Study of synthetic jets in boundary layers

Wen, Xin

2015

Wen, X. (2015). Study of synthetic jets in boundary layers. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/64554>

<https://doi.org/10.32657/10356/64554>

STUDY OF SYNTHETIC JETS IN BOUNDARY LAYERS

Wen Xin

School of Mechanical and Aerospace Engineering

2015

STUDY OF SYNTHETIC JETS IN BOUNDARY LAYERS

Wen Xin

School of Mechanical and Aerospace Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

2015

Acknowledgments

I would like to express my sincere thanks and appreciation to my supervisors, Dr. Tang Hui (Hong Kong PolyU), and Dr. Duan Fei (NTU) for their invaluable guidance, support and suggestions. Their knowledge, suggestions, and discussions help me to become a capable researcher. Their warm personality has also won my highest respect.

I also want to thank my colleagues, for their generous help. I want to thank Dr. Wang Haiming, Dr. Daniel New, Dr. Gao Lei, Dr. He Bin, Wang lixian, Wang Chenglei and Zang bin for their generous help on my experiments. I also want to thank Dr. Ji Xiaona, Xiang Junting and Chen Song for helping me setup simulation frameworks. I would like to thank Dr. Shan Zhong from University of Manchester for sharing the test data. I would like to thank Dr. Mark Jabbal and Dr. Zhou Jue for valuable discussion on both experiments and simulations. My gratitude also goes to my friends in my research room and my basketball team.

Last but not least, I want to thank my family, for their constant love and encouragement. I owe my deepest gratitude and love to my wife. It is her support and companion that make my research work run more smoothly and make my life more colorful.

Contents

Acknowledgments	i
Table of Contents	v
Abstract	vi
List of Figures	xvii
List of Tables	xviii
List of Abbreviations	xix
List of Symbols	xx
List of Notations	xxii
 1 Introduction	 1
1.1 Background	1
1.2 Aims and Objectives	4
1.3 Thesis Outline	5
 2 Literature Review	 7
2.1 Flow separation control	7
2.1.1 Flow separation	7
2.1.2 Flow separation control technology	8
2.2 Synthetic jets (SJs) in quiescent conditions	11
2.2.1 Dimensional analysis	12
2.2.2 Formation and evolution of SJs in quiescent conditions	14
2.3 SJs in crossflows	21
2.3.1 Dimensional analysis	21
2.3.2 SJs in attached crossflows	22
2.3.3 SJs in separated crossflows	30
2.4 Remarks	34

3	Methodology	36
3.1	Dimensional analysis	36
3.2	Experimental methodology	38
3.2.1	Test rig setup and SJ actuators design	38
3.2.2	Stereo color dye visualization system	41
3.2.3	PIV measurement system	43
3.3	Numerical methodology	48
3.3.1	Governing equations and their discretization	48
3.3.2	Computational geometry and mesh	50
3.3.3	Solver and boundary conditions	52
3.3.4	Validation	53
3.4	Data analysis methods	57
3.4.1	Vortex identification	58
3.4.2	Particle tracking	59
3.4.3	Proper orthogonal decomposition	60
3.4.4	Dynamic mode decomposition	62
3.5	Remarks	64
4	Single SJs in Crossflows	65
4.1	Test conditions	65
4.2	SJ-induced hairpin vortices in boundary layers	66
4.2.1	Hairpin vortices in the LBL	67
4.2.2	Hairpin vortices in the TBL	73
4.2.3	Comparisons in LBL and TBL	79
4.3	Role of SJ-induced hairpin vortices in flow separation control	83
4.3.1	Effects on velocity fields	83
4.3.2	Effects on wall shear stress	87
4.3.3	Effects on boundary-layer shape factor	89
4.4	Remarks	91

5	SJ Arrays in Attached Crossflows	93
5.1	Test conditions	93
5.2	Qualitative study	95
5.2.1	SJs visualized by particle-tracking and Q -criterion	96
5.2.2	Evolution of single and twin SJs	98
5.2.3	Influence of $\Delta\phi$	101
5.2.4	Influence of Re_L , VR , and St	109
5.2.5	A model for prediction of vortex patterns	115
5.3	Quantitative study	117
5.3.1	Experimental settings	118
5.3.2	Single SJs in a LBL	121
5.3.3	In-line twin SJs in a LBL	123
5.3.4	POD analysis	131
5.3.5	DMD analysis	136
5.4	Remarks	140
6	SJ Arrays in a Separated Crossflow	142
6.1	Test conditions	142
6.2	PIV measurement and dye visualization	143
6.3	Uncontrolled separated boundary layer	143
6.4	SJ-controlled separated flow	145
6.4.1	SJ-induced flow structures in separated flow	145
6.4.2	Time-averaged flow control effect	150
6.5	POD analysis	151
6.6	Remarks	156
7	Conclusions and Recommendation for Future Work	158
7.1	Conclusions	158
7.2	Recommendations for Future Work	160
7.2.1	Single SJs in boundary layers	160
7.2.2	SJ arrays in boundary layers	161

Publications	162
References	163

Abstract

The control of flow separation plays a more and more vital role in the design of systems involving fluid flows. Active flow separation control devices have attracted considerable attentions, since much better performance improvement can be achieved when compared with passive flow separation control methods. As a zero-net-mass-flux actuator, a synthetic jet (SJ) actuator is a promising active flow separation control device which has demonstrated success in some simulations and laboratory experiments.

In order to make this technology more feasible in real-world applications, this research aims to uncover more underlying physics associated with SJ-based flow separation control. Specifically, the flow structures induced by single SJs or SJ arrays in boundary layers and their impacts on boundary layers in the context of flow separation control are studied. Both a computational fluid dynamics (CFD) framework and a water-tunnel test rig are developed to facilitate the investigation. Advanced data analysis methods, i.e., proper orthogonal decomposition (POD) and dynamic mode decomposition (DMD), are applied to extract coherent flow structures from velocity fields to gain meaningful physical insights on the SJ array interactions.

The research is focusing on circular-SJ-induced flow structures, especially hairpin vortices. Similarities and differences of single SJs in laminar boundary layers (LBLs) and turbulent boundary layers (TBLs) are studied first using CFD simulations. It is found that the SJ-induced hairpin vortex in the TBL is asymmetric, oscillates laterally, and dissipates fast, whereas it is symmetric and persistent in the LBL. To achieve control effect in the TBL similar to in the LBL, a much stronger SJ is required.

Next, the interactions of in-line twin SJs in an attached LBL are studied using stereoscopic color dye visualization, particle image velocimetry (PIV) measurement, and CFD-based particle trace. Three types of vortex structures are identified at various operational

phase differences : one combined vortex at $\pi/2$, two completely separated vortices at $3\pi/2$, and partially interacting vortex structures at 0 and π . The one combined vortex is the strongest and can easily penetrate the boundary layer. The two completely separated vortices are the weakest, but can produce the greatest impact to the near-wall flow in the time-average sense. The partially interacting flow structures generally show intermediate impact. It is also observed that the vortices issued from the upstream SJ actuator are able to maintain their coherence more easily than their counterpart issued from the downstream actuator. Based on the flow visualization results, a simple formula is proposed to predict the resulting vortex pattern for the twin SJ interaction. The quantitative results not only confirm the above observations, but also reveal the impact of the twin SJs on the boundary layer. It is found that, among the four cases with different phase differences, it is the case at π instead of at $3\pi/2$ that shows the greatest near-wall velocity surplus. Furthermore, through the POD and DMD analyses the most energetic and dynamically representative coherent structures are extracted.

The twin SJ induced flow structures are then applied to a separated LBL over an inclined flat plate. The one combined vortex at $\pi/2$ phase difference produces the widest separation delay region in the spanwise direction, but shows a limited impact in the wall-normal and streamwise directions. On the contrary, the two completely separated vortices at $3\pi/2$ phase difference induce the narrowest separation delay region, but effectively suppress flow separation in the wall-normal direction and last for a longest streamwise distance. The partially interacting vortex structures perform an intermediate separation control effect, with the flow separation being more suppressed at π than at 0 phase difference.

Through this research, a more thorough understanding in underlying physics associated with SJ-based flow separation control has been achieved, which can be extended to future SJ-technology applications.

List of Figures

1.1	Flow separation over an airfoil (From Wikipedia).	2
1.2	Schematic of synthetic jet actuator.	3
2.1	Streamline and streamwise velocity profile near the separation point (Deen, 1998).	8
2.2	Configuration of VGs for generating counter rotating streamwise vortices (Gordar & Stanislas, 2006).	9
2.3	Contours of streamwise velocity from (a) uncontrolled flow and (b) flow controlled by SJs (Ye et al., 2006).	11
2.4	Schematic diagram of a SJ actuator.	12
2.5	Comparison of instantaneous jet exit velocity profiles between from the modeling of the cavity flow (case 1-3) and from analytical descriptions (sin and flat top profiles) (Rizzetta et al., 1999).	15
2.6	Saddle point showed by phase-averaged streamline maps (Glezer & Amitay, 2002).	16
2.7	Four different flow patterns of circular SJs: (a) laminar jet, $Re_{U_o} = 3336$, $St_{U_o} = 0.03$; (b) laminar rings, $Re_{U_o} = 7784$, $St_{U_o} = 0.012$; (c) transitional jet, $Re_{U_o} = 11121$, $St_{U_o} = 0.009$; (d) turbulent jet $Re_{U_o} = 66991$, $St_{U_o} = 0.009$. (Cater & Soria, 2002).	17
2.8	Flow patterns of (a) circular SJs and (b) equivalent continuous jet.(Cater & Soria, 2002).	17
2.9	Interaction between twin circular SJs in quiescent conditions at a) $d/D_o = 5.7$, b) $d/D_o = 2.3$, and c) $d/D_o = 1.7$. (Waton et al., 2010)	18

2.10	Contour maps of phase-averaged vorticity from the interaction between twin plane SJs at (a) $\Delta\phi = 0^\circ$ at $t/T = 0.17$ and (b) $\Delta\phi = 80^\circ$ at $t/T = 0.61$ (Smith & Glezer, 2005).	19
2.11	Time-averaged flow field with vector arrows and contour for (a) single circular SJ, and (b) twin circular SJs at $\Delta\phi = 180^\circ$ (Greco et al., 2013). SJs are injected from left to right	20
2.12	Vorticity contours at the end of blowing for a plane SJ with VR equals (a) $+\infty$; (b) 0.95; (c) 0.21; (d) 0.10 (Mittal & Rampunggoon, 2001). . .	23
2.13	Stereoscopic dye and surface liquid crystal images of a SJ at (a) hairpin vortices $VR = 0.14$, $L = 1.4$, (b) stretched vortex rings $VR = 0.27$, $L = 2.7$, (c) tilted/distorted vortex rings $VR = 0.5.1$, $L = 5.1$ (Jabbal & Zhong, 2008).	23
2.14	Iso-surface of $Q = 0.1$ showing (a) the hairpin vortices and (b) tilted vortex ring with accompanying structures (Zhou et al., 2009).	24
2.15	Vortex structure induced by single circular SJs in TBL, (a) Iso-surface of $Q = 0.2$ colored with streamwise vorticity, and (b) contours of time-averaged streamwise vorticity in a spanwise wall-normal plane (Javadi & El-Askary, 2011).	25
2.16	(a) Vortices generated by single circular SJs in TBL, and (b) contours of phase-averaged streamwise velocity in a wall-parallel plane (Javadi & El-Askary, 2011).	25
2.17	Sketch of side and top-view of twin SJs at (a) $\Delta\phi = 54^\circ$ and (b) 108° (Honami & Motosuke, 2012).	27
2.18	(first row) Time-averaged streamwise velocity contours at $x/Do = 25$ and (second row) PSD plots of hotwire anemometer output signal measured at $x/Do = 10$, $y/Do = 1$ for (a) $\Delta\phi = \pi/2$ or 90° and (b) $\Delta\phi = 3\pi/2$ or 270° (Liddle & Wood, 2005).	28
2.19	Surface visualisation of twin SJs at yaw angle (a) $\gamma = 15^\circ$ and (b) $\gamma = 0^\circ$ (Liddle & Wood, 2005).	29
2.20	The reattached flow between two consecutive eddies induced by plane SJs operates at $F^+ = 0.14$ and $C_\mu = 1\%$, plotted by (a) Q -criterion isosurface and (b) pressure field and streamlines (Dandois et al., 2007).	31

2.21	(a) Oil flow visualization demonstrating the flow separation control of array of circular SJs (Wood et al., 2000) and (b) oil streaklines with corresponding flow topology of a streamwise vortex pair induced by a circular SJ on a cylinder (Crook, 2002).	32
2.22	Hairpin vortices induced by circular SJs with TBL separation: (a) iso-surfaces of $Q = 5$ coloured with streamwise vorticity, (b) a conceptual model of the vortical structures which produce the delay of flow separation (Zhong & Zhang, 2013).	34
3.1	Schematic of (a) the test plate for attached flow and (b) the twin SJ actuators (all numbers are in mm).	38
3.2	Schematic of the test plate for separated flow (all numbers are in mm).	39
3.3	Schematic of synchronization system.	40
3.4	Schematic of the stereoscopic dye visualization system.	42
3.5	(a) PIV raw image with zoom-in IAs (b) the velocity map processed from PIV raw image pair.	44
3.6	Schematic of setup for PIV measurement at a spanwise plane.	45
3.7	Photo of setup for PIV measurement at mid-span streamwise plane.	46
3.8	Measurement uncertainties of PIV with respect to uniform spatial shift and seeding density (Adapted from Willert & Gharib (1991)).	48
3.9	Computational geometry and boundary conditions for (a) single SJs in LBL and TBL and (b) twin SJs in LBL.	51
3.10	Variation of SJ actuator diaphragm velocity in an actuation cycle.	52
3.11	Comparison of instantaneous and time-averaged streamwise velocity profiles from single-SJ-LBL simulation with the PIV data extracted from the publication of Zhou et al. (2009). δ is the local boundary layer thickness.	54
3.12	Comparison of instantaneous and time-averaged streamwise velocity profiles from twin-SJ-LBL simulation at $\Delta\phi = 0^\circ$ with the PIV data obtained from current experimental results. δ is the local boundary layer thickness.	54

3.13	Comparison of (a) mean streamwise velocity U^+ (solid symbol: PIV data (Zhong, 2012), hollow symbol: current LES simulation, lines: theoretical predictions) and (b) velocity fluctuations (lines: DNS (Spalart, 1988), symbols: current LES), where u'^+ and v'^+ are streamwise and wall-normal velocity fluctuations, respectively. All the velocities are normalized by friction velocity. The peak difference is found to be about 8.8% in the fluctuation profiles.	55
3.14	Instantaneous turbulence structures in the TBL. The vortex structures are identified using iso-surfaces of $Q = 25$	56
3.15	Comparison of FFT spectra of wall shear stress at $x = 1D_o$ from two selected periods of time. The difference between the spectrum peaks is less than 2%.	56
3.16	Comparison of (left) CFD visualization results and (right) current dye visualization results of the twin SJs at $Re_L = 164$, $St = 0.091$, $VR = 0.23$ and at phase difference $\Delta\phi = \pi/2$. (The lines indicates the edge of boundary layer.)	59
4.1	Phase-averaged hairpin vortices in the LBL (left) and in the TBL (right) at $t = 3T/4$ at $VR = 0.17$ and $L = 1.7$. The vortex structures are identified by iso-surfaces of $Q = 10$. The contours represent streamwise vorticity. .	66
4.2	Instantaneous flow structures plotted with $Q = 0.5$ and wall shear stress in LBL at (a) maximum blowing ($t = T/4$), (b) beginning of ingestion ($t = T/2$) at $VR = 0.17$ and $L = 1.7$	68
4.3	Instantaneous flow structures plotted with $Q = 0.5$ and wall shear stress in LBL at (a) maximum ingestion ($t = 3T/4$), and (b) beginning of blowing ($t = T$) at $VR = 0.17$ and $L = 1.7$	69
4.4	(a) Instantaneous flow structures plotted with $Q = 0.5$, (b) velocity vectors with contour of spanwise vorticity in the mid-span plane at $t = T/4$ in LBL, and (c) deduction of the translating velocity of the hairpin head at $VR = 0.17$ and $L = 1.7$	72
4.5	Flow structures at maximum blowing ($t = T/4$) in TBL at $VR = 0.17$ and $L = 1.7$	74

