of the nonslender wing (see Figures 4.27 and 4.40). The $\Gamma/U_\infty c$ reached its final steady-state value with time
delay, and time delay for the decelerating jet is significantly larger than that for the accelerating jet.

The variations of breakdown location $X_{bd}/c$ and circulation $\Gamma/U_\infty c$ with time are qualitatively similar to the nonslender delta wing case. Figure 4.53 presents the normalized time constant $\tau/T$ obtained from $X_{bd}$ and $\Gamma/U_\infty c$ as a function of $f^*$ at $\alpha=35^\circ$. It can be seen that, for both accelerating and decelerating jet blowing cases, the time constant normalized by the period $\tau/T$ increases with $f^*$, and the time constant is larger for the decelerating jet case. The time constants of $\Gamma/U_\infty c$ are larger than that of $X_{bd}/c$. The corresponding variation of the time constant normalized by the convective time unit, $\tau U_\infty /c$, is presented in Figure 4.54. It can be observed that, similar to the nonslender wing, $\tau U_\infty /c$ of accelerating blowing configurations are smaller than $\tau U_\infty /c$ of decelerating blowing configurations. Furthermore, the magnitudes of $\tau U_\infty /c$ are comparable with those of nonslender ($\Lambda=50^\circ$) wing cases. Similar results were also obtained at the post-stall angle of attack $\alpha=40^\circ$ (Figures 4.55 and 4.56).

### 4.3.3 Transient Trailing-Edge Blowing

Transient trailing-edge blowing was also tested. For this case, the jet momentum coefficient $C_\mu$ follows the same cosine wave as the periodic case, $C_\mu = 0.215 + 0.215 \cos(2\pi f^* t + \pi)$, but operates in only one transient period. Figure 4.57 presents phase-averaged variations of $X_{bd}/c$ for the nonslender wing ($\Lambda=50^\circ$) with a transient trailing-edge blowing at $\alpha=20^\circ$ (Figure 4.57(a)) and $\alpha=25^\circ$ (Figure 4.57(b)). The dynamic response of $X_{bd}/c$ to transient trailing-edge blowing exhibits a “quasi-cosine” wave with phase lag. The phase lag $\phi$ of $X_{bd}/c$ increases with increasing $f^*$, while the peak amplitude of $X_{bd}$ tends to decrease with increasing $f^*$.

This is similar to the dynamic response of $X_{bd}/c$ to periodic blowing. On the other hand, at $f^*=0.09$ and $\alpha=20^\circ$ (Figure 4.57(a)), as $C_\mu$ increases from 0 to 0.43 (similar to accelerating blowing), $X_{bd}/c$ reaches the peak value at $t/T=1.3$. However, as $C_\mu$
decreases from 0.43 to 0 (similar to decelerating blowing), \( X_{bd}/c \) goes back to the original value at \( t/T=2.8 \), suggesting a significantly larger time delay than in the accelerating case. These observations are similar to those of accelerating and decelerating jet momentum flux.

The dependence of phase lag \( \phi \) of phase-averaged \( X_{bd}/c \) on the dimensionless frequency \( f^* \) is presented in Figure 4.58. It can be observed that the phase lag \( \phi \) increased with \( f^* \). This observation is similar to previous investigations of unsteady wings [11, 67-69, 74], and periodic trailing-edge blowing (see section 4.3.1). Note that here phase lag \( \phi \) is measured from \( t=0 \) to time of \( X_{bd}/c \) reaching the peak value. The phase lags \( \phi_b \) of transient trailing-edge blowing are larger than those of periodic trailing-edge blowing. The dependence of peak amplitude of phase-averaged \( X_{bd}/c \) on the dimensionless frequency \( f^* \) is presented in Figure 4.59. It can be seen that \( \Delta X_{bd}/c \) decreases with increasing \( f^* \), which is similar to the periodic case.

Transient trailing-edge blowing experiments were also conducted over the slender wing (\( \Lambda=65^\circ \)). Figure 4.60 presents phase-averaged variations of \( X_{bd}/c \) for the slender wing with a transient trailing-edge blowing at \( \alpha=35^\circ \) (Figure 4.60(a)) and \( \alpha=40^\circ \) (Figure 4.60(b)). The response of \( X_{bd}/c \) is similar to that of the nonslender wing. As \( f^* \) is increases, the phase lag \( \phi \) of \( X_{bd}/c \) increases, while the peak amplitude of \( X_{bd} \) tends to decrease. The dependence of phase lag \( \phi \) and peak amplitude of \( X_{bd}/c \) on dimensionless frequency \( f^* \) are shown in Figures 4.61 and 4.62.

For both slender and nonslender delta wings, the dynamic responses of wing flows to transient trailing-edge blowing are similar to those of periodic and accelerating & decelerating blowing.

### 4.3.4 Periodic Pitching Trailing-Edge Jet

#### 4.3.4.1 Slender Wing

The jet pitch angle \( \beta \) of a periodically pitching trailing-edge jet follows a cosine wave, \( \beta = 20 + 20\cos(2\pi f t + \pi) \), with a peak-to-peak amplitude of 40°, a
Chapter 4  Unsteady Trailing-Edge Jet

time-averaged value of 20°, and f is the oscillatory frequency of β. For all experiments, the jet spanwise location was kept constant at $y_{jet}/(b/2)=-0.6$, and the jet momentum coefficient $C_μ=0.43$. Figure 4.63 presents the typical flow visualization images of leading-edge vortices over a slender delta wing ($Λ=65°$) at $α=20°$ and $f^*=$ 0.009, 0.045, 0.09, respectively. For $f^*=0.009$, at $t/T = 0$ and $β = 0°$, the vortex breakdown of the jet (left) side occurs at $x/c ≈ 0.76$, while at $t/T = 0.5$ and $β = 40°$, the vortex breakdown occurs at $x/c ≈ 0.82$. This observation is consistent with the steady trailing-edge blowing for the same configuration (see Chapter 3).

The phase-averaged variations of vortex breakdown location $X_{bd}/c$ over the slender wing ($Λ=65°$) at $α=20°$ are presented in Figure 4.64. For each $f^*$ tested, the dynamic response of $X_{bd}/c$ to the periodically varying $β$ exhibits a periodic manner with phase lag. The phase lag tends to increase with increasing $f^*$, while the amplitude of $X_{bd}/c$ tends to be decreasing with increasing $f^*$. Force measurements over the same slender wing show similar trends. Figure 4.65 presents the variation of the phase-averaged $C_N$ for the slender wing ($Λ=65°$) at $α=10°$, 20°, 30° and 40°, respectively. For all angles of attack tested, similar to $X_{bd}/c$, the normal force coefficient $C_N$ also follows a periodic cosine wave, with increasing phase lag and decreasing amplitude as $f^*$ is increased. The variation of $C_N$ forms a hysteresis loop when plotted as a function of $β$, which confirms the existence of phase lag. The hysteresis loops of $C_N$ at different angles of attack are shown in Figure 4.66. In Figure 4.66, the dash lines and blank symbols show the variation of $C_N$ with a statically pitched jet as a function of $β$; the loop with solid lines shows the variation of $C_N$ versus $β$ of a periodically pitching jet. For each $α$ tested, the hysteresis loop tends to rotate in the clockwise direction when $f^*$ is increased, suggesting the phase lag increases with increasing $f^*$.

With periodically varying $β$, the phase lags $ϕ$ of $X_{bd}/c$ and $C_N$ strongly depend on the pitching frequency $f^*$. Figure 4.67 presents the variations of phase lag $ϕ$ of $X_{bd}/c$ and $C_N$ as a function of $f^*$. It can be observed that $X_{bd}/c$ and $C_N$ exhibit similar trends of increasing $ϕ$ with $f^*$. This observation is similar to previous observations of unsteady wings [11, 67-69, 74], and periodic trailing-edge blowing cases (see
The phase lag $\phi_N$ of $C_N$ is smaller than the phase lag $\phi_b$ of $X_{bd}/c$, which is similar to the observations of periodic blowing jet (see Chapter 4.3.1). This observation suggests that the development of vortex breakdown due to periodically pitching jets also lags behind wing aerodynamic forces, providing evidence that potential lift also contributes to the dynamic response of wing aerodynamics.

Similarly, time constant $\tau$ of the periodic variation of $C_N$ can be estimated from the measured phase lag, assuming that the dynamic response of $C_N$ to periodically pitching jet is similar to that of a first-order system to a sinusoidal input [11, 74]. Figure 4.68 presents the normalized time constant $\tau U_\infty/c$ estimated from $C_N$ for the slender wing ($\Lambda=65^\circ$). The estimated time constant $\tau U_\infty/c$ of $C_N$ varied in the range of 0.5 to 1.5, which is comparable to those of periodic trailing-edge blowing (see Figure 4.15).