4.6	Flow structures at beginning of ingestion ($t = T/2$) in TBL at $VR = 0.17$ and $L = 1.7$. Refer to Figure 4.5 for the color map.	75
4.7	Flow structures at maximum ingestion ($t = 3T/4$) in TBL at $VR = 0.17$ and $L = 1.7$. Refer to Figure 4.5 for the color map.	76
4.8	Flow structures at beginning of blowing ($t = T$) in TBL at $VR = 0.17$ and $L = 1.7$. Refer to Figure 4.5 for the color map.	77
4.9	(a) Phase-averaged flow structures plotted with $Q = 25$, (b) velocity vectors with contour of spanwise vorticity in the mid-span plane at $t = T$ in TBL, (c) deduction of the translating velocity of the hairpin head, at $VR = 0.17$ and $L = 1.7$	78
4.10	(a) Schematic diagram illustrating the four characteristic angles for a typical hairpin vortex (Haidari & Smith, 1994); (b) geometrical evolution of hairpin vortices in the LBL (solid lines) and TBL (dashed lines) at $VR = 0.17$ and $L = 1.7$; (c) mean velocity profiles; (d) shear stress in the LBL and TBL.	80
4.11	Conceptual sketches of vortical structures (a) in LBLs and (b) in TBLs at $VR = 0.17$ and $L = 1.7$	82
4.12	Profiles of (a) streamwise velocity and (b) velocity gradient at various spanwise locations in a cross-flow plane of $x = 3Do$ in the LBL at SJ working conditions of $VR = 0.17$ and $L = 1.7$	84
4.13	Profiles of (a) streamwise velocity and (b) velocity gradient at various spanwise locations in a cross-flow plane of $x = 3Do$ in the TBL at SJ working conditions of $VR = 0.17$ and $L = 1.7$	85
4.14	Streamwise vorticity and velocity vector in a cross-flow plane of $x = 3Do$ at beginning of ingestion ($t = T/2$) in the TBL at SJ working conditions of $VR = 0.17$ and $L = 1.7$	87
4.15	Time-averaged excess wall shear stress: (a) contours on the wall and (b) spanwise distribution at $x = 3Do$ and $x = 12Do$. The SJ-LBL case is on the left and the SJ-TBL case on the right at $VR = 0.17$ and $L = 1.7$. . .	88
4.16	Shape factor along streamwise direction at various spanwise locations: (a) without SJs at mid-span plane, (b) in the LBL with SJs, (c) in the TBL with SJs, at $VR = 0.17$ and $L = 1.7$	90

5.1	Particle traces of single SJs at $t = 0$ using side cross-section view (upper row) and plan view (bottom row) at (a) case 5 with $Re_L = 164$, $St = 0.091$ and $VR = 0.23$, (b) case 4 with $Re_L = 72$, $St = 0.091$ and $VR = 0.16$, (c) case 3 with $Re_L = 82$, $St = 0.0045$ and $VR = 0.12$	96
5.2	Particle traces and iso-surface of $Q = 5$ of single SJs at $t = 0$ using side cross-section view (upper row) and plan view (bottom row).	97
5.3	Evolution of vortex structures in a crossflow in case 5. Upper two rows: stereoviews of a single SJ. Bottom two rows: stereoviews of twin SJs with zero phase difference. The horizontal line represents the edge of the boundary layer.	98
5.4	Evolution of particle trace of single SJ and twin SJs at $\Delta\phi = 0$ at case 5 using side cross-section and plan views. Upper two rows: a single SJ. Bottom two rows: twin SJs with zero phase difference. The horizontal dash line represents the edge of the boundary layer.	100
5.5	Stereoscopic dye images of the twin SJs at various phase differences for case 5. The horizontal line represents the edge of the boundary layer. . .	102
5.6	Particle trace of twin SJs at four phase difference at $t = 0$ in case 5 using side cross-section and plan views.	104
5.7	Particle trace of twin SJs at $\Delta\phi = \pi/2$ in case 5 at $t = 0$ using span cross-section view at three streamwise locations.	105
5.8	Trajectory of fluid particles released from the twin SJ actuators for case 5. From left to right: single SJ, twin SJs with $\Delta\phi = \pi/2$, twin SJs with $\Delta\phi = 3\pi/2$. From top to bottom: particle released at center of the SJ actuator orifice exit, particle released at $z/D_o = 0.4$ (side view), particle released at $z/D_o = 0.4$ (plan view). The trajectories are superimposed by SJ vortex structures (semitransparent structures) at $t/T = 0.25$. The larger dots represent the points on the corresponding vortex structures. The horizontal dashed line represents the edge of the boundary layer. . .	106
5.9	Phase diagram at three stations in the mid-span plane for case 5. From left to right: single SJ, twin SJs with $\Delta\phi = \pi/2$, twin SJs with $\Delta\phi = 3\pi/2$. From top to bottom: Station 1 ($x = 5D_o$, $y = 3.4D_o$), Station 2 ($x = 5D_o$, $y = 2.4D_o$) and Station 3 ($x = 5D_o$, $y = 1.4D_o$).	108

5.10	Stereoscopic dye visualization of (left) case 5 and (right) case 11 showing the influence of Re_L on single- and twin-SJ induced vortex structures. The twin SJs are introduced with zero phase difference. The horizontal line represents the edge of the boundary layer.	110
5.11	Stereoscopic dye visualization of (left) case 1 and (right) case 9 showing the influence of VR on single- and twin-SJ induced vortex structures. The twin SJs are introduced with zero phase difference.	111
5.12	Stereoscopic dye visualization of (left) case 2 and (right) case 9 showing the influence of St on single- and twin-SJ induced vortex structures. The twin SJs are introduced with zero phase difference.	111
5.13	Particle trace of twin SJs at four phase difference at $t = 0$ in case 4 with $Re_L = 72$, $St = 0.091$ and $VR = 0.16$ using side cross-section and plan views.	113
5.14	Particle trace of twin SJs at four phase difference at $t = 0$ in case 3 with $Re_L = 82$, $St = 0.045$ and $VR = 0.12$ using side cross-section and plan views.	114
5.15	Summary of side view visualization at different phase difference for all cases, showing the spacing and resulting interaction between the vortices produced by the twin SJ actuators. The horizontal line represents the edge of the boundary layer.	116
5.16	Comparison of PIV-measured mean velocity profile and the Blasius solution at $x = 4D_o$ in the mid-span plane.	120
5.17	(a) Stereoscopic dye images of a single SJ in a LBL. The horizontal line in the side view indicates the edge of the boundary layer. (b) Snapshots of streamwise vorticity contour in spanwise wall-normal plane $x = 8D_o$ during an actuating cycle, (c) Contour of wall-normal velocity and velocity vectors and (d) structure and spanwise vorticity contour at the streamwise mid-span plane at $t = 0.2T$	121
5.18	Time history of hairpin vortex circulation.	122
5.19	Stereoscopic dye images of the twin SJs at four phase differences in case 10, i.e. $L = 1.7$, $Re_L = 145$, $St = 0.091$ and $VR = 0.16$	124

5.20	Contour of streamwise vorticity in the $x = 8D_o$ plane during one actuating cycle. Refer to Figure 5.17b for the color map.	125
5.21	Contour of wall-normal velocity and velocity vectors at four phase differences at streamwise mid-span plane. Refer to Figure 5.17c for the color map.	125
5.22	Evolution of value of vortex strength of twin SJs at $\Delta\phi = \pi/2$ and $\Delta\phi = 3\pi/2$ and single SJs at (a) mid-span plane and (b) spanwise wall-normal plane. ‘UP’ and ‘DS’ in figure indicates the SJ issued from upstream and downstream actuator.	127
5.23	Contour of time-averaged streamwise vorticity and velocity vectors in the $x = 8D_o$ plane	129
5.24	Contour lines of time averaged wall-normal velocity (without colour, using the same contour levels as in Figure 5.17c) superimposed by contours of streamwise velocity difference between SJ influenced flows and the background boundary layer flow (with colour) and velocity vectors. The vectors are for time-averaged absolute velocities.	130
5.25	POD analysis for the single SJ case: (a) POD energy levels of the first 10 modes, (b) scatters of coefficients a_1 vs a_2 (black solid circle) and a_3 vs a_4 (green hollow square), (c) FFT spectra of a_1 and a_2 , and (d) a_3 and a_4 . .	132
5.26	Wall-normal velocity contour of first 4 POD modes for single SJ case at mid-span plane.	133
5.27	POD analysis for $\Delta\phi = \pi/2$ case: (a) POD energy levels of the first 10 modes, (b) scatters of coefficients a_1 vs a_2 (black solid circle) and a_3 vs a_4 (green hollow square), (c) FFT spectra of a_1 and a_2 , and (d) a_3 and a_4 . .	134
5.28	Wall-normal velocity contour of first 4 POD modes for $\Delta\phi = \pi/2$ case at mid-span plane. Refer to Figure 5.26 for the color map.	135
5.29	POD analysis for $\Delta\phi = 3\pi/2$ case: (a) POD energy levels of the first 10 modes, (b) scatters of coefficients a_1 vs a_2 (black solid circle) and a_3 vs a_4 (green hollow square), (c) FFT spectra of a_1 and a_2 , and (d) a_3 and a_4 . .	136
5.30	Wall-normal velocity contour of first 4 POD modes for $\Delta\phi = 3\pi/2$ case at mid-span plane. Refer to Figure 5.26 for the color map.	137

5.31	DMD analysis for the single SJ case: (a) scatters of DMD eigenvalue, and contours of wall-normal velocity of (b) mode Ψ_1 and (c) mode Ψ_3 (using the same contour levels as in POD modes).	138
5.32	DMD analysis for the $\Delta\phi = \pi/2$ case: (a) scatters of DMD eigenvalue, and contours of wall-normal velocity of (b) mode Ψ_1 and (c) mode Ψ_3 . . .	138
5.33	DMD analysis for the $\Delta\phi = 3\pi/2$ case: (a) scatters of DMD eigenvalue, and contours of wall-normal velocity of (b) mode Ψ_1 and (c) mode Ψ_3 . . .	139
6.1	Dye visualization of the flow separation over the inclined plate without active control.	144
6.2	Time-averaged baseline flow of streamwise velocity contour and streamlines (a) at mid-span wall-normal plane and (b) at a spanwise wall-parallel plane, S_L/D_o indicates the averaged separated line within $z = -5D_o$ to $z = 5D_o$	145
6.3	Dye visualization of the flow structure induced by single SJs over the inclined plate. (Red dashed line indicates the edge of boundary layer) . .	146
6.4	Dye visualization of the flow structure induced by twin SJs at (a) $\Delta\phi = 0$ and (b) $\Delta\phi = \pi/2$ over the inclined plate.	147
6.5	Dye visualization of the flow structure induced by twin SJs at (a) $\Delta\phi = \pi$ and (b) $\Delta\phi = 3\pi/2$ over the inclined plate.	148
6.6	Contours of phase-averaged streamwise velocity at $t/T = 0.2$ at mid-span wall-normal plane. (Refer to Figure 6.2a for color map)	149
6.7	Contour of time-averaged streamwise velocity and streamlines at mid-span wall-normal plane. Refer to Figure 6.2a for the color map.	150
6.8	Contour of time-averaged streamwise velocity with streamlines in the plane parallel to the inclined plate. Refer to Figure 6.2b for the color map. . .	152
6.9	POD analysis for the single SJ case at mid-span wall-normal plane: (a) POD energy levels of the first 10 modes, (b - d) contour of streamwise velocity of first 3 POD modes. (Black dashed line: boundary layer edge, Red solid line: separation line)	153

- 6.10 POD analysis for the $\Delta\phi = \pi/2$ case at mid-span wall-normal plane: (a) POD energy levels of the first 10 modes, (b - d) contour of streamwise velocity of first 3 POD modes. Refer to Figure 6.9 for the color map. . . 154
- 6.11 POD analysis for the $\Delta\phi = 3\pi/2$ case at mid-span wall-normal plane: (a) POD energy levels of the first 10 modes, (b - d) contour of streamwise velocity of first 3 POD modes. Refer to Figure 6.9 for the color map. . . 155

List of Tables

3.1	Mesh information for the single-SJ simulations.	51
5.1	Case summary	94
5.2	Estimation of s value at different St and $\Delta\phi$	116

Nomenclature

CFD	Computational Fluid Dynamics
DMD	Dynamic Mode Decomposition
DNS	Direct Numerical Simulation
DPM	Discrete Particle Model
FFT	Fast Fourier Transform
IA	Interrogation Area
SJ	Synthetic Jet
LBL	Laminar Boundary Layer
LES	Large Eddy Simulation
N-S	Navier-Stokes
PIV	Particle Image Velocimetry
POD	Proper Orthogonal Decomposition
PSD	Power Spectral Density
TBL	Turbulent Boundary Layer
URANS	Unsteady Reynolds-Averaged Navier-Stokes
VG	Vortex Generator
2D	2 Dimension
3D	3 Dimension

List of Symbols

a_n	Coefficient for n th POD mode
C_μ	Momentum coefficient
D_d	Diaphragm area
D_o	Orifice area
D_c	SJ actuator cylinder cavity diameter
d/D_o	Non-dimensional jet-axe-distance or orifice-axes-distance
G	Companion matrix in DMD
f	Diaphragm oscillation frequency
FR_j	Frequency ratio between SJs
F^+	Reduced frequency
H	Shape factor
H_c	SJ actuator cylinder cavity height
h	Orifice depth or thickness
L	Dimensionless stroke length
L_o	Stroke length
M	Total positions of velocity vectors in a given snapshot
N	Number of snapshots used for POD and DMD
Re_L	Reynolds number
Re_θ	Reynolds number based on the momentum thickness
S	Stokes number; symmetric components of the velocity gradient tensor (Section 3.4.1)
St	Strouhal number in cross flow
St_q	Strouhal number in quiescent condition
S_L	Averaged separated line within $z = -5D_o$ to $z = 5D_o$
s	non-dimensional spacing between the two SJ vortices
T	SJ actuator actuating cycle
U_∞	Freestream velocity
$\bar{U}_o$	Time-averaged blowing velocity over an entire actuation cycle

$u'^+ \& v'^+$	Normalized velocity fluctuations
$u'v'^+$	Normalized Reynolds stress
VR	Velocity ratio between $\bar{U}_o$ to U_∞
VR_j	Velocity ratio between SJs
V_1^N	Raw velocity matrix for DMD process
x^+	Streamwise coordinate normalised by friction velocity and ν
$\bar{x}$	Filtered variable in LES
y^+	Wall coordinate normalised by friction velocity and ν
z^+	Spanwise coordinate normalised by friction velocity and ν
$\alpha_1 \& \alpha_2$	Orientation of the hairpin leg to the wall
$\beta_1 \& \beta_2$	Orientation of the hairpin head to the wall
Δ	Diaphragm oscillation amplitude
$\Delta\phi$	Phase difference
Δt	Time interval
δ	Boundary layer thickness
e_{total}	Velocity uncertainty of PIV measurement
γ	Yaw angle between SJ arrays to crossflow
Γ_o	Vorticity flux
Γ	Vorticity based on normalized velocity and dimensions
λ	Eigenvalues of a Matrix in POD
$\mu_r \& \mu_i$	Real part and image part of transformed eigenvalues of G
μ_t	Subgrid-scale turbulent viscosity
Φ_n	n th POD mode
Ψ_n	n th DMD mode
ν	Fluid kinematic viscosity
∇u	Velocity gradient tensor
ρ	Fluid density
τ_{ij}	Subgrid-scale stress
τ_w	Wall shear stress

Notation

$(X)^T$	Matrix transpose
$(X)^{-1}$	Matrix inverse
$ X $	Matrix norm of X
$qr(X, 0)$	QR-decomposition of matrix X
$eig(X)$	Return the eigenvalues and eigenvectors of matrix X

Chapter 1

Introduction

1.1 Background

Flow control is a means of generating a desired change in flow behavior. Its purposes can be separation preventing/promoting, transition delaying/advancement, turbulence enhancement/suppression, and noise reduction (Löfdahl & Gad-el-Hak, 1999). Since the beginning of twenty century, flow control has attracted significant attention for its potential in enhancing the performance of various systems involving fluid flows, such as aircrafts, ships, and automobiles.