Figures 4.69 and 4.70 show the dependence of the peak-to-peak amplitude of phase-averaged breakdown location $\Delta X_{bd}/c$ and normal force coefficient $\Delta C_N$ on dimensionless frequency $f^*$. It can be observed that $\Delta X_{bd}/c$ and $\Delta C_N$ exhibit similar trends of decreasing with increasing $f^*$. This observation is similar to previous investigations for unsteady wings [11, 67-69, 74], and periodic trailing-edge blowing (see Chapter 4.3.1).

Figure 4.71 shows the variations of mean values of normal force coefficient $C_{N,\text{mean}}$ as a function of dimensionless frequency $f^*$ over the slender wing. It can be observed that $C_{N,\text{mean}}$ remains constant in the whole frequency range, similar to that of static blowing ($f^*=0$) configurations. This observation indicates that the mean value of periodic $C_N$ is independent of the frequency $f^*$ of periodically varying $\beta$, suggesting that a dynamically pitching jet at the trailing-edge has a small influence on the time-averaged wing aerodynamics.

### 4.3.4.2 Nonslender Wing

In order to investigate the effect of sweep angle on the dynamic response of wing aerodynamics to periodically pitching thrust vectoring, force measurements were performed over a nonslender wing ($\Lambda=50^\circ$) at $\alpha=10^\circ$, $15^\circ$, $20^\circ$, and $25^\circ$,
respectively. The phase-averaged variations of normal force coefficient $C_N$ are presented in Figure 4.72. Similar to the slender wing, the response of $C_N$ to the periodically varying $\beta$ exhibits a periodic cosine wave variation with increasing phase lag and decreasing amplitude as $f^*$ is increased. The hysteresis loop of $C_N$ (Figure 4.73) tends to rotate in the clockwise direction as $f^*$ is increased, suggesting an increasing phase lag with increasing $f^*$. Figure 4.74 presents the dependence of the phase lag of $C_N$ on the dimensionless frequency $f^*$. It can be observed that $\phi_N$ of $C_N$ increases with increasing frequency for all the values of $\alpha$ being tested. The phase lags of nonslender wing are comparable to those of slender wing. The variations of normalized time constant $\tau_{U_{\infty}}/c$ are qualitatively similar to the slender delta wing case (see Figure 4.75). At all angles of attack, the peak-to-peak amplitude $\Delta C_N$ decreases with the increasing $f^*$ (see Figure 4.76). For nonslender wing, $f^*$ has limited effect on the mean value $C_{N,\text{mean}}$, as shown in Figure 4.77. In summary, the dynamic response of wing aerodynamics over a nonslender wing to periodically varying $\beta$ is similar to that of a slender wing in every aspect.

### 4.4 Conclusions

Flow visualization, particle image velocimetry and force measurements were conducted to investigate the effects of unsteady trailing-edge thrust vectoring on delta wing aerodynamics. Periodic and transient variations of the jet momentum coefficient were considered. Experiments were carried out on both slender ($\Lambda = 65^\circ$) and nonslender ($\Lambda = 50^\circ$) stationary delta wings at stall and post-stall incidences. The following conclusions can be drawn:

a) For the periodic trailing-edge blowing, the dynamic response of leading-edge vortex breakdown location $X_{bd}$ and normal force coefficient $C_N$ exhibit similar periodic trends with phase lags. The phase lag $\phi$ increases with increasing frequency $f^*$ of the periodic variations of the momentum
coefficient. For the variation of vortex breakdown, the estimated time constant is larger than those reported in the literature for unsteady wings undergoing pitching or plunging. The phase lag of the normal force is smaller than that of the vortex breakdown, indicating that both the potential lift and vortex lift play a role in the dynamic response.

b) For the accelerating and decelerating jet momentum flux, both the breakdown location and normal force reached their steady-state values with a time delay for the nonslender delta wing at a post-stall incidence. This is similar to the response of vortex breakdown for transient pitch-up or pitch-down motions of delta wings. Time delay for the decelerating jet is significantly larger than that for the accelerating jet. Phase-averaged PIV measurements confirmed that the leading-edge vortex was gradually re-formed from the stalled flow under the effect of accelerating trailing-edge blowing, or vice versa for decelerating trailing-edge blowing. Variation of the calculated circulation and estimated time constant reveal similar results to those of vortex breakdown and normal force. The normalized time constant $\tau U_\infty / c$ for the decelerating case varied in the range of 6 to 9, whereas it is around 2 to 3 for the accelerating case.

c) Similar results were obtained at the stall angle of attack. Near-surface streamline patterns revealed how the reattachment of the shear layers varied in response to accelerating and decelerating blowing. The range of estimated time constant for accelerating and decelerating jets is similar to those of the post-stall angle of attack.

d) The effects of accelerating and decelerating trailing-edge blowing on the slender ($\Lambda = 65^\circ$) delta wing are similar to those of the nonslender ($\Lambda = 50^\circ$) wing. Flow visualization and PIV measurements indicate similar magnitudes of $\tau U_\infty / c$ to the nonslender wing case.
e) For both slender and nonslender delta wings, the dynamic responses of wing flows to transient trailing-edge blowing are similar to those of periodic and accelerating and decelerating jet momentum flux.

f) For periodically pitching trailing-edge jet, the dynamic response of leading-edge vortex breakdown location $X_{bd}$ and normal force coefficient $C_N$ exhibit similar periodic trends with phase lags for both nonslender and slender wings. The phase lag $\phi$ increases with increasing frequency $f^*$ of the periodic variations of jet pitch angle $\beta$. The estimated time constants $\tau_{U_\infty/c}$ of $C_N$ are comparable to those of previous results. The peak-to-peak amplitude of the phase-averaged breakdown location $\Delta X_{bd}/c$ and normal force coefficient $\Delta C_N$ strongly depend on $f^*$, with a trend of decreasing with increasing $f^*$. The mean value $C_{N,\text{mean}}$ of periodic $C_N$ is however independent of frequency.
Figure 4.1: Food-colouring dye flow visualization over nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing at different $f^*$, $\alpha=20^\circ$. 
Figure 4.2: Phase-averaged vortex breakdown location as a function of normalized time $t/T$ over nonslender delta wing ($\Lambda=50^\circ$), (a) $\alpha=20^\circ$, (b) $\alpha=25^\circ$. 
Figure 4.3: Phase-averaged normal force coefficient as a function of normalized time $t/T$ over nonslender delta wing ($\Lambda=50^\circ$), (a) $\alpha=20^\circ$, (b) $\alpha=25^\circ$. 
Figure 4.4: Variation of phase lags of the dynamic response of normal force ($\phi_N$) and vortex breakdown ($\phi_b$) as a function of dimensionless blowing frequency over nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing.

Figure 4.5: Variation of normalized time constant $\tau U_\infty / c$ of vortex breakdown ($\tau_b$) and normal force coefficient ($\tau_N$) over nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing, at $\alpha = 20^\circ$ and $25^\circ$. 
Figure 4.6: Variation of peak-to-peak amplitude of vortex breakdown location $\Delta X_{bd}$ as a function of dimensionless frequency $f^*$ of nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing, at $\alpha = 20^\circ$ and $25^\circ$.

Figure 4.7: Variation of peak-to-peak amplitude of normal force coefficient $\Delta C_N$ as a function of dimensionless frequency $f^*$ over nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing, at $\alpha = 20^\circ$ and $25^\circ$. 
Figure 4.8: Variation of mean value of vortex breakdown location $X_{bd,\text{mean}}/c$ as a function of dimensionless frequency $f^*$ over nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing, at $\alpha = 20^\circ$ and $25^\circ$.

Figure 4.9: Variation of mean value of normal force coefficient $C_{N,\text{mean}}$ as a function of dimensionless frequency $f^*$ of nonslender delta wing ($\Lambda=50^\circ$) with periodic trailing-edge blowing, at $\alpha = 20^\circ$ and $25^\circ$. 
Figure 4.10: Food-colouring dye flow visualization over slender delta wing ($\Lambda=65^\circ$) with periodic trailing-edge blowing at different $f^*$, $\alpha=35^\circ$. 
Figure 4.11: Phase-averaged vortex breakdown location as a function of normalized time $t/T$ over slender delta wing ($\Lambda=65^\circ$), (a) $\alpha=35^\circ$, (b) $\alpha=40^\circ$. 
Figure 4.12: Phase-averaged normal force coefficient $C_N$ as a function of normalized time $t/T$ over slender delta wing ($\Lambda=65^\circ$) at $\alpha=30^\circ$.