As one type of flow control, flow separation control is usually used to delay or eliminate flow separation so that enhanced aero/hydrodynamic performance can be achieved. When a flow is retarded, for example, by an adverse pressure gradient along a wall, the fluid particles in the boundary layer gradually slow down. At some point, where the near-wall streamline starts leaving the wall, the flow is said to separate, and the point is called the separation point (Maskell, 1955; Gad-el-Hak, 2000). Figure 1.1 clearly shows a separated flow over an airfoil that is at a high angle of attack. It is well known that this flow separation can result in increased drag and reduced lift.

Control of flow separation can be dated back to 1904 when Prandtl pioneered the modern use of flow control in his epoch-making presentation (Prandtl, 1904). He explained the mechanism of flow separation and described several experiments in which boundary-layer separation was delayed. The methods for flow separation control generally fall into two categories : passive control that does not require auxiliary power, and active control that requires extra energy expenditure. Vortex generator (VG) is a

Figure 1.1: Flow separation over an airfoil (From Wikipedia).

typical passive flow separation control device, first introduced in 1950s (Taylor, 1948). Although effective and easy to implement, it introduces drag penalty when the flow is not separated. In contrast, devices for active flow separation control are largely innocuous except when activated, and are able to deliver variable power (Amitay et al., 2001). A variety of active flow separation control techniques has been employed, such as steady blowing/suction and periodic excitation. For example, in his famous paper, Prandtl (1904) successfully used steady suction/blowing to delay boundary layer separation on the surface of a cylinder. Although effective, steady blowing/suction requires complex piping systems to deliver added/removed mass. As one example of periodic excitation, pulsed jets were reported to be more effective than steady blowing/suction, but they also need complex piping systems (Eroglu & Breidenthal, 2001).

Synthetic jets (SJs) as another active flow separation control means has received considerable attention since the 1990s (Smith & Glezer, 1998; Amitay et al., 1998). A typical SJ actuator consists of a small cavity with an oscillating diaphragm on the bottom side and an orifice/slot on another side, as showed in Figure 1.2. The diaphragm's periodic downward and upward motion generates a succession of vortex rings/pairs that propagates away from the orifice, forming a "synthetic jet". The advantage of SJs is that they have zero net mass flux and do not require complex piping system, but they can produce non-zero momentum flux. In addition, the oscillatory nature of SJs results in greater fluid entrainment in the near-wall region if compared to continuous jets (Cater & Soria, 2002).

Figure 1.2: Schematic of synthetic jet actuator.

Extensive experimental and numerical investigations have been conducted to demonstrate the capability of SJs in delaying flow separation over various objects, including circular cylinders (Amitay et al., 1997; Crook et al., 1999; Glezer & Amitay, 2002), inclined plates (Dandois et al., 2007; Zhang & Zhong, 2010), and airfoils (McCormick, 2000; Wood et al., 2009; Tang et al., 2014). These investigations revealed that, in addition to the SJ momentum coefficient and operational frequency, vortex structures induced by SJs in boundary layers are also of importance for SJ-based flow separation control. These vortex structures are able to enhance mixing and momentum exchange in boundary layers and hence help delay the occurrence of flow separation. It was further found that, depending on the jet-to-freestream velocity ratio and dimensionless stroke length, different vortex structures can be produced, i.e. hairpin vortices, stretched vortex rings, and tilted/distorted vortex rings (Zhong & Wood, 2005). Among these vortex structures it is hairpin vortices and stretched vortex rings that are responsible for SJ-based flow separation control (Zhang & Zhong, 2010; Jabbal & Zhong, 2010).

Although most of real-world applications are in TBLs (TBLs), to the author's knowledge, many lab-scale flow-separation-control experiments and simulations were only focused in laminar boundary layers (LBLs). This is partially because the investigation in LBLs is relatively easier, and partially because logically understanding the physics in LBLs shall come before the understanding in TBLs. Due to the influence of turbulence,

SJ-induced vortex structures in TBLs may behave quite differently from those in LBLs, and so does their capability in flow separation control.

In addition, compared to extensive investigations on single SJs, investigations on multiple SJs or SJ arrays, especially on interaction of SJ-array induced vortex structures in boundary layers, are insufficient to support real-world applications. Waton et al. (2010) has revealed that the interaction between neighboring SJs in crossflows generates complex flow structures, which may enhance or reduce the flow separation control effectiveness. To determine the unknown influence of this interaction, therefore, a better understanding of the SJ-array-induced vortex structures is desirable.

1.2 Aims and Objectives

The present PhD research aims to uncover more underlying physics associated with flow separation control using SJs and to make this technology more feasible in real-world applications. Specifically, two critical issues are to be addressed:

- (i) How does the nature of a crossflow, i.e., whether it is laminar or turbulent, affect the performance of SJs in flow separation control?
- (ii) How do the array configuration and operating condition of an SJ array affect the control effectiveness through changing the interacting vortex structures?

To facilitate this research, several tasks are planned as follows:

- (i) To establish a computational fluid dynamics (CFD) framework for simulating behavior of single SJs and SJ arrays in different boundary layers.
- (ii) To design and develop a water tunnel test rig for the investigation of single SJs and SJ arrays in different crossflows.
- (iii) To compare the similarities and differences of flow structures induced by single SJs in LBLs and TBLs, and the impact of these flow structures on the boundary layers.
- (iv) To observe and analyze the resulting flow structures generated by SJ arrays in attached crossflows in the context of flow separation control.

- (v) To observe and analyze the effect of the SJ-array induced flow structures on separated crossflows.

To focus the discussion and analysis of the present research, several assumptions are made. First, only SJs produced from circular orifices are studied. Compared to rectangular SJs, circular SJs are space saving and can be arrayed easily. In addition, they are more effective in mixing enhancement (Kim et al., 2010). Second, among the various types of SJ-induced vortex structures, the focus is given to hairpin vortices, because they are most effective in SJ-based flow separation control (Zhang & Zhong, 2010; Jabbal & Zhong, 2010). Third, for SJ arrays, as the first effort towards a comprehensive understanding of their interaction in crossflows, the interaction of only two in-line SJs in LBLs is studied.

This research involves both experimental and numerical investigations. The experiments are conducted in a low-speed water tunnel using stereoscopic color dye visualization and particle image velocimetry (PIV) measurements. The CFD simulations are conducted to provide more detailed flow information, involving both laminar and turbulent simulations. As for the data processing, both Q - and λ_{ci} criteria are used to identify vortex structures. The discrete particle model (DPM) is used to track the movement of particles issued from SJ actuators. In addition, to obtain meaningful physical insights on SJ array interactions, the proper orthogonal decomposition (POD) and dynamic mode decomposition (DMD) analysis methods are applied to extract coherent flow structures from velocity fields.

1.3 Thesis Outline

This thesis is organized as follows: Chapter 2 provides a comprehensive literature survey on SJ-based flow separation control, with focus placed on the behavior of single SJs and SJ arrays in quiescent flows, in attached crossflows, and in separated crossflows. Chapter 3 describes the technical methodologies used in this PhD research. Chapter 4 discusses the similarity and difference between the behavior of a single SJ in LBL and TBL. Chapter 5 presents and analyzes twin in-line SJs at various working conditions in an attached crossflow. Chapter 6 investigates the flow separation control effect of

various flow structures induced by the twin SJs in a separated crossflow. And Chapter 7 concludes this thesis with recommendations for future work provided.

Chapter 2

Literature Review

This chapter is intended to provide a comprehensive literature survey of investigations to date on SJs and SJ arrays in the context of flow separation control. This review also identifies the areas where further investigations are required and explains the motivations for current research. The review outlines the background knowledge about flow separation, the concept and methods of flow separation control, the behaviors of SJs and SJ arrays in quiescent condition, attached and separated crossflows.

2.1 Flow separation control

2.1.1 Flow separation

Flow separation was first explained by Prandtl (1904) in his milestone presentation in which the boundary layer theory was introduced. Due to viscosity of fluid, a boundary layer forms along a stationary solid surface along which a crossflow travels. Fluid in a boundary layer are slowed down by wall friction. If the flow is sufficiently retarded, for example, by an adverse pressure gradient, the momentum of those particles is reduced. Compared to the freestream, due to the insufficient momentum for them to continue their motion, the fluid particles near the wall suffer a greater deceleration as a result. At some point (or line), the streamline nearest to the wall leaves the body, as shown at point 2 in Figure 2.1, and the boundary layer is said to separate (Maskell, 1955; Gad-el-Hak, 2000). Immediate downstream from the separation point, the flow is reversed in near wall region as shown at point 3.

Figure 2.1: Streamline and streamwise velocity profile near the separation point (Deen, 1998).

Because of the large energy loss associated with flow separation, it often limits the performance of air, land, and sea vehicles; turbomachines; diffusers; and a variety of other important systems involving fluid flow. For example, the performance of wing is of significant importance to the performance of an airplane. Flow separation can degrade the performance of a wing: a wake region is generated to increase the drag and reduce the lift (Kundu & Cohen, 2004).

2.1.2 Flow separation control technology

According to the mechanism of flow separation, near-wall momentum addition is a straightforward and common approach to control residual flow separation. The additional momentum can be provided either through local redirection into the wall region or from an external source. To achieve these, various methods of flow separation control are used which can be classified into two types: passive and active separation controls (Gad-el-Hak, 2000).

Figure 2.2: Configuration of VGs for generating counter rotating streamwise vortices (Gordar & Stanislas, 2006).

Passive techniques do not require auxiliary power, such as VGs which have demonstrated effective control capacity (Taylor, 1948; Lin, 2002). VGs consist of small vanes and have been used on the leading edge of aircraft wings and vertical tails. As shown in Figure 2.2, counter rotating streamwise vortices are induced when the flow passes through VGs. Particles with high streamwise momentum are swept along helical paths towards the surface to mix with and, to a certain extent, replace the retarded near-wall flow, hence delaying flow separation. This method is frequently used because of its simplicity. However, they do not have the ability to provide a time-varying control action and they are only effective over a small operational range. Furthermore, the parasitic drag produced by VGs is inevitable.

Active methods require energy expenditure to postpone separation. Active momentum addition is achieved generally through streamwise vortex generation, turbulence or Reynolds stress amplification, and direct addition of high momentum fluid (Gad-el-Hak, 2000). Although these mechanisms can work independently, they are usually coupled in the active-control applications. In comparison to passive flow control, the primary advantages of active flow control were summarized by Kral (1999). First, active flow control leverages and controls a natural stability of the flow to achieve a large effect at the expense of small, localized energy input. Second, active control can be used to control complex, dynamical processes, since the device of active control can be operative ‘on

demand' when needed, and its input power level can be varied according to the demands of the local flow condition.

Typically, active control methods include steady suction/blowing jets and pulsed jets. The basic principle of steady suction is to remove the low-momentum fluid in the boundary layer and force the outer high-momentum fluid into the boundary layer (Lachmann, 1961). It has been demonstrated to be capable of delaying flow separation on a variety of wind tunnel models. But, due to complex piping system and considerable power required to operate the suction devices, control efficiency of this method is limited.

Through a more direct way, steady blowing injects high momentum fluid parallel to the wall to augment the shear-layer momentum or normal to the wall to enhance the mixing rate (Delery, 1985). It is a straightforward flow separation control technique that has been applied to military fighters. Steady blowing has been investigated for a variety of different locations on wings and at the shoulder of a deflected flap (Lachmann, 1961).

Pulsed jets are remarkable for its capability of vorticity-generation which enhances boundary-layer momentum transport (McManus & Magill, 1996; Magill & McManus, 2001). In addition to streamwise vortices, large-scale turbulent vortex structures are generated in a boundary layer as a result of pulsing the wall jets. At a preferred range of frequencies of the periodic excitation, flow reattachment can be obtained (Bhattacharjee et al., 1986; Wengle et al., 2010; Dejoan & Leschziner, 2004). Compared to steady suction/blowing, pulsed jets are able to achieve a similar level of flow control effect with less energy consumption (Gad-el-Hak, 2000; McManus & Magill, 1996), but they still require the complex piping system.

To circumvent the drawback incurred by the complex piping system while keeping all the other advantages of pulsed jets, a novel means of periodic excitation, i.e. synthetic jets (SJs), has been proposed for flow separation control (Smith & Glezer, 1998).

Like pulsed jets, SJs and SJ arrays are able to effectively delay flow separation, which has already been proved by many investigations in the laboratory and simulations on various aerodynamic models (Amitay et al., 1997; Dandois et al., 2007; Crook et al., 1999; Zhong & Zhang, 2013). As shown in Figure 2.3, the flow is almost fully reattached to the airfoil with the actuation of SJs. A number of researches have been conducted to obtain deep understanding of the fluid physics of single SJs and SJ arrays, in terms of

Figure 2.3: Contours of streamwise velocity from (a) uncontrolled flow and (b) flow controlled by SJs (Ye et al., 2006).

their performances in quiescent conditions, attached crossflows, and separated crossflows. Note that although there is a wide range of studies covering the SJs issued from various shapes of orifice, such as circular orifice (Cater & Soria, 2002; Crook & Wood, 2001; Zhong & Zhang, 2013), thin slot (high-aspect-ratio rectangular orifice)(Smith & Glezer, 1998; Smith et al., 1999; Dandois et al., 2007) and finite-span rectangular orifice (Shani et al, 2011), this literature survey is mainly focused on the investigations of single SJs and SJ arrays issued from circular orifices with necessary studies on the other shapes of orifices.

2.2 Synthetic jets (SJs) in quiescent conditions

Before the discussion on the behaviours of single SJs and SJ arrays in crossflows for the purpose of flow separation control, it is useful to understand their fundamental performance in quiescent conditions. In this section, dimensional analysis is first discussed. Non-dimensional parameters governing the performance of single SJs, and typical parameters that impact the behaviors of SJ arrays are discussed. Then, the understanding of formation and evolution of single SJs in quiescent conditions is presented. At last,

Figure 2.4: Schematic diagram of a SJ actuator.

investigations on the interactions between SJ arrays under various parameters are reviewed.