Figure 4.13: Variation of phase lags of the dynamic response of normal force ($\phi_N$) and vortex breakdown ($\phi_b$) as a function of dimensionless blowing frequency $f^*$ for slender delta wing ($\Lambda=65^\circ$) with periodic trailing-edge blowing.
Chapter 4  Unsteady Trailing-Edge Jet

Figure 4.14: Variation of peak-to-peak amplitude of vortex breakdown location $\Delta X_{bd}/c$ and normal force coefficient $\Delta C_N$ as a function of dimensionless frequency over slender delta wing ($\Lambda=65^\circ$) with periodic trailing-edge blowing.

Figure 4.15: Variation of normalized time constant $\tau U_\infty/c$ of vortex breakdown ($\tau_b$) and normal force coefficient ($\tau_N$) over slender delta wing ($\Lambda=65^\circ$) with periodic trailing-edge blowing.
Figure 4.16: Variation of mean value of phase-averaged vortex breakdown location $X_{bd}/c$ and normal force coefficient $C_N$ as a function of dimensionless frequency over slender delta wing ($\Lambda=65^\circ$) with periodic trailing-edge blowing.
Figure 4.17: Dynamic response of vortex breakdown over nonslender delta wing ($\Lambda=50^\circ$) at $\alpha=25^\circ$, for (a) accelerating $C_\mu$; (b) decelerating $C_\mu$. 

129
Figure 4.18: Dynamic response of vortex breakdown of nonslender delta wing $(\Lambda=50^\circ)$ at $\alpha=20^\circ$, for (a) accelerating $C_\mu$; (b) decelerating $C_\mu$. 
Figure 4.19: Dynamic response of normal force coefficient of nonslender delta wing ($\Lambda=50°$) at $\alpha=25°$, for (a) accelerating $C_\mu$; (b) decelerating $C_\mu$.  

(a) 

(b)
Figure 4.20: Dynamic response of normal force coefficient of nonslender delta wing ($\Lambda=50^\circ$) at $\alpha=20^\circ$, for (a) accelerating $C_\mu$; (b) decelerating $C_\mu$. 

(a) 

(b)
Figure 4.21: Phase-averaged vorticity in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.22: Phase-averaged velocity vectors in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.23: Phase-averaged streamline pattern in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.24: Phase-averaged vorticity in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $a=25^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.25: Phase-averaged velocity vectors in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.26: Phase-averaged streamline pattern in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=25^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Chapter 4  Unsteady Trailing-Edge Jet

Figure 4.27: Variation of normalized circulation of vortical flow in a cross-flow plane at x/c=0.3 over nonslender delta wing for accelerating and decelerating jet momentum coefficient, f* = 0.09, α=25°, Λ=50°.

Figure 4.28: Variation of normalized time constants τ/T of vortex breakdown, normal force coefficient and circulation over nonslender delta wing for accelerating and decelerating jet momentum coefficient, α=25°, Λ=50°.
Figure 4.29: Variation of normalized time constant $\tau U_\infty/c$ of vortex breakdown, normal force coefficient and circulation over nonslender delta wing for accelerating and decelerating jet momentum coefficient, $\alpha=25^\circ$, $\Lambda=50^\circ$. 
Figure 4.30: Phase-averaged vorticity in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.31: Phase-averaged velocity vectors in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.32: Phase-averaged streamline pattern in a cross-flow plane over nonslender delta wing for accelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.33: Phase-averaged vorticity in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.34: Phase-averaged velocity vectors in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.35: Phase-averaged streamline pattern in a cross-flow plane over nonslender delta wing for decelerating momentum coefficient, $\alpha=20^\circ$, $x/c=0.3$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.36: Near-surface streamline pattern for the nonslender ($\Lambda = 50^\circ$) wing for accelerating momentum coefficient, $\alpha=20^\circ$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.37: Magnitude of time averaged velocity near the wing surface for the nonslender (Λ = 50°) wing for accelerating momentum coefficient, α=20°, f* = 0.09. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.38: Near-surface streamline pattern for the nonslender ($\Lambda = 50^\circ$) wing for decelerating momentum coefficient, $\alpha=20^\circ$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.39: Magnitude of time averaged velocity near the wing surface for the nonslender ($\Lambda = 50^\circ$) wing for decelerating momentum coefficient, $\alpha = 20^\circ$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.40: Variation of normalized circulation of vortical flow in a cross-flow plane at \(x/c=0.3\) over nonslender delta wing for accelerating and decelerating momentum coefficient, \(f^*=0.09\), \(\alpha=20^\circ\), \(\Lambda=50^\circ\).