2.2.1 Dimensional analysis

Consider a typical SJ actuator, which has one circular orifice and one oscillating diaphragm as shown in Figure 2.4, the behavior of the SJ depends on eight parameters: 1) diaphragm oscillation amplitude, Δ ; 2) diaphragm oscillation frequency, f ; 3) orifice diameter, D_o ; 4) orifice depth or thickness, h ; 5) diaphragm diameter, D_d ; 6) cavity depth, H_c ; 7) fluid kinematic viscosity, ν ; and 8) fluid density, ρ . According to the Buckingham-Pi theorem, these parameters can be condensed into the following five independent, non-dimensional parameters that describe the actuator geometric and operating conditions (Zhong et al., 2007):

$$\pi_1 = f D_o^2 / \nu, \pi_2 = \Delta / D_o, \pi_3 = D_d / D_o, \pi_4 = H_c / D_o, \pi_5 = h / D_o$$

In principle, characteristics of a SJ at its orifice plane can be expressed by the five non-dimensional parameters. However, in practice, other dimensionless parameters are commonly used instead of some of the aforementioned parameters (Zhong et al., 2007; Jabbar & Zhong, 2010). They are related directly to the time averaged jet exit velocity,

and therefore make the actuator geometry implicit. They are the dimensionless stroke length L , the Reynolds number Re_L , the Strouhal number St_q in quiescent condition, and the Stokes number S .

The non-dimensional stroke length L describes the relative length of fluid column ejected during the blowing stroke (Zhong et al., 2007), and is found to be closely related to the formation and saturation of SJs (Holman et al., 2005; Gharib et al., 1998). L is defined as

$$L = \frac{L_o}{D_o} = \frac{\bar{U}_o}{fD_o} \quad (2.1)$$

where L_o is the stroke length representing the actual length of the fluid column, and $\bar{U}_o$ is the time-averaged blowing velocity over an entire actuation cycle T . If the fluid is assumed incompressible, it can be proved that $\bar{U}_o$ is linearly proportional to $\Delta f (\frac{D_d}{D_o})^2$ (Tang et al., 2007). Then, it is easy to obtain that

$$L = \frac{\bar{U}_o}{fD_o} \propto \frac{\Delta D_d^2}{D_o^3} = \pi_2 \pi_3^2 \quad (2.2)$$

The stroke length L_o based Reynolds number Re_L , is proportional to the total circulation ejected through the orifice during the blowing cycle (Zhong et al., 2007) and is defined as

$$Re_L = \frac{\bar{U}_o L_o}{\nu} \quad (2.3)$$

Hence Re_L is a useful indicator of the vortex strength (Tang & Zhong, 2006; Jabbal et al., 2006). Similar to L , Re_L can also be conveniently used to replace π_1 , π_2 and π_3 as

$$Re_L \propto \frac{f \Delta D_o^2}{\nu} \left(\frac{\Delta}{D_o}\right)^2 \left(\frac{D_d}{D_o}\right)^4 = \pi_1 \pi_2^2 \pi_3^4 \quad (2.4)$$

The Stokes number S is defined as the ratio of unsteady forces to viscous forces

$$S = \sqrt{\frac{2\pi f D_o^2}{\nu}} \quad (2.5)$$

Zhou et al. (2009) revealed that a minimum Stokes number is required for the roll up of SJ vortices. S can be expressed by L and Re_L as

$$S = \sqrt{2\pi \frac{Re_L}{L^2}} \quad (2.6)$$

Strouhal number in quiescent condition St_q , as a dimensionless frequency, characterizes the spacing and hence interaction of successive vortex structures (Jabbal et al., 2006), it can be defined as

$$St_q = \frac{fD_o}{\bar{U}_o} \quad (2.7)$$

By substituting Eqs. 2.7 into Eqs. 2.1, we obtain the relationship between St_q and L

$$L = \frac{L_o}{D_o} = \frac{\bar{U}_o}{fD_o} = \frac{1}{St_q} \quad (2.8)$$

It can be seen that the Strouhal number is the inverse of the dimensionless stroke length.

For SJ arrays in quiescent conditions, more parameters governing the multiple-SJs flow are introduced. Typically, they are non-dimensional jet-axis-distance d/D_o , phase difference $\Delta\phi$, jet-velocity ratio VR_j and jet-frequency ratio FR_j . Not like to single SJs in quiescent conditions, dimensional analysis of SJ arrays is insufficiently studied. And, only the first two parameters, d/D_o and $\Delta\phi$, have been preliminarily investigated in quiescent condition (Smith & Glezer, 2005; Waton et al., 2010; Greco et al., 2013). It is found that d/D_o mainly affects the strength of interactions between SJ arrays. Interactions can only happen within a certain upper limit of d/D_o (Smith & Glezer, 2005; Waton et al., 2010). $\Delta\phi$ governs the sequence of SJ arrays issued from the orifices, and is found to induce various flow structures at different $\Delta\phi$ (Smith & Glezer, 2005; Greco et al., 2013).

2.2.2 Formation and evolution of SJs in quiescent conditions

2.2.2.1 Formation of SJs

Many investigations have been undertaken to reveal the formation of SJs in quiescent conditions both experimentally and numerically. Holman et al. (2005) described SJs formation from a circler orifice as “during the expulsion portion of the cycle, a vortex ring can form near the orifice and, under certain operating conditions, convect away from the orifice to form a time-averaged jet”. According to the periodic movement of the diaphragm, different velocity profiles will be induced at the near orifice region, which is responsible for forming the SJs. In addition, the velocity variation and distribution are found to be significantly affected by the flow inside the SJ actuator (Rizzetta et al., 1999), as shown in Figure 2.5.

Figure 2.5: Comparison of instantaneous jet exit velocity profiles between from the modeling of the cavity flow (case 1-3) and from analytical descriptions (sin and flat top profiles) (Rizzetta et al., 1999).

Then, for circular SJs (issued from circular orifice), Holman et al. (2005) revealed the formation criterion of the dimensionless stroke length $L \approx 0.5$. Note that for consistence, parameters used in literatures are converted to the non-dimensional parameters defined in section 2.2.1 wherever possible. Milanovic & Zaman (2005) provided a even smaller criterion of $L = 0.25$ by observing the centerline velocity profiles of circular SJs. The formation criterion of plane SJs (issued from thin slot) was found to be $L > 1$ by Ingard & Labate (1950) and Smith et al. (1999). The discrepancy of these criteria is believed to be related to the geometry of the orifice lip. Holman et al. (2005) found that a smaller jet formation constant for orifices with a sharp exit as compared to those with a finite radius of curvature. This statement was also confirmed by Fugal et al (2005) who studied the formation of a plane SJ using numerical simulations and found that the threshold is about $L = 2$ for a sharp lip and about $L = 10$ for a rounded lip.

In addition, it is known that a criterion exists for saturation of a vortex ring. Gharib et al. (1998) found it to be $L \approx 4$ beyond which tails form behind the vortex ring. For the circular SJs, the experiments of Jabbar & Zhong (2008) showed that the upper threshold in quiescent conditions occur at $L = 4$, above which secondary vortices form due to

Figure 2.6: Saddle point showed by phase-averaged streamline maps (Glezer & Amitay, 2002).

the saturation of the vortex circulation within the primary vortical structure. However, Milanovic & Zaman (2005) observed that the upper threshold of saturation is $L = 5$.

2.2.2.2 Evolution of SJs

Glezer & Amitay (2002) found the near-field evolution of SJs is dominated by the periodic formation, advection, and interactions of discrete vortical structures. They found a stagnation point on the jet centerline downstream of the orifice to be generated by the periodical reversal in flow direction, indicating that the suction flow is confined within a finite region near the exit plane, as shown in Figure 2.6.

In the near field of a circular SJ actuator, Cater & Soria (2002) observed four different flow patterns of vortex rings at different Re_{U_o} and St_{U_o} in quiescent condition in a smoke visualization experiment. Here, $Re_{U_o} = U_o D_o / \nu$ and $St_{U_o} = f D_o / U_o$, where U_o is a characteristic velocity scale. With increasing the value of Re_{U_o} , they found that a sequence of “laminar rings” issued from SJ actuator turned to a “turbulent jet ” as shown in Figure 2.7.

Figure 2.7: Four different flow patterns of circular SJs: (a) laminar jet, $Re_{U_o} = 3336$, $St_{U_o} = 0.03$; (b) laminar rings, $Re_{U_o} = 7784$, $St_{U_o} = 0.012$; (c) transitional jet, $Re_{U_o} = 11121$, $St_{U_o} = 0.009$; (d) turbulent jet $Re_{U_o} = 66991$, $St_{U_o} = 0.009$. (Cater & Soria, 2002).

Figure 2.8: Flow patterns of (a) circular SJs and (b) equivalent continuous jet. (Cater & Soria, 2002).

In the far field of circular SJs, Cater & Soria (2002) found that the far-field behaviour of circular SJs is close to that of conventional turbulent round jet but with a larger spreading rate and decay constant, as shown in Figure 2.8. For a plane SJ, Smith & Glezer (1998) also found that, in the far field, the plane SJs is similar to conventional plane jet in terms of cross-stream distributions of the time-averaged velocity and the corresponding rms fluctuations. In addition, a larger decay constant of the mean centerline velocity of the plane SJs was found compared to conventional plane jet. But the spreading rate of the plane SJs was found to be lower, which is opposite to the case of circular SJs.

2.2.2.3 Interactions of SJ arrays

Compared to those on single SJs, investigations on SJ arrays in quiescent conditions are very limited. Existing research on the SJ arrays mainly focuses on the simplest SJ arrays, i.e. twin SJs, in which the effect of the non-dimensional jet-axis-distance, d/D_o or d/h_s (h_s width of a slot orifice), and phase different $\Delta\phi$ are studied.

Figure 2.9: Interaction between twin circular SJs in quiescent conditions at a) $d/D_o = 5.7$, b) $d/D_o = 2.3$, and c) $d/D_o = 1.7$. (Waton et al., 2010)

Non-dimensional jet-axis-distance is an important criterion for enabling interactions between neighbour SJs. Waton et al. (2010) studied the influence of d/D_o between twin circular SJs with no phase difference, i.e. $\Delta\phi = 0$, using smoke visualization in

a quiescent chamber as shown in Figure 2.9. They found that no obvious interaction happens at sufficiently large jet-axis-distance, i.e. $d/D_o = 5.7$. By reducing the distance d/D_o to 2.3, they visualized that adjacent SJs begin to alter their trajectory and move toward each other in the far field. Finally, at $d/D_o = 1.7$, they found an immediate interaction when these twin SJs are issued out from orifices resulting in a single distinct vortex ring. In phase opposition $\Delta\phi = \pi$ or 180° , Greco et al. (2013) found another criterion of $d/D_o = 1.1$ to generate obvious interaction between twin circular SJs by PIV measurement. For twin SJs from thin slots, Smith & Glezer (1998, 2005) found that obvious interactions happen at various phase difference at $d/h_s = 3$. The discrepancy of these criteria is believed to be related to the various actuating conditions and geometries of the actuators on which the behaviors of both circular SJs and plane SJs are largely dependent as discussed previously.

Figure 2.10: Contour maps of phase-averaged vorticity from the interaction between twin plane SJs at (a) $\Delta\phi = 0^\circ$ at $t/T = 0.17$ and (b) $\Delta\phi = 80^\circ$ at $t/T = 0.61$ (Smith & Glezer, 2005).

Within a sufficient small d/D_o that allows the interactions between adjacent SJs, the resulting flow patterns are reported to vary according to the phase difference $\Delta\phi$ between adjacent SJs. At $\Delta\phi = 0$ between twin circular SJs, Waton et al. (2010) observed from

Figure 2.11: Time-averaged flow field with vector arrows and contour for (a) single circular SJ, and (b) twin circular SJs at $\Delta\phi = 180^\circ$ (Greco et al., 2013). SJs are injected from left to right

their smoke observations that a single, large vortex ring is resulted and propagates away from the orifice as shown in Figure 2.9c. Similarly, for twin plane SJs, Smith & Glezer (1998, 2005) observed from their PIV measurements that the inner vortices of each vortex pair cancel each other, resulting in a single, larger SJ as shown in Figure 2.10a. When $\Delta\phi \neq 0^\circ$, Smith & Glezer (2005) found that the merged jet from twin plane SJs is tilted (vectored) toward the jet that is leading in phase from the observation of phase-averaged flow as shown in Figure 2.10b. The degree of vectoring increased with the phase angle until the merged jet flowed along the surface of the exit plane at $\Delta\phi > 110^\circ$. This behaviour was also confirmed by Hasnain & Flatau (2012) who reproduced the interactions using simulations. After the phase angle exceeded 120° , Smith & Glezer (2005) found the successive vortex pairs do not merge and the vortex pair that is lagging in phase begins to be influenced by the suction cycle at the adjacent orifice. In phase opposition, i.e. $\Delta\phi = 180^\circ$ or π , between twin circular SJs, Greco et al. (2013) found an almost merged jet on the symmetry axis of the time-average field, and its jet centerline velocity value is higher and the decrease rate is slower coupled with a smaller jet width compared to single SJ, as shown in Figure 2.11.

2.3 SJs in crossflows

2.3.1 Dimensional analysis

In the flow-separation-control applications, single SJs or SJ arrays are issued into a crossflow. Therefore, not only the SJ actuator and configurations of SJ arrays, but the external crossflow also influences their behaviors and hence their flow control effectiveness. For single SJs issued into an attached crossflow, the list of physical parameters described in section 2.2.1 on which the single SJ flow depends should be extended to include three more physical parameters. They are the local boundary layer thickness δ , the freestream velocity U_∞ , and the local wall shear stress τ_w (Zhong et al., 2007). Based on the dimensional analysis, the characteristics of the SJ at its orifice exit plane depends on the following dimensionless parameters,

$$\begin{aligned}\pi_1 &= fD_o^2/\nu, \pi_2 = \Delta/D_o, \pi_3 = D_d/D_o, \pi_4 = H_c/D_o, \\ \pi_5 &= h/D_o, \pi_6 = \delta/D_o, \pi_7 = fD_o/U_\infty, \pi_8 = \tau_w/\rho D_\infty^2\end{aligned}$$

Similar to the purpose of having the non-dimensional parameters like L and Re_L , in the discussion of single SJs in crossflows, a velocity ratio VR is often introduced to represent the relative strength between the SJ velocity and the freestream velocity of the attached crossflow (Zhong et al., 2007). The velocity ratio VR quantifies the ratio of the SJ velocity to the crossflow velocity as

$$VR = \frac{\bar{U}_o}{U_\infty} \quad (2.9)$$

Similar to the momentum coefficient used in many literature (Milanovic & Zaman, 2005), the velocity ratio determines the trajectory of SJs when they penetrate boundary layers (Zhong & Wood, 2005; Jabbar & Zhong, 2008): a small VR value indicates a trajectory closer to the wall. As $\bar{U}_o$ is linearly proportional to $\Delta f (\frac{D_d}{D_o})^2$ in incompressible flow (Tang et al., 2007), VR can then be used to replace π_2 , π_3 and π_7 as

$$VR \propto \frac{\Delta}{D_o} \left(\frac{D_d}{D_o}\right)^2 \frac{fD_o}{U_\infty} = \pi_2(\pi_3)^2\pi_7 \quad (2.10)$$

Therefore, five non-dimensional parameters are frequently used to exam the behavior of single SJs in a crossflow, i.e. the non-dimensional stroke length L , the stroke length based Reynolds number Re_L , the Stokes number S , the Strouhal number St in crossflows,

and the velocity ratio VR . Note that, when a crossflow is involved, the Strouhal number St is usually defined by bulk cross-flow velocity U_∞ as

$$St = \frac{fD_o}{U_\infty} = \frac{VR}{L} \quad (2.11)$$

St is used to describe the frequency of the SJ in the crossflow, mainly effects the spacing of successive SJ vortex structures in the crossflow direction (Zhong et al., 2007). The larger the St value, the smaller the spacing.

For the behaviors of SJ arrays in attached crossflows, besides the parameters discussed in section 2.2.1 for SJ arrays in quiescent conditions, more parameters are introduced. In total, there are five major parameters including non-dimensional jet-axis-distance d/D_o , phase difference $\Delta\phi$, jet-velocity ratio VR_j , jet-frequency ratio FR_j and yaw angle γ (the angle between the cross-flow direction and the line connecting the orifices of SJ actuators). Some of these parameters have been preliminarily investigated in existing research, and will be discussed in next section.