Figure 4.41: Variation of normalized time constants \(\tau/T\) of vortex breakdown, normal force coefficient and circulation over nonslender delta wing for accelerating and decelerating momentum coefficient, \(\alpha=20^\circ\), \(\Lambda=50^\circ\).
Figure 4.42: Variation of normalized time constant $\tau U_\infty / c$ of vortex breakdown, normal force coefficient and circulation over nonslender delta wing for accelerating and decelerating momentum coefficient, $\alpha=20^\circ$, $\Lambda=50^\circ$. 
Figure 4.43: Dynamic response of vortex breakdown over slender delta wing, \( \Lambda=65^\circ, \alpha=35^\circ \), for (a) accelerating \( C_\mu \); (b) decelerating \( C_\mu \).
Figure 4.44: Dynamic response of vortex breakdown over slender delta wing, \( \Lambda=65^\circ \), \( \alpha=40^\circ \), for (a) accelerating \( C_\mu \); (b) decelerating \( C_\mu \).
Figure 4.45: Dynamic response of normal force coefficient over slender delta wing, \( \Lambda=65^\circ, \alpha=30^\circ \), for (a) accelerating \( C_\mu \); (b) decelerating \( C_\mu \).
Figure 4.46: Phase-averaged vorticity in a cross-flow plane over slender delta wing for accelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.47: Phase-averaged velocity vectors in a cross-flow plane over slender delta wing for accelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.48: Phase-averaged streamline pattern in a cross-flow plane over slender delta wing for accelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^*=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.49: Phase-averaged vorticity in a cross-flow plane over slender delta wing for decelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.50: Phase-averaged velocity vectors in a cross-flow plane over slender delta wing for decelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $f^* = 0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.51: Phase-averaged streamline pattern in a cross-flow plane over slender delta wing for decelerating momentum coefficient, $\alpha=35^\circ$, $x/c=0.8$, $\text{Re}=0.09$. The inset shows the variation of the momentum coefficient with symbols showing the instants of PIV measurements.
Figure 4.52: Variation of normalized circulation of vortical flow in a cross-flow plane at x/c=0.8 over slender delta wing for accelerating and decelerating jet momentum coefficient, f* = 0.09, α=35°, Λ=65°.

Figure 4.53: Variation of normalized time constants τ/T of vortex breakdown and circulation over slender delta wing for accelerating and decelerating jet momentum coefficient, α=35°, Λ=65°.
Figure 4.54: Variation of normalized time constant $\tau U_x/c$ of vortex breakdown and circulation over slender delta wing for accelerating and decelerating jet momentum coefficient, $\alpha=35^\circ$, $\Lambda=65^\circ$.

Figure 4.55: Variation of normalized time constants $\tau/T$ of vortex breakdown over slender delta wing for accelerating and decelerating jet momentum coefficient, $\alpha=40^\circ$, $\Lambda=65^\circ$. 
Figure 4.56: Variation of normalized time constant $\tau U/c$ of vortex breakdown over a slender delta wing for accelerating and decelerating jet momentum coefficient, $\alpha=40^\circ$, $\Lambda=65^\circ$. 
Figure 4.57: Phase-averaged variations of $X_{bd}/c$ over nonslender wing with transient trailing-edge blowing, $\Lambda=50^\circ$, (a) $\alpha=20^\circ$, (b) $\alpha=25^\circ$. 
Figure 4.58: Variation of phase lags of the dynamic response of vortex breakdown ($\phi_b$) as a function of dimensionless blowing frequency for nonslender wing with transient trailing-edge blowing.

Figure 4.59: Variation of peak amplitude of the dynamic response of vortex breakdown ($\Delta X_{bd}/c$) as a function of dimensionless blowing frequency for nonslender wing with transient trailing-edge blowing.
Figure 4.60: Phase-averaged variations of $X_{bd}/c$ over slender wing with transient trailing-edge blowing, $\Lambda=65^\circ$, (a) $\alpha=35^\circ$, (b) $\alpha=40^\circ$. 
Figure 4.61: Variation of phase lags of the dynamic response of vortex breakdown ($\phi_b$) as a function of dimensionless blowing frequency for slender wing with transient trailing-edge blowing.