2.3.2 SJs in attached crossflows

Before investigating the flow control effectiveness of single SJs and SJ arrays in separated crossflows, it is a logical step to understand the interactions of SJs and SJ arrays with attached crossflows. The coherent vortex structures induced by single SJs and SJ arrays are given focus in this literature survey due to their capability of transporting free-stream momentum to the boundary layer hence delaying flow separation.

2.3.2.1 Single SJs in attached crossflows

The investigation of vortical structures produced by single SJs in attached crossflows includes examining the evolution of the structures and their influence on the near-wall flow. This is essential for obtaining an improved understanding of the interaction of single SJs with crossflows, and is helpful to find the desired vortical structures on delaying flow separation.

When a boundary layer is applied on SJs, crossflow speed and the local vorticity in the boundary layer impact the evolution of SJs. The influence of crossflow can be directly examined at various VR . Mittal & Rampunggoon (2001) simulated the interaction of a

Figure 2.12: Vorticity contours at the end of blowing for a plane SJ with VR equals (a) $+\infty$; (b) 0.95; (c) 0.21; (d) 0.10 (Mittal & Rampungoon, 2001).

Figure 2.13: Stereoscopic dye and surface liquid crystal images of a SJ at (a) hairpin vortices $VR = 0.14$, $L = 1.4$, (b) stretched vortex rings $VR = 0.27$, $L = 2.7$, (c) tilted/distorted vortex rings $VR = 0.5.1$, $L = 5.1$ (Jabbal & Zhong, 2008).

plane SJ with a laminar flat plate boundary layer at different velocity ratios, i.e. $VR = +\infty$ (quiescent external flow), 0.95, 0.21, and 0.10. Different behaviors of vortex pairs and SJ trajectory were recognized according to various VR as shown in Figure 2.12. They found that the decrease of VR results in the decrease of the orientation angle between the emerging vortex structures and the flat plate. In addition, a clear cancel-out of upstream vortex pair was observed at low VR case, due to the local vorticity in the boundary layer.

Different to the behaviours of plane SJs, vortex rings issued from circular SJ actuators are expected to have more 3D features. Zhong & Wood (2005) used dye flow visualization to study the nature of vortical structures produced by circular SJs in a LBL. Highly stretched hairpin vortices, stretching vortex rings and tilted/distorted vortex rings were

Figure 2.14: Iso-surface of $Q = 0.1$ showing (a) the hairpin vortices and (b) tilted vortex ring with accompanying structures (Zhou et al., 2009).

recognized according to different L and VR . Subsequently, Jabbal & Zhong (2008, 2010) observed three SJ-induced structures similar to that in Zhong & Wood (2005)'s work, together with their influence on the wall as shown in Figure 2.13. From their influence on the wall shear stress, both hairpin vortices and stretched vortex rings were believed to be potentially useful in flow separation control. Hierarchy of these coherent vortices were further revealed by Zhou et al. (2009). They examined the formation of hairpin structures and tilted-vortex-ring structures using their simulation results. For the hairpin vortices case, they revealed a hierarchy of coherent vortices consisting of primary hairpin vortices, secondary vortices and horseshoe vortex using Q -criterion (Hunt et al., 1988) in Figure 2.14a. For the tilted vortex ring case, the vortex ring was found accompanied by a pair of trailing vortices which further induced a pair of tertiary structures as shown in Figure 2.14b. From their simulation results of flow structures together with wall shear stress, they provided a further insight of the formation of the corresponding patterns of wall shear stress observed in Jabbal & Zhong (2008)'s experiment.

Compared to those on vortex structures induced by single SJs in LBL, investigations on single-SJ induced vortex structures in TBLs are very limited due to the increased level of complexity of experiments and simulations. Hairpin vortices induced by single

Figure 2.15: Vortex structure induced by single circular SJs in TBL, (a) Iso-surface of $Q = 0.2$ colored with streamwise vorticity, and (b) contours of time-averaged streamwise vorticity in a spanwise wall-normal plane (Javadi & El-Askary, 2011).

Figure 2.16: (a) Vortices generated by single circular SJs in TBL, and (b) contours of phase-averaged streamwise velocity in a wall-parallel plane (Javadi & El-Askary, 2011).

circular SJs are commonly identified responsible for enhancing mixing in a TBL (Dandois & Garner, 2006; Wu & Leschziner, 2009; Javadi & El-Askary, 2011). In their work of examining grid resolution and turbulent models, Dandois & Garner (2006) observed that the main structure induced by circular SJs in TBL in the near orifice region is the hairpin vortices as plotted by iso-surface of Q in Figure 2.15a. Using large eddy simulation (LES), Wu & Leschziner (2009) simulated a circular SJ issued into a fully turbulent flat-plate boundary layer at a momentum-thickness Reynolds number $Re_\theta = 2380$. These vortex structures had a hairpin shape and broke up into turbulent patches very soon. Furthermore, using iso-surface of vorticity, Javadi & El-Askary (2011) also captured a hairpin vortex issued from a circular SJ actuator into a TBL as shown in Figure 2.16a. In addition to the primary hairpin vortices, one pair of counter-rotating vortices attached to the wall were also observed below the main hairpin vortices with opposite vorticity signs by Dandois & Garner (2006) as shown in Figure 2.15b. Similarly, Wu & Leschziner (2009) also observed a pair of wall vortices formed underneath the primary streamwise-vortex pair. Furthermore, Javadi & El-Askary (2011) found that, similar to the hierarchy of hairpin vortices induced by SJs in LBL, secondary streamwise vortices formed at the lateral edges of the orifice, and horseshoe vortex at upstream of orifice are induced as shown in Figure 2.16b.

Besides the complex discrete flow structures induced by single SJs in crossflows, the trajectory of single SJs is found to inherit some features of continuous jet. For the single circular SJs in laminar crossflow, Gordon & Soria (2002) found that the least-square fitted parameters to the SJ jet trajectory equation, based on VR which is defined by maximum SJ velocity, are within the range of reported continuous jet values for these parameters. For the single circular SJs in a turbulent crossflow, Milanovic & Zaman (2005) also found that the trajectory of SJs shows similar behaviors to that of continuous jet and is majorally dependent on the VR^2 under same definition to Gordon & Soria (2002)'s work. Similarly, Jabbal & Zhong (2008) revealed that VR , defined by $\bar{U}_o$ as in section 2.2.1, indicates the trajectory of single SJs in LBLs as well as the orientation of emerging vortex structures.

2.3.2.2 SJ arrays in attached crossflows

Compared to single SJs in crossflows, the interactions between SJ arrays and attached crossflows has not been addressed with a sufficient level of details due to the increased level of complexity of experimental setup and simulation frameworks. Variation of actuating signals for each SJ actuator can lead to the change of phase difference $\Delta\phi$, jet-velocity ratio VR_j and jet-frequency ratio FR_j between neighbour SJs. Layout change of SJ arrays affects the non-dimensional jet-axis-distance d/D_o or d/h_s and yaw angle γ . Typically, there are two types of SJ array layout: the line connecting the orifices parallel to the cross-flow direction and perpendicular to the cross-flow direction. In current study, we name the first type of layout as in-line configuration $\gamma = 0^\circ$ and side-by-side configuration $\gamma = 90^\circ$ for the second type of layout. Limited investigations have been carried out to study in-line configuration or transitional configuration, i.e. $0^\circ \leq \gamma < 90^\circ$, of SJ arrays in attached crossflows (Waton et al., 2010; Liddle & Wood, 2005; Honami & Motosuke, 2012) due to the intensive induced interactions. Side-by-side configuration is often used to extend the spanwise influence of SJ arrays on separated crossflows.

Figure 2.17: Sketch of side and top-view of twin SJs at (a) $\Delta\phi = 54^\circ$ and (b) 108° (Honami & Motosuke, 2012).

If the layout of SJ arrays is fixed, difference of the actuating signals leads to various interactions. First, as a type of discrete jets, interactions between SJ arrays are largely dependent on the phase difference $\Delta\phi$ which governs the emerging sequences. Using

Figure 2.18: (first row) Time-averaged streamwise velocity contours at $x/Do = 25$ and (second row) PSD plots of hotwire anemometer output signal measured at $x/Do = 10$, $y/Do = 1$ for (a) $\Delta\phi = \pi/2$ or 90° and (b) $\Delta\phi = 3\pi/2$ or 270° (Liddle & Wood, 2005).

vorticity iso-surfaces, Honami & Motosuke (2012) plotted the interacting flow structures issued from in-line twin circular SJ actuators at two phase differences $\Delta\phi = 54^\circ$ and 108° as shown in Figure 2.17. They found that the vortex structure issued from downstream actuator (rear-jet in the figure) is strongly affected by the jet issued from upstream actuator (front-jet in the figure) due to the interaction between the longitudinal and transverse vortices, whereas the jet from upstream actuator keep more coherent structure in the interaction process compared with the jet from downstream actuator. Liddle & Wood (2005) examined the effect of more phase differences, i.e. $\Delta\phi = 0, \pi/2$ or $90^\circ, \pi$

Figure 2.19: Surface visualisation of twin SJs at yaw angle (a) $\gamma = 15^\circ$ and (b) $\gamma = 0^\circ$ (Liddle & Wood, 2005).

or 180° , $3\pi/2$ or 270° . They demonstrated from their PIV measurement and hotwire results that flow structures induced by twin circular SJs at $\Delta\phi = \pi/2$ have a impact on boundary layer with a highest penetration as presented in the first row of Figure 2.18a. On the other hand, flow structures induced at $\Delta\phi = 3\pi/2$ show greater interaction with the immediate near-wall flow as shown in the first row of Figure 2.18b. Also, their power spectral density (PSD) analysis of the downstream velocity histories showed distinct differences in the $\Delta\phi = 3\pi/2$ case, with a major peak at a value of twice the actuation frequency, compared with the three other cases in which the major peak occur at the actuation frequency, as demonstrated in the second row of Figure 2.18.

The jet strength difference VR_j between adjacent SJs is also an important parameter that impacts the interactions. Iai et al. (2010) studied the interactions of in-line twin circular SJs. VR_j was defined as a ratio of maximum jet velocity of SJs from downstream actuator to upstream one, and was within a range of $0.5 \leq VR_j \leq 1.33$. They found that the circulation of the jets is dependent on the velocity ratio VR_j . When the VR_j became larger, the higher level of circulation was obtained among the cases. But, the maximum vorticity had almost the same level among the cases except the further downstream locations more than $30Do$.

When the individual actuators are driven by same control signal, identical SJs are issued from actuator arrays at same time. As such, the yaw angle γ of SJ arrays according

to the crossflow direction, is found to be a major factor that impact the interactions within a sufficient small value of d/D_o (Waton et al., 2010; Liddle & Wood, 2005). Waton et al. (2010) carried out a preliminary study of flow interaction between a pair of circular SJs in crossflows at different γ using smoke and surface visualization. They suggested that, effect of the yaw angle could enhance, at $\gamma = 0^\circ$, or reduce, at $\gamma = 15^\circ$ and 45° , the amount of vorticity in the flow. By using surface visualization and 2D PIV measurement, Liddle & Wood (2005) also revealed that destructive interaction may happen at $\gamma = 15^\circ$. In addition, they also observed that the interaction at $\gamma = 15^\circ$ is wider in spanwise range compared to in-line configuration, with the focus of surface pattern slew towards the downstream actuator as shown in Figure 2.19.

2.3.3 SJs in separated crossflows

In controlling flow separation using SJs or SJ arrays, three possible mechanisms generally take place (Tang et al., 2014). First, extra momentum is directly added into the crossflow during blowing phase of SJ actuators, adding energy to the retarding boundary layer. Second, additional random turbulence is generated by the oscillation of SJs at frequencies in a certain range which influences the instability of the separated shear flow (Seifert & Pack, 1999; Kotapati et al., 2010). Third, the successive vortex structures are produced by SJs that promote the mixing in the boundary layer (Gad-el-Hak, 2000). Although these processes can happen independently, they are usually coupled in the applications of SJs and SJ arrays for delaying flow separation.

For the first two mechanisms above, momentum coefficient C_μ and the reduced frequency F^+ are important parameters and are extensively studied in most of existing research (Bhattacharjee et al., 1986; Hasan & Khan, 1992; Nishri, 1995). C_μ is the ratio between oscillatory momentum of SJs with bulk flow momentum indicating the forcing amplitude. For F^+ , there is a variety of definitions. For a 2D ramp, F^+ can be defined by the height of the ramp H_r as $F^+ = fH_r/U_\infty$ or the uncontrolled separation length L_s as $F^+ = fL_s/U_\infty$ (Dandois et al., 2007). For the application on airfoil, F^+ is usually defined by distance from SJ actuator to airfoil trailing edge.

Ozawa et al. (2010) found that the forcing frequency F^+ of a circular SJ, has stronger influence on its effective elimination of the separation bubble than the forcing amplitude

Figure 2.20: The reattached flow between two consecutive eddies induced by plane SJs operates at $F^+ = 0.14$ and $C_\mu = 1\%$, plotted by (a) Q -criterion isosurface and (b) pressure field and streamlines (Dandois et al., 2007).

C_μ . Furthermore, Dandois et al. (2007) also demonstrated that, with a proper choice of the oscillating frequency, separation can be drastically reduced at a momentum coefficient $C_\mu = 1\%$ as shown in Figure 2.20.

Compared to the studies of F^+ and C_μ , the discussion on the third mechanism, i.e. SJ-vortex-induced flow control, is much less. This issue is not trivial, and is believed to play an important role in enhancing mixing near the separated region and hence delaying separation (Gad-el-Hak, 2000; Greenblatt et al., 1996; Zhong & Zhang, 2013). From their LES simulation results, Dandois et al. (2007) found that plane SJ actuation strongly modified the separated flow by generating spanwise vortex. The flow was found to reattach between succession of induced vortices as shown in Figure 2.20. Complex flow structures are found to be induced by SJs issued from finite-span square orifices, which are responsible for delaying flow separation (Shani et al, 2011; Elimelech et al , 2011; Vasile & Amitay, 2013). Using both experimental and numerical methodologies, Shani et al (2011) studied three-dimensional flow structures and interactions of SJs issued from finite-span square orifices in crossflows on an aerofoil. They found that, at low value of VR , due to the finite span of the slot, small and organized secondary structures or a streak-like pattern is induced in the mean flow which is believed to play an important role in various flow control applications. When VR was increased, turbulent vortical structures were found to be dominant, leading to larger spanwise structures similar to what was found in Dandois et al. (2007)'s work.

Figure 2.21: (a) Oil flow visualization demonstrating the flow separation control of array of circular SJs (Wood et al., 2000) and (b) oil streaklines with corresponding flow topology of a streamwise vortex pair induced by a circular SJ on a cylinder (Crook, 2002).

Unlike plane SJs issued from thin slot or SJs from finite-span square orifices, which have been investigated extensively in separated flows on various aerodynamic models (Amitay et al., 1997; Amitay & Glezer, 2002; Dandois et al., 2007; Shani et al, 2011), the behaviours of SJs issued from circular orifices in separated flows is less studied. However, SJ issuing from an array of circular orifices can also be effective and are important in flow control application on civil aircraft scale (Zhong et al., 2007; Tang et al., 2007; Zhang & Zhong, 2011), they are more space saving and easily arranged. In addition, it was also reported that array of circular orifices is more effective in fluid mixing than a thin slot with same exit area (Kim et al., 2010). Due to the confined spanwise extent of circular SJs, they are expected to behave differently on interacting with a separated flow. For the application of circular SJ arrays on delaying separation, side-by-side configuration, $\gamma = 90^\circ$, is often used to expend the spanwise influence.