Figure 4.62: Variation of peak amplitude of the dynamic response of vortex breakdown ($\Delta X_{bd}/c$) as a function of dimensionless blowing frequency for slender wing transient trailing-edge blowing.
Figure 4.63: Food-colouring dye flow visualization for slender wing at different dimensionless frequencies $f^*$ with a periodically pitching jet, $\alpha=20^\circ$. 
Figure 4.64: Phase-averaged variations of $X_{bd}/c$ for slender wing ($\Lambda=65^\circ$) with a periodically pitching jet, $\alpha=20^\circ$. 
Figure 4.65: Phase-averaged variations of $C_N$ for slender wing with a periodically pitching jet, (a) $\alpha=10^\circ$, (b) $\alpha=20^\circ$, (c) $\alpha=30^\circ$, (d) $\alpha=40^\circ$. 
Figure 4.65: Continued
Figure 4.66: Hysteresis loops of phase-averaged variations of $C_N$ for slender wing with a periodically pitching jet, column (a) $\alpha=10^\circ$, (b) $\alpha=20^\circ$, (c) $\alpha=30^\circ$, (d) $\alpha=40^\circ$. 
Chapter 4                           Unsteady Trailing-Edge Jet

Figure 4.66:   Continued
Figure 4.67: Variations of phase lags of $C_N$ ($\phi_N$) and $X_{bd}/c$ ($\phi_b$) as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet.

Figure 4.68: Variations of normalized time constant $\tau U_\infty/c$ of $C_N$ as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet.
Figure 4.69: Variations of peak-to-peak amplitude of vortex breakdown location $\Delta X_{bd}/c$ as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet, $\Lambda=65^\circ$, $\alpha=20^\circ$.

Figure 4.70: Variations of peak-to-peak amplitude of normal force coefficient $\Delta C_N$ as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet.
Figure 4.71: Mean values of normal force coefficient $c_{N,\text{mean}}$ as a function of dimensionless frequency $f^*$ for slender wing with a periodically pitching jet.
Figure 4.72: Phase-averaged variations of $C_N$ for nonslender wing with a periodically pitching jet, (a) $\alpha=10^\circ$, (b) $\alpha=15^\circ$, (c) $\alpha=20^\circ$, (d) $\alpha=25^\circ$. 
Figure 4.72: Continued
Figure 4.73: Hysteresis loops of phase-averaged variations of $C_N$ for nonslender wing with a periodically pitching jet, column (a) $\alpha=10^\circ$, (b) $\alpha=15^\circ$, (c) $\alpha=20^\circ$, (d) $\alpha=25^\circ$. 
Figure 4.73: Continued
Figure 4.74: Variations of phase lags of $C_N$ ($\phi_N$) as a function of dimensionless frequency $f^*$ for nonslender wing with a periodically pitching jet.

Figure 4.75: Variations of normalized time constant $\tau U_\infty / c$ of $C_N$ as a function of dimensionless frequency $f^*$ for nonslender wing with a periodically pitching jet.
Figure 4.76: Variations of peak-to-peak amplitude of normal force coefficient $\Delta C_N$ as a function of dimensionless frequency $f^*$ for nonslender wing with a periodically pitching jet.

Figure 4.77: Variations of mean value of normal force coefficient $C_{N,\text{mean}}$ as a function of dimensionless frequency $f^*$ for nonslender wing with a periodically pitching jet.
CHAPTER 5      SUMMARY

This chapter presents an overview of the project, along with the main conclusions obtained from the experimental research.

5.1 Static Trailing-Edge Blowing

The interaction of statically pitched trailing-edge jets with leading-edge vortices over stationary delta wings and its effects on the wing aerodynamics were investigated. The effects of jet location, pitch angle, yaw angle, nozzle geometry, and wing sweep angle on aerodynamic forces and vortex-jet interaction were investigated. Wind tunnel and water tunnel experiments were performed to simulate thrust vectoring and quantify the aerodynamic effects by means of force measurements, flow visualization, and velocity measurements.

Under-vortex blowing was found to have a significant effect on the aerodynamic forces over both nonslender and slender wings, due to the promotion of earlier reattachment and delay of vortex breakdown. The largest effect of blowing was observed near the stall incidence and post-stall region, where earlier reattachment of the shear layer occurs and vortex breakdown is delayed. The jet pitch angle $\beta$ has a relatively small effect. Force measurements revealed that the effect of nozzle geometry can be important, as the entrainment effect of the jet depends on it. The jet-vortex interaction, distortion of jet vortices, and merging of wing and jet vortices are more pronounced for the rectangular nozzle and have a larger influence on the delta wing aerodynamics. The effect of jet yaw angle is small for the nonslender wing, whereas the aerodynamics of the slender wing is very
sensitive to the jet yaw angle.

5.2 Unsteady Trailing-Edge Blowing

The effects of dynamic thrust vectoring are important for the flight control of UCAVs. The literature reported the hysteresis and time-lag of vortical flows and vortex breakdown over pitching or plunging wings. The effects of dynamically varying momentum coefficient or jet pitch angle of a trailing-edge jet on delta wing aerodynamics were investigated, with an emphasis on quantifying hysteresis and phase lags. In order to simulate the dynamic thrust vectoring for a maneuver, the jet momentum coefficient or jet pitch angle was varied as a function of time. Both periodic and transient variations of the momentum coefficient $C_\mu$ or jet pitch angle were investigated. Water tunnel experiments were performed to simulate the unsteady thrust vectoring and quantify its effects by means of force measurements, flow visualization and velocity measurements at stall and post-stall incidences. The effect of sweep angle on the dynamic response of wing flows to dynamic thrust vectoring was tested.

For the periodic trailing-edge blowing, it was found that the dynamic response of leading-edge vortex breakdown and wing normal force coefficient exhibit phase lags for both nonslender and slender delta wings. The phase lag $\phi$ increases with increasing frequency $f^*$ of the periodic variations of the momentum coefficient. For the variation of vortex breakdown, the estimated time constant is larger than those reported in the literature for unsteady wings undergoing pitching or plunging. The phase lag of the normal force is smaller than that of the vortex breakdown, indicating that both potential lift and vortex lift play a role in the dynamic response. For the accelerating and decelerating trailing-edge blowing, both vortex breakdown location and normal force reached their steady-state values with a time delay for both slender and nonslender delta wings. Time delay for the decelerating jet is significantly larger than that of the accelerating jet. Variations of the circulation and reattachment
process near the wing surface also revealed similar results. The range of the estimated time constants is similar at the stall and post-stall incidences for both the slender and nonslender wings. For both slender and nonslender wings, the dynamic responses of wing flows to transient trailing-edge blowing exhibit similar trends of both periodic and accelerating and decelerating blowing. For periodically pitching trailing-edge jet, the dynamic response of leading-edge vortex breakdown and wing normal force coefficient exhibit phase lags for both nonslender and slender delta wings. The phase lag $\phi$ increases with increasing frequency $f^*$ of the periodic variations of jet pitch angle $\beta$. This trend is similar to that of periodic trailing-edge blowing. The estimated time constants $\tau_{U_\infty}/c$ of $C_N$ are comparable to those of previous results.

5.3 Scope for Future Work

A further potential area of work is to consider the interaction of the dynamic thrust vectoring on a manoeuvring wing in order to simulate an even more realistic case. The present investigation focuses on the interactions of unsteady trailing-edge blowing with vortex flows over a stationary wing. More extensive experiments are required in order to understand the effects of unsteady trailing-edge blowing jet on the dynamic wings with more complex manoeuvres, such as rolling and pitching wing motions. This could pave the road for the practical use of thrust vectoring control on future UCAVs.

Another recommendation is the investigation on the influences of steady and unsteady trailing-edge jet on the pressure gradient near the wing surface. Pressure gradient is very important parameter related to vortex breakdown locations, forces and moments on the wings, and dynamic response of unsteady thrust vectoring control. It is therefore felt that, given more time and resources, it would be beneficial to quantify the variations of pressure gradient with both steady and unsteady
trailing-edge blowing. This could improve our understanding on the relationship between pressure gradient and vortex flows over delta wings.

5.4 Closing Comments

This thesis has described the results of a set of experiments on the effects of static and unsteady thrust vectoring on the characteristics of delta wing aerodynamics. The results suggest that thrust vectoring at the trailing-edge is an effective, convenient and economical method, which benefits the stability and control of highly manoeuvrable and flexible UCAVs. Under-vortex blowing with rectangular nozzle at stall and post-stall regimes could lead to the maximum effectiveness of trailing-edge blowing. The responses of wing flows to dynamic trailing-edge blowing exhibit hysteresis and phase lag, without significant influence of sweep angle. Time constants obtained from these measurements could benefit the design of flight control systems.
CHAPTER 6 REFERENCES


66. Wolffelt, K.W., “Investigation on the Movement of Vortex Burst Position with


73. Xie, W.S., “An Experimental Investigation of Buffeting Flows over Delta Wings”, 1999, M.S. Thesis, Department of Mechanical Engineering, University of Cincinnati, Cincinnati, OH.


APPENDIX     LIST OF PUBLICATIONS PRODUCED FROM THE PROJECT