The ability of circular SJs for delaying TBL separation was proved by Wood et al. (2000) using array of side-by-side circular SJ actuators on a cylinder. As demonstrated in Figure 2.21a, separation line is obviously postponed with the actuation of SJ arrays. Furthermore, using oil streamlines, Crook (2002) obtained the footprint of streamwise

vortical structure that is responsible for delaying flow separation on the cylinder, as shown in Figure 2.21b. Based on that, a streamwise vortex pair was believed to be produced by the SJs in the separated TBL. These streamwise vortices are capable of entraining the high momentum fluid from outer region of the boundary layer to the near-wall region, and therefore enhancing fluid mixing and energizing the boundary layer to resist the separation. By correlating these footprints to near-wall impact of coherent structures induced by single circular SJs in an attached flow, Jabbal & Zhong (2008) further proposed that they are hairpin vortices and stretched vortex rings responsible for delaying the separation.

The above hypothesis is further confirmed by Zhang & Zhong (2010) by applying SJ arrays in a separated LBL. Using an array of side-by-side circular SJs for controlling laminar flow separation, they revealed that a delay in flow separation is associated with the presence of streaks of high streamwise velocity on the inclined plate. By linking the delayed flow separation and the near-wall impact of the coherent vortical structures produced by SJs (Zhou & Zhong, 2010), hairpin vortical structures was found to deliver the best flow control effect with the least energy consumption in Zhang & Zhong (2010)'s tests.

Hairpin vortices were also found to be responsible for delaying TBL separation by Zhang & Zhong (2011) and Zhong & Zhang (2013) as shown in Figure 2.22a. They built a more complete physical mode for flow separation delay which involves a hierarchy of vortical structures showed in Figure 2.22b. Note that both the primary hairpin vortices and the pair of streamwise vortices near to the wall are similar to what are observed in studies of SJs in an attached TBL as discussed in previous section 2.3.2 (Dandois & Garner, 2006; Wu & Leschziner, 2009; Javadi & El-Askary, 2011). Zhang & Zhong (2011) suggested that the induced streamwise vortex pair, which are found locate closer to the wall and persist during a substantial portion of the actuation cycle, provides the main mechanism of flow separation delay by producing a downwash motion, which bring relatively more energetic fluids towards the wall. Nevertheless, they also found the heads of the hairpin vortices located above play an important role by supplying high-momentum fluids from the outer portion to the inner portion of the boundary layer, which is subsequently brought to the near-wall region by the induced streamwise vortices.

Figure 2.22: Hairpin vortices induced by circular SJs with TBL separation: (a) iso-surfaces of $Q = 5$ coloured with streamwise vorticity, (b) a conceptual model of the vortical structures which produce the delay of flow separation (Zhong & Zhang, 2013).

2.4 Remarks

In this chapter, some existing investigations on the flow separation control methods have been reviewed, especially the research related to SJs. SJ actuator is a promising flow separation control technology due to its zero-net-mass-flux feature and capability of efficiently delaying separation. Related studies have improved the understanding of the behaviours of SJs in quiescent condition, attached and separated crossflows. Non-dimensional parameters were derived that govern the behaviours of single SJs in both quiescent conditions and crossflows. Under various values of these parameters, distinct vortical structures induced by single circular SJs in attached crossflows were recognized and their potential flow control effects were examined. Hairpin vortices induced by circular SJs in separated crossflows were further found to be efficient to suppress separation in both LBLs and TBLs. Compared to that on single SJs, investigations on the interactions of SJ arrays are very few, it was found that phase difference between adjacent SJs significantly impacts the interacting structures in both quiescent conditions and crossflows, and their influence on boundary layers.

However, issues remain unresolved, or at least are not fully resolved. These issues, from the author's point of view, are important for applying SJ technology in real world applications, which therefore requires a deeper understanding of the fluid mechanics of SJs and SJ arrays in crossflows. They also form the objectives of the present research. Firstly, many lab-scale-flow-separation-control experiments and simulations were only focused in LBLs, especially the fundamental studies on the SJ-vortex-boundary-layer interaction. For the real world applications, there is a need to investigate the characteristic of SJ-induced structures in a TBL. Although some existing researches had obtained interacting results about this issue, detailed information about the SJ-induced structures evolution in a TBL as well as the differences between their impact on a LBL and TBL still remain unaddressed. Secondly, SJ array induced vortices in crossflows are insufficiently studied. Although some existing studies revealed that the interactions of SJ arrays at various actuating conditions and configurations lead to more complex vortex structures than single SJs, a holistic picture of the resulting vortex structures is not obtained. Less attention was put on their accompanying structures, development and impact on boundary layers. Furthermore, the flow control effect of the vortex structures induced by SJ arrays is not addressed so far. In this thesis, the unaddressed issues are investigated to uncover more underlying physics associated with flow separation control using SJs. Note that, among distinct flow structures induced by single SJs in crossflows, hairpin vortices are mainly focused in this thesis. As hairpin vortices are of importance to TBLs (Acarlar & Smith, 1987; Zhou et al., 1996; Adrian, 2007), and are also found to be responsible for the flow separation delay using SJs (Zhang & Zhong, 2010, 2011).

Chapter 3

Methodology

Experiments and CFD simulations have been conducted in this research so as to investigate the characteristics of single SJs and SJ arrays in attached and separated crossflows. The experimental studies are focused on the twin SJ interactions in LBLs and also provide the validation data for current twin-SJ-LBL simulations which in return reveal more details of the interactions. In experiments, stereoscopic color dye visualization and 2D digital PIV are used to obtain qualitative flow patterns and quantitative information respectively. For the SJ arrays, twin SJ actuators are aligned in line with the crossflow direction, and phase difference $\Delta\phi$ between them are varied. Comparison of behaviors of single SJs in a LBL and a TBL is conducted by CFD simulations solely, and experiment is focused on the study of twin SJs. To validate the simulation of single SJs in different boundary layers, other existing experimental results are used. In both simulations and experiments, SJs are issued from circular orifice driven by a piston-movement diaphragm. Post-processing is conducted to identify the vortex structures using Q - and λ_{ci} criterions. Both POD analysis and DMD analysis of the PIV data are conducted to extract representative coherent structures from energy and dynamics aspects, respectively. In addition, particle tracking simulation using DPM is also conducted to further examine the interactions between twin SJs.

3.1 Dimensional analysis

The SJ actuator used in this thesis has a cylindrical cavity and circular orifice, as shown in Figure 2.4 Chapter 2. Its piston-type diaphragm oscillates in a sinusoidal manner, whose velocity can be described as

$$u(t) = \pi \Delta f \sin(2\pi f t) \quad (3.1)$$

As discussed in section 2.2.1 in Chapter 2, the time-averaged jet velocity $\bar{U}_o$ over an entire actuation cycle T needs to be firstly determined to calculate the non-dimensional parameters. If the working fluid is incompressible as in the present study, $\bar{U}_o$ can be estimated in terms of Δ and f from the piston movement of diaphragm from Eqs.3.1 (Tang et al., 2007)

$$\bar{U}_o = \frac{1}{T} \int_0^{T/2} u_o(t) dt = \Delta f \left(\frac{D_d}{D_o}\right)^2 \quad (3.2)$$

where Δ is the peak-to-peak diaphragm oscillation amplitude, f is the oscillation frequency, D_d is the diameter of the moving diaphragm and D_o is the diameter of the orifice. Then, five non-dimensional parameters used to examine the behavior of single SJs in a crossflow can be obtained, i.e. the non-dimensional stroke length L , the stroke length based Reynolds number Re_L , the Stokes number S , the Strouhal number St in crossflows, and the jet-to-crossflow velocity ratio VR .

For the study of SJ arrays, to make the present investigation more focused, some parameters of SJ arrays are fixed to simplify the analysis, such as twin-SJ actuators are aligned in-line to the freestream flow, i.e. $\gamma = 0^\circ$, jet-streamwise-distance $d/D_o = 2$, the velocity ratio between neighbour SJs $VR_j = 1$ and actuating frequency ratio $FR_j = 1$. As such, one more non-dimensional parameter is required to describe the resulting flow. That is $\Delta\phi$, the operational phase difference of the two SJ actuators. Therefore, including the five parameters that govern the behaviors of single SJs, there are in total six non-dimensional parameters that can be used to characterize the behavior of in-line SJs in crossflows. Note among the first five parameters, only three are independent as discussed in section 2.2.1 and 2.3.1 in Chapter 2, that is, if Re_L , St and VR are chosen as the independent parameters, L and S can be expressed as

$$L = \frac{VR}{St}, \quad S = \sqrt{2\pi \frac{Re_L}{L^2}} = \sqrt{2\pi Re_L \left(\frac{St}{VR}\right)^2} \quad (3.3)$$

Hence the behavior of the in-line twin SJs in crossflows in this thesis can be characterized by four independent non-dimensional parameters, i.e. Re_L , St , VR , and $\Delta\phi$.

Figure 3.1: Schematic of (a) the test plate for attached flow and (b) the twin SJ actuators (all numbers are in mm).

3.2 Experimental methodology

The experimental investigation is conducted in a water tunnel with a test section of 1 m (L) x 0.45 m (W) x 0.45 m (H). A uniform steady flow with a speed up to 0.2 m/s can be generated in the test section. Experimental methods are used to obtain both qualitative and quantitative information using stereo color dye visualization and 2D PIV measurement respectively.

3.2.1 Test rig setup and SJ actuators design

Two test plates with twin SJ actuators are designed for attached-flow and separated-flow studies respectively as shown in Figure 3.1 and Figure 3.2 as well as the corresponding coordinate systems. The test plate consists of 2 pieces of flat plates for study of twin SJs in attached flow (Figure 3.1a) and 4 pieces of plates for the study in a separated flow (Figure 3.2). All the plates have a 10 mm thickness and 430 mm width. These plates are joined using hinges, such that the angle between them is adjustable. As shown in Figure 3.1a and Figure 3.2, the most upstream horizontal plate is 600 mm long, with a 1:5 elliptical edge adopted on the upstream plate to prevent flow separation at the leading edge. In the study of twin SJs in attached flows, a flat plate with 150 mm length is added and the angle is fixed at 180° to the horizontal plate to simply extend the total length of the test plate to 750 mm as shown in Figure 3.1a. In the study of

Figure 3.2: Schematic of the test plate for separated flow (all numbers are in mm).

twin SJs in a separated flow, as shown in Figure 3.2, a transitional plate (in black) is added to the horizontal plate with a small upward angle of 3° (close side view in Figure 3.2) to introduce a smooth inclined angle. The transitional plate is about 60 mm long, and is specially designed to bend upwards with a 5° angle at 10 mm downstream from its upstream edge to introduce obvious flow separation. A third flat plate with 150 mm length is connected to the downstream edge of the transitional plate, and therefore is inclined to the horizontal plate with 8° upward angle. In such a case, the boundary layer developing along the horizontal plate will separate at some point along the inclined plates, creating a separation region to which flow control with in-line SJs can be applied. At most downstream, a 150-mm-long flat plate is attached. The incidence angle of this plate can be adjusted to ensure the boundary layer attaching to the horizontal plate (Zhang & Zhong, 2010). In addition, waterproof paper with $50 \mu\text{m}$ thickness is used to cover the gap between plates to ensure smooth transition.

As depicted in Figure 3.1a, the origin of the coordinate system used in the study of twin SJs in attached crossflows is set at the midpoint of twin orifices, with the x axis pointing to the crossflow flow direction, y axis downward, and z axis to the spanwise

Figure 3.3: Schematic of synchronization system.

direction. In the study of twin SJs in a separated flow, the coordination is same to that in attached flow except for the origin of the coordinate system is set at middle point on the joint of the transitional plate (where 5° angle happens) as shown in Figure 3.2, after which flow separation is observed. Therefore, the origin is close to 140 mm, i.e. $28D_o$, downstream from the midpoint of twin orifices.

As shown in the side view of Figure 3.1a, two SJ actuators are mounted on the test plate, with their cavities located on the upper surface of the test plate and their orifices flush to the lower surface. Each SJ actuator has a cylindrical cavity with an orifice plate at its bottom side and a moving diaphragm clamped to its top side, as depicted in the close view in Figure 3.1b. In the present study, the orifices of the two SJ actuators have a diameter of $D_o = 5\text{mm}$ and a depth of $h = 5\text{mm}$. They are not located at the centerline of their respective cavities in current experiment. Instead, they are designed to be close to each other, with the center-to-center distance fixed at $d = 10\text{ mm}$, i.e. $d/D_o = 2$. The centers of these two orifices are aligned in line with the crossflow direction, i.e. $\gamma = 0$, and their midpoint is located at 470 mm downstream from the main horizontal plate's leading edge. The cavities have a diameter of $D_c = 82\text{mm}$ and a depth of $H_c = 25\text{mm}$. The diaphragm of the SJ actuators is made of a thin rubber sheet sandwiched

by two metal plates of diameter $D_d = 45$ mm, whose center is attached to a permanent magnetic shaker (LDS V201 from Brüel & Kjær) via a steel rod. A 2.5 mm gap between the moving metal plates and their surrounding base plates ensures a piston-like motion of the diaphragm.

When both the SJ actuators are in operation, the oscillation amplitude and frequency of their diaphragms are controlled by two synchronized sine wave signals using LabVIEW which are amplified by power amplifiers (PA25E-CE from Brüel & Kjær). The operational phase difference between these two SJ actuators can be tuned with a resolution of 1° . To read the oscillation amplitude, the motion of the diaphragm is measured using an eddy current displacement sensor (ECL202 from Lion Precision). When PIV is used for measurement, TTL signal is also generated to synchronize the PIV timing controller and SJ actuators. The synchronization system is showed in Figure 3.3.

3.2.2 Stereo color dye visualization system

The marking of patterns in a flowing liquid by means of dye can be achieved by injecting the dye into the liquid or by generating it with an appropriate chemical reaction in the liquid (Merzkirch, 1987). Between these two methods, the first one is used for flow visualization in this thesis. The dye can be released either from a small ejector tube placed at a desirable position in the flow field or from small orifices. In this thesis, the dye is released in the SJ actuator cavity and injected into the crossflow during the blowing phase. A dye suitable for the visualization of flow patterns has to fulfill a number of requirements. Besides some general properties that apply to any foreign material used for flow visualization (e.g., noncorrosive) there are mainly three conditions that dye should meet, i.e. neutral buoyancy, high stability against mixing, and good visibility (Merzkirch, 1987).

A dye is neutrally buoyant if it has the same specific weight as the working fluid, in current cases, water. This can be met by mixing the prepared dye with alcohol. However, under the action of inertial or centrifugal forces, the mixing dye filaments can also either decay or not indicate the true flow direction. The latter problem is minimized if the dye solution can be prepared by complete dilution of the dye (food coloring in current study) in the water (Merzkirch, 1987). As the dye propagates in the flow, mixing with

Figure 3.4: Schematic of the stereoscopic dye visualization system.

the working fluid can make the dye lose clarity and rapidly decay. It restricts this method mainly to laminar flows or low fluid velocities. Good visibility is achieved by choosing the dye colour that is most contracts to the background color with sufficient light. In addition, if multiple colour dyes are used, the contract between these dye colors should also be taken into consideration.

In current studies, to visualize and differentiate twin SJs in the crossflow, food dye of two different colors is used to fill the SJ actuators. The upstream SJ actuator is filled with red dye and the downstream SJ actuator filled with green dye to make sharp contract between twin SJs with a white color background. At the blowing phase of diaphragm movement, dye will be ejected to the crossflow through orifices. The dye is premixed with methanol to achieve a density very close to water's and sufficiently diluted with working water. In the experiments, a color high-speed camera (MotionBLITZ EoSens) is used to capture the dye pattern produced by the SJs from the side view, and a DSLR camera (Cannon EOS 60D) is used underneath the water tunnel test section to capture the dye pattern from the plan view as depicted in Figure 3.4. Both the cameras work at the same frame rate of 60 fps, providing a quasi-three-dimensional dye visualization of the twin SJs.

3.2.3 PIV measurement system

Besides the qualitative flow patterns captured by dye visualizations, quantitative information, i.e. the interactions of twin SJs and their impact on a boundary layer as well as their flow control effect on a separated flow, need to be obtained. Therefore, 2D digital PIV is used for flow field measurement and provides validation data for corresponding CFD simulations in this thesis. Its principle and implementation have been introduced by Raffel & Willert (2007). The following section will briefly describe PIV and its implementation in current research.

3.2.3.1 Principle of PIV

PIV is based on the simple equation that speed equals to travel distance divided by time taken. A PIV system typically consists of several sub-systems. Particles need to be added to the flow for tracking the fluid movement. With the help of optics, laser is used to illuminate the scattered particles in a plane of the flow at least twice within a short time interval Δt . The light reflected by the particles has to be recorded by cameras either on a single frame or on a pair of frames. The displacement of the particles between the time interval Δt can be determined using standard procedures. If both exposures of laser were captured on the same frame, a process called auto-correlation was used for this procedure. However, the flow direction is not clear if using this correlation method. Most often, PIV recordings are evaluated by cross-correlating two frames of single exposure of the tracer ensemble which is used in current experiment. Therefore, cross-correlation procedure will be only discussed in the following sections. After obtain the raw vector map, sophisticated post-processing is required to handle the great amount of velocity data.

Before calculating velocity information from the PIV recording, the image pairs are firstly divided in small sub-areas called “interrogation areas” (IA), as shown in Figure 3.5a. The averaged displacement vector of the tracer particles in the first and second frame is determined for each IA by means of cross-correlation procedures. A displacement vector map can be obtained by performing this procedure throughout the whole images for all IAs. In order to speed up the process of correlation, this calculation is generally computed numerically by means of efficient fast Fourier transform (FFT) algorithms.

Figure 3.5: (a) PIV raw image with zoom-in IAs (b) the velocity map processed from PIV raw image pair.

The vector of local flow velocity map is calculated from division of the displacement vector map from the light sheet by the time interval Δt while taking magnification factor into account.

As the cross-correlation procedure can always produce results no matter the recording image conditions, there are some necessary rules of thumb to be followed for obtaining meaningful results. First, the size of the particles should occupy more than 2 pixels in the recorded images. In addition, the minimum number of particles within each IA for the cross-correlation processing should be about 5 (Raffel & Willert, 2007). It is generally recommended to keep the maximum displacement of the particles below a quarter of the side of the IA (Keane & Adrian, 1992). Based on this rule, the maximum velocities and the time interval between two consecutive pulses then can be calculated.

The raw vector maps produced from cross-correlation need to be post-processed because some vectors are incorrect due to the noise signals which are also termed as outliers.

Figure 3.6: Schematic of setup for PIV measurement at a spanwise plane.

Typically, there are three validation methods: peak-height validation, velocity-range validation and moving-average validation. The purpose of validation methods is to recognize, reject and remove these outliers and possibly substitute other vectors instead of the rejected vectors. The substituted vector is estimated from the surrounding measured vectors. Then, the vector maps are ready for fluid dynamics processing, as shown in Figure 3.5b.

3.2.3.2 Experimental procedures for PIV measurement

In current experiment, to facilitate the PIV measurements, the entire water tunnel is seeded with Dantec Dynamics polyamide seeding particles with a mean diameter of $20\ \mu\text{m}$ and density of $1030\text{kg}/\text{m}^3$. According to the Stokes drag law, the settling velocity of these particles is about $7\ \mu\text{m}/\text{s}$, much lower than the crossflow speed. This suggests that the buoyancy neutral seeding particles are capable of following the flow accurately (Hjelmfelt & Mockros, 1966; Mei, 1999). As shown in Figure 3.6, a laser sheet of approximately $1 \sim 2\ \text{mm}$ thickness is generated by a 200 mJ double pulsed Nd:YAG laser generator to illuminate the seeding particles. A FlowSense 2M CCD camera with a Nikon

Figure 3.7: Photo of setup for PIV measurement at mid-span streamwise plane.

105mm/60mm lens is used to capture fields of view at different conditions. The resulting velocity vectors are resolved using a two-frame cross-correlation algorithm, in which a 32×32 pixel or 16×16 pixel (IA) with an overlap ratio of 50% is used for different measurement. Although the laser could achieve higher frequency up to 15Hz, the actual measurements are taken at the frequency of 8Hz. As in the PIV measurement, SJ actuator is actuated at 2Hz. In order to capture sufficient flow fields, i.e. 8 frames, in one actuating cycle in current study, 2 runs of PIV measurement are conducted for one case. The first run of PIV measurement begins at certain phase of actuator diaphragm movement controlled by LabVIEW program as presented in Figure 3.3. And, 4 pairs of PIV images per actuating cycle are captured. Then, control single of PIV measurement is shifted and delayed by 45° to start the other run. Therefore, there are totally 8 pair of PIV images during one actuating cycle. The software, FlowManager from Dantec dynamics, employs the standard cross-correlation technique and the cross-correlation peak could be resolved with a sub-pixel accuracy of approximately 0.1 pixels. A photo in Figure 3.7 shows more clearly the setup of a PIV measurement on mid-span streamwise plane with the test plate in the water tunnel.

3.2.3.3 Uncertainty analysis for PIV measurement

Errors associated with digital PIV algorithms often are decomposed into two components: mean bias error and RMS (random) error (Huang et al., 1997). By satisfying the constraints of PIV measurements and careful alignment, i.e. interval time, particle size, and particle concentration, it is possible to make valid measurements in over 90~95% of the IAs with small bias errors. With the peak-compensation technique in the process of correlation peak detection (Huang et al., 1997), the mean bias error could be reduced to be negligible, i.e. one magnitude less compared to the RMS error. Therefore, the RMS error becomes the only major error in the present PIV measurement. It is also found that RMS error is affected by the IA size, particle displacement as well as seeding density (Willert & Gharib, 1991). In a 32×32 pixel IA, while particle displacement is less than 8 pixels with 6 particles per IA which is close to the setup of current PIV measurement, RMS fluctuation is found to be about 0.08 pixels (Willert & Gharib, 1991; Gao, 2011), as shown in Figure 3.8. Therefore, the overall uncertainty of the measured velocity components e_{total} is about $0.08 \text{ pixels} / 8 \text{ pixels} = 1\%$. A standard central difference scheme is used to calculate the vorticity,

$$\omega_{i,j} = \frac{v_{i+1,j} - v_{i-1,j}}{2\Delta x} - \frac{u_{i,j+1} - u_{i,j-1}}{2\Delta y} \quad (3.4)$$

and the corresponding error propagation is calculated using standard derivation under the assumption of $\Delta u = \Delta v$ and $\Delta x = \Delta y$, as

$$\Delta\omega = \frac{\Delta u}{\Delta x} = \frac{U \times e_{total}}{\Delta x} \quad (3.5)$$

where U is the field velocity and Δx is the measured grid dimension (Raffel & Willert, 2007). In a 32×32 pixels IA with 50% overlap, the uncertainty in velocity measurement is estimated at $e_{total} = 1\%$ as discussed above, which results in $\Delta\omega = 0.7s^{-1}$. In the region of SJ-induced-vortex head, it is found that the maximum vorticity is about $\omega \approx 48s^{-1}$. Therefore, the uncertainty in the derived vorticity results is about 3.3% (Gao, 2011). With a 16×16 pixel IA, RMS error of velocity components is increased by a factor of approximately 2 (Willert & Gharib, 1991), as such, uncertainty in velocity and vorticity measured from corresponding flow fields is increased to 2% and to 5.6% respectively. According to previous studies (Jabbal & Zhong, 2010; Zhang & Zhong, 2010), 60 and 120 image pairs are used to get the phase-averaged flow field for SJs in attached LBL and separated LBL, respectively.

Figure 3.8: Measurement uncertainties of PIV with respect to uniform spatial shift and seeding density (Adapted from Willert & Gharib (1991)).

3.3 Numerical methodology

To obtain 3D detailed information of SJ-induced structures, 3D CFD models are also built to simulate the behaviours of single SJs in LBL and TBL as well as twin SJs in LBL.

3.3.1 Governing equations and their discretization

For SJ-LBL simulations, the unsteady incompressible Navier-Stokes (N-S) equations are directly solved

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (3.6)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = \nu \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{1}{\rho} \frac{\partial p}{\partial x_i} \quad (3.7)$$

where p is the pressure, ρ and ν the assumedly constant, uniform density and kinematic viscosity of the working fluid respectively.

For CFD simulations on SJs in TBL, LES is used in current numerical simulation of SJs in a TBL. Turbulent flows are characterized by eddies with a wide range of length and time scales. Direct numerical simulation (DNS) is able to resolve the whole spectrum of turbulent scales without any modeling. However, the computational cost required for DNS is usually very high, especially for high Reynolds numbers flows. Although unsteady Reynolds-averaged Navier-Stokes (URANS) modeling can simulate turbulent

flow with much less computational resources, it cannot predict turbulent quantities well for SJs in turbulent crossflows and usually underpredicts turbulent fluctuations (Dandois & Garner, 2006; Javadi & El-Askary, 2011). It is suggested that LES would be the appropriate way, which can provide more details of the flow structure than URANS, while costs less computational resource than DNS (Dandois & Garner, 2006; Javadi & El-Askary, 2011). In LES, small eddies are modeled, while large eddies are resolved directly. Resolving only the large eddies allows one to use much coarser mesh and larger time step values in LES than in DNS. After filtering the time-dependent N-S equation, the governing equation is solved in LES. The filtering process filters out the eddies whose scales are smaller than grid spacing used in simulation. The finite-volume discretization implicitly provides the filtering operation:

$$\bar{\Phi}(x) = \frac{1}{V} \int_V \Phi(x') dx', x' \in V \quad (3.8)$$

where $\bar{\Phi}(x)$ is the filtered variable, V is the volume of a computational cell. By filtering the incompressible N-S equations, one obtains that (Sagaut, 2006)

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (3.9)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) = \nu \frac{\partial}{\partial x_j} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} - \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} \quad (3.10)$$

where τ_{ij} the subgrid-scale stress defined by

$$\tau_{ij} \equiv \rho (\overline{u_i u_j} - \bar{u}_i \bar{u}_j) \quad (3.11)$$

The subgrid-scale stresses, τ_{ij} , are unknown and require modeling. The Boussinesq hypothesis (Hinze, 1975; Erlebacher, 1992) is employed to compute subgrid-scale turbulent stresses in current incompressible flows from

$$\tau_{ij} \approx -2\mu_t \bar{S}_{ij} \quad (3.12)$$

where μ_t is the subgrid-scale turbulent viscosity, $\bar{S}_{ij}$ is the rate-of-strain tensor for the resolved scale defined as

$$\bar{S}_{ij} \equiv \frac{1}{2} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (3.13)$$

To model μ_t , Wall-Adapting Local Eddy-Viscosity (WALE) (Nicoud & Ducro, 1999) model is used in current LES simulation of single-SJ in TBL. Although Smagorinsky model (Smagorinsky, 1963) based on isotropy of the small-scale assumption has been broadly used because of its simplicity and accuracy, it does not have the versatility for various flow fields (Javadi & El-Askary, 2011; Ozawa et al., 2010). In the dynamic Smagorinsky-Lilly model (Germano et al., 1996), the Smagorinsky model coefficient is dynamically computed and varies in time and space over a fairly wide range. Although the Smagorinsky model and dynamic Smagorinsky-Lilly model are widely used, they give the nonphysical behaviour of μ_t near the wall (Nicoud & Ducro, 1999; Mathey et al., 2006). The WALE model is based, instead, on the symmetric part of the square of the velocity gradient tensor which is designed to return the correct wall asymptotic behavior for wall bounded flows.

In the SJ-LBL simulations, the N-S equations are discretized using the second-order implicit scheme in time and using the second-order upwind scheme in space. The Pressure-Implicit with Splitting of Operators (PISO) method is employed for pressure-velocity coupling. In the SJ-TBL simulations, the filtered N-S equations are then discretized by a bounded central differencing scheme in space to restrain unphysical oscillations, and by a second-order implicit scheme in time.

3.3.2 Computational geometry and mesh

The dimensions of the domain for single SJs in boundary layers are $75D_o$ in streamwise (x) direction, $30D_o$ in wall-normal (y) direction, and $20D_o$ in spanwise (z) direction as shown in Figure 3.9a. The origin of the coordinate systems is set at the center of the SJ actuator orifice exit, which locates in the mid-span plane and $15D_o$ downstream from the inlet of the computational domain. The coordination is set as the x axis pointing to the crossflow flow direction, y axis upward, and z axis to the spanwise direction. Although not shown in this figure, the SJ actuator is included in the simulations, whose orifice axis is along y axis, i.e. perpendicular to the boundary layer flows, as shown in Figure 2.4 Chapter 2. According to previous experimental work of Jabbal et al. (2006) which is also used to validate current frameworks of single-SJ-LBL simulation, it has a circular diaphragm with a diameter of $D_d = 45\text{mm}$, and a cylinder cavity with a height of H_c

Figure 3.9: Computational geometry and boundary conditions for (a) single SJs in LBL and TBL and (b) twin SJs in LBL.

Table 3.1: Mesh information for the single-SJ simulations.

Domain	Cavity	Orifice	Out flow domain	Total
Mesh number	100 x 80 x 90	40 x 30 x 30	280 x 100 x 120	3,760,520

$= 25\text{mm}$. Its orifice has a circular shape with diameter $D_o = 5\text{mm}$ and a depth of $h = 5\text{mm}$. In the present study, both the single-SJ-LBL and single-SJ-TBL simulations use the same set of mesh for convenience. As shown in Table 3.1, the total mesh number is about 3.8 million. With this mesh, the TBL is resolved with $y^+ \approx 0.5$ in the wall-normal direction, $x^+ \approx 1$ in the streamwise direction, and $z^+ \approx 1$ in the spanwise direction. The mesh gradually becomes coarser in regions away from the wall and from the SJ and its wake. This mesh is more than enough for the LBL case. Zhou et al. (2009) used a set of mesh less than 1.5 million cells to simulate a SJ-LBL case with a half of the current domain and similar SJ actuator operating conditions. In their mesh sensitivity study, three different sets of mesh density are examined. The coarse density is about half of that in current research, the medium one is close to current setup, and the fine density is about two times of current setup. It is found that the difference between medium mesh and fine mesh is only 1%. Their mesh sensitivity study indicated that this amount of mesh cells achieves the mesh convergence.

Due to the large number of cases in the study of twin SJs in LBL and in order to focus on the flow field where intensive interaction happens after the orifices ($x < 20D_o$), the

domain of twin-SJ-LBL simulations is reduced to $40D_o$ from the center of twin orifices to downstream outlet boundary, while the other geometries of the external crossflow domain are kept same to single-SJ simulations, as shown in Figure 3.9b. The geometry of actuators and configurations are set same to current experiment as discussed in section 3.2 except that the round geometry of the cavities and diaphragms is replaced by a simple square geometry with same area, due the increased difficulty in creating the mesh. The coordinate system of twin-SJ-LBL simulation is same to that of single SJ simulations, except for the origin is set at the middle point of twin orifices as shown in Figure 3.9b.

Figure 3.10: Variation of SJ actuator diaphragm velocity in an actuation cycle.

3.3.3 Solver and boundary conditions

A commercial CFD code, ANSYS FLUENT 13.0, is utilized to solve the unsteady 3D incompressible N-S equations. The boundary conditions are set same for all current simulations, i.e. single-SJ-LBL, single-SJ-TBL and twin-SJ-LBL, as depicted in Figure 3.9. The pressure outlet condition is applied at both the outlet on the right and the top surface of the flow domain. The periodic condition is employed on both lateral sides

to allow the flow to freely go in and out of the computational domain in the spanwise direction. The no-slip condition is applied on the flat plate at the bottom as well as on the SJ actuator orifice and cavity walls. Instead of using a realistic moving boundary condition, a time-dependent velocity boundary condition as described in Eqs. 3.1 is utilized at the neutral position of the SJ actuator diaphragm. During an actuation cycle, $t/T = 0$ (and 1), $1/4$, $1/2$, and $3/4$ correspond to the beginning of blowing, maximum blowing, beginning of ingestion, and maximum ingestion, respectively, as depicted in Figure 3.10. At the inlet of the flow domain on the left, a Blasius velocity profile is applied in the LBL case. In the TBL case, the mean velocity profile obtained from a set of PIV data (Zhong, 2012) is employed, which is superimposed by perturbations from a fluctuating vorticity field (Sergent, 2002). The turbulence intensity is set as 3% according to experimental result.

The time stepping for single-SJ-LBL and single-SJ-TBL simulations are set as 120 steps per actuation cycle, which is adequate for the single-SJ-LBL case according to the previous study by Zhou et al. (2009). For the single-SJ-TBL case, the time interval from this setting (4.2 ms) is even smaller than the Kolmogorov time scale (5.4 ms) that is estimated based on the TBL thickness and freestream velocity. Hence the current time stepping is believed to be capable of capturing the evolution of turbulence structures. For the twin-SJ-LBL simulations, more time steps are used as 240 during one cycle due to the complex interactions and to capture detailed movement of tracking particles.

The simulation data for the SJ-LBL case are taken after 40 actuating cycles, when the flow becomes stable. The data from a selected cycle are used to process the instantaneous and time-averaged flow information. For the single-SJ-TBL case, 150 actuation cycles are run to achieve stable status for the background TBL flow, after which the SJ actuator is enabled. The single-SJ-TBL flow becomes stable after another 100 cycles. An additional 50 cycles are then run to obtain the phase-averaged and time-averaged flow information using a commercial software Tecplot.

3.3.4 Validation

To validate the single-SJ-LBL and twin-SJ-LBL simulation frameworks, the PIV data obtained from Zhou et al. (2009) and current experiments are used for comparison. In

Figure 3.11: Comparison of instantaneous and time-averaged streamwise velocity profiles from single-SJ-LBL simulation with the PIV data extracted from the publication of Zhou et al. (2009). δ is the local boundary layer thickness.

Figure 3.12: Comparison of instantaneous and time-averaged streamwise velocity profiles from twin-SJ-LBL simulation at $\Delta\phi = 0^\circ$ with the PIV data obtained from current experimental results. δ is the local boundary layer thickness.

Figure 3.13: Comparison of (a) mean streamwise velocity U^+ (solid symbol: PIV data (Zhong, 2012), hollow symbol: current LES simulation, lines: theoretical predictions) and (b) velocity fluctuations (lines: DNS (Spalart, 1988), symbols: current LES), where u'^+ and v'^+ are streamwise and wall-normal velocity fluctuations, respectively. All the velocities are normalized by friction velocity. The peak difference is found to be about 8.8% in the fluctuation profiles.

experiment described in Zhou et al. (2009)'s publication, although the SJ actuator has the same geometry as in current single-SJ-LBL simulation, the freestream velocity is $U_\infty = 0.05$ m/s, and the diaphragm oscillates with $\Delta = 0.5$ mm and $f = 1$ Hz. Therefore the flow and SJ actuator operating conditions are adjusted accordingly in the simulation. Twin-SJ-LBL simulation framework is validated by current experimental data collected under the freestream velocity $U_\infty = 0.11$ m/s, the actuator diaphragm oscillation $\Delta = 0.105$ mm with $f = 2$ Hz and no phase difference between these two actuators as $\Delta\phi = 0^\circ$. Figure 3.11 and Figure 3.12 compares the instantaneous and time-averaged streamwise velocity profiles at $x = 3D_o$ in the mid-span plane from single-SJ-LBL simulation and $x = 4D_o$ from twin-SJ-LBL simulation to PIV results respectively. The peak difference in the time average sense is found to be about 8% and 4% respectively. The reasonably good agreements between the simulation results and the experimental data prove the capability of the current simulation framework in reproducing the SJ-LBL interaction flow field.

For the single-SJ-TBL case, the background TBL flow is simulated first before introducing the SJ. The freestream velocity is $U_\infty = 0.1$ m/s, and the Reynolds number based

Figure 3.14: Instantaneous turbulence structures in the TBL. The vortex structures are identified using iso-surfaces of $Q = 25$.

Figure 3.15: Comparison of FFT spectra of wall shear stress at $x = 1D_o$ from two selected periods of time. The difference between the spectrum peaks is less than 2%.

on the momentum thickness is set as $Re_\theta = 420$, and the boundary layer thickness is about $6D_o$ at orifice exit. After the flow is stable, the mean streamwise velocity profile from LES simulation at $x = 3D_o$ in the mid-span plane is compared with the PIV data (Zhong, 2012) as well as the theoretical predictions, as shown in Figure 3.13a. The good agreements in both the viscous sublayer and log layer demonstrate the capability of the current simulation in predicting TBL mean velocities. Due to the lack of fluctuation information from the PIV data, the profiles of the normalized velocity fluctuations, i.e. u'^+ , v'^+ and $u'v'^+$, in the mid-span plane from the present simulation are compared with the DNS results obtained in a zero-pressure-gradient TBL at a slightly lower Reynolds number $Re_\theta = 300$ from Spalart (1988). Figure 3.13b shows that the simulation is able to capture the key features of the velocity fluctuation profiles in terms of the trend, peak value and location of peak. The agreements in near wall region are particularly good, meaning the current mesh and time step setup is fine enough to resolve the small-scale dynamics in the TBL viscous sublayer. The instantaneous turbulence structures in the TBL are presented in Figure 3.14 using a Q value of 25 based on the Q -criterion (Hunt et al., 1988). As expected, the turbulence structures are not only introduced from the inlet but also generated from the wall. The production of auto-generated hairpin vortices validates the sustainability of the simulated TBL. Once the current simulation framework for the background TBL is validated, the SJ is introduced. The wall shear stress at $x = 1D_o$ in the mid-span plane are processed using FFT. As shown in Figure 3.15, two peaks are captured at frequencies of 2 Hz and 4 Hz, which are the SJ actuating frequency and its multiplication, respectively. The magnitudes of the peaks from two periods are compared, and difference of less than 2% is obtained. This confirms that the simulation achieves its statistically stable status within the first 100 cycles. According to this result, the SJ-TBL data starting from the 100th SJ actuation cycle will be used for the analysis hereafter.

3.4 Data analysis methods

The velocity fields obtained from both PIV measurements and numerical simulations need to be post-processed to better reveal the SJ-induced flow structures. Post-processing methodologies used in this thesis are presented in this section.

3.4.1 Vortex identification

To outstanding the SJ-induced flow structures from background flow field, some criteria can be used for identification vortex, as Q (Hunt et al., 1988), λ_2 (Jeong & Hussain, 1995), Δ (Chong, 1990), and λ_{ci} (Zhou et al., 1999). However, no single definition of a vortex is currently universally accepted, despite that vortices are still an important concept in fluid dynamics (Chakraborty, 2005). In this thesis, the Q -criterion is used to capture the vortices from 3D flow fields of CFD results because it is a good compromise between computational cost and quality (Dandois & Garner, 2006). In 2D flow fields obtained from PIV measurement, λ_{ci} is used to define the edge of vortices and their locations.

For an incompressible flow, the Q criterion identifies vortices with positive second invariant of ∇u defined as

$$Q = 0.5(\|\Omega\|^2 - \|S\|^2) \quad (3.14)$$

where $\|\Omega\| = \text{tr}[\Omega\Omega^t]^{1/2}$ and $\|S\| = \text{tr}[SS^t]^{1/2}$; Ω and S are the anti-symmetric and symmetric components of the velocity gradient tensor ∇u , defined as $\Omega = \frac{1}{2}(\nabla u - (\nabla u)^t)$ and $S = \frac{1}{2}(\nabla u + (\nabla u)^t)$. Thus, Q represents the local balance between the rotation rate and the strain rate. It implies that positive Q iso-surfaces isolate areas where the strength of rotation overcomes the strain, thus a coherent vortex can be defined as a region where $Q > 0$ (Zhou et al., 2009). It has been used widely in visualizations of SJ-induced vortices from simulation results (Dandois & Garner, 2006; Zhou et al., 2009). In current research, Q criterion is used to define the vortices in the 3D flow fields obtained from CFD simulations.

The λ_{ci} criterion of Zhou et al. (1999) is based on the Δ criterion and uses the imaginary part of the complex conjugate eigenvalue of ∇u to identify vortices. When ∇u has complex conjugate eigenvalues, in the locally curvilinear coordinate system spanned by the vectors (u_r, u_{cr}, u_{ci}) and locally translating with the fluid particle, flow is found to be locally swirling in the plane spanned by (u_{cr}, u_{ci}) and is stretched or compressed along u_r . The ‘swirling strength’, given by λ_{ci} is a measure of the local swirling rate inside the vortex. This criterion has advantages that it not only identifies the vortex core region, but also identifies the strength and the local plane of swirling (Chakraborty,

Figure 3.16: Comparison of (left) CFD visualization results and (right) current dye visualization results of the twin SJs at $Re_L = 164$, $St = 0.091$, $VR = 0.23$ and at phase difference $\Delta\phi = \pi/2$. (The lines indicates the edge of boundary layer.)

2005). Therefore, in 2D flow field obtained from PIV measurement, λ_{ci} criterion is used to define the edge of flow vortices as well as to locate the vortices by finding the maximum λ_{ci} value within the defined area.

3.4.2 Particle tracking

Although stereoscope color dye visualization as discussed in section 3.2.2 can present quasi three-dimensional identification of the interacting structures, discrete particles are released from the orifices in the CFD framework to obtain more details of the twin-SJs interactions. DPM is used to model the particles movement within the SJs and the density of the released particles is set as the same as that of water to make sure the particles follow the movement of water closely. The trajectory of a discrete particle is predicted by integrating the force balance on the particle with a Lagrangian reference frame. It equates the particle inertia with the forces acting on the particle. When the density of particles is equal to the fluid velocity as used in current research, the equation can be written as

$$\frac{du_p}{dt} = F_D(u - u_p) + F_x \quad (3.15)$$

where u is the fluid phase velocity, u_p is the particle velocity, F_x is an additional acceleration term, $F_D(u - u_p)$ is the drag force per unit particle mass. Figure 3.16 compares the simulated patterns of particles released from the twin SJ actuators and those obtained from current dye visualization at the same instant. It can be seen that the simulated

particle patterns match with dye visualization patterns pretty well in terms of the shape, size and location of the vortex structures, which validates the present CFD framework.

3.4.3 Proper orthogonal decomposition

The POD is nowadays a well-established mathematical procedure, which was first introduced by Lumley (1967) for detection of coherent structures embedded within the flow. The present analysis of PIV data uses the snapshot POD (Sirovich & Kirby, 1987). Therefore, each instantaneous 2D velocity field $\mathbf{u}(t)$ is considered to be a snapshot of the flow as

$$\mathbf{u}(t) = \bar{\mathbf{u}} + \sum_{n=1}^N a_n(t) \Phi_n \quad (3.16)$$

where $\bar{\mathbf{u}}$ is the mean velocity field, Φ_n deterministic spatial POD modes, $a_n(t)$ the temporal coefficient corresponding to the n th POD mode, and N the number of snapshots used in the calculation.

To obtain POD modes and coefficients, the instantaneous fluctuating velocity component u_j^n and v_j^n are used where n runs through the N snapshots and j runs through the total M positions of velocity vectors in a given snapshot. Fluctuating velocity components from N snapshots are arranged in two matrixes U and V as

$$U = [u^1, u^2, \dots, u^N] = \begin{pmatrix} u_1^1 & \dots & u_1^N \\ \vdots & \vdots & \vdots \\ u_M^1 & \dots & u_M^N \end{pmatrix} \quad (3.17)$$

$$V = [v^1, v^2, \dots, v^N] = \begin{pmatrix} v_1^1 & \dots & v_1^N \\ \vdots & \vdots & \vdots \\ v_M^1 & \dots & v_M^N \end{pmatrix} \quad (3.18)$$

Therefore, the corresponding spatial correlation matrix C_a of the total energy in the flow at every instance in time is then created as

$$C_u = UU^T \quad (3.19)$$

$$C_v = VV^T \quad (3.20)$$

$$C_a = (C_u + C_v)/M \quad (3.21)$$

The POD process requires the solution of the eigenvalue problem

$$C_a A = \lambda A \quad (3.22)$$

where A is the matrix of eigenvectors of the C_a matrix and λ is its eigenvalues. The solutions are arranged in a descending order according to the value of eigenvalues, i.e. energy level. The mode shapes $\phi_n(u)$ and $\phi_n(v)$ can be calculated and normalized as (Meyer et al, 2007)

$$\phi_n(u) = \frac{\sum_{k=1}^N A_n^k u^k}{\|\sum_{k=1}^N A_n^k u^k + \sum_{k=1}^N A_n^k v^k\|}, n = 1, \dots, N \quad (3.23)$$

$$\phi_n(v) = \frac{\sum_{k=1}^N A_n^k v^k}{\|\sum_{k=1}^N A_n^k u^k + \sum_{k=1}^N A_n^k v^k\|}, n = 1, \dots, N \quad (3.24)$$

where A_n^k is the k th element of the n th eigenvector of C_a , and $\|\cdot\|$ is the discrete 2-norm. Then, the total fluctuation energy of the flow is given by the sum of the eigenvalues $\sum_{n=1}^N \lambda_n$, and each POD mode ϕ_n is assigned an energy percentage such as $\lambda_n / \sum_{n=1}^N \lambda_n$.

The 2D POD mode Φ_n can be constructed as

$$\Phi_n = [\phi_n(u), \phi_n(v)] \quad (3.25)$$

In current study, the snapshot 2D POD is made using the computing language MATLAB, detail steps can be found in Andrianne et al. (2011) and Chen et al. (2013). From the previous study of sensitivity of POD analysis in relation to the number of available snapshots, it was found $N = 200$ is sufficient for providing statistically converged results for at least the first eight modes in the case involving SJs and turbulent separated flows (Ben Chiekh et al., 2013). In current study, $N = 240$ is used for the case of twin-SJs

in attached crossflows. And, $N = 400$ is used for the case of twin-SJs in a separated crossflow due to the complex interactions.

It has been shown that the eigenvalues used for sorting all POD modes is associated with the total kinetic energy in the snapshots (Fukunaga, 1990). Therefore, the first few modes reflect the dominant flow structures (Ben Chiekh et al., 2013). In addition, it was found that vortex shedding phenomenon is often associated to pairs of POD modes with similar energy level and with regions of similar dimensions at negative and positive values (Ben Chiekh et al., 2013; Lengani et al., 2014).

3.4.4 Dynamic mode decomposition

The recently developed DMD (Schmid, 2010) constitutes a suitable alternative to POD as it extracts spatial modes based on their single-frequency content rather than sorting them according to their contribution to the total energy. The procedural steps for computing the DMD modes are given in details in the works of Schmid (2010, 2011). After the decomposition, DMD provides the following representation of a flow field $\mathbf{u}(t)$ (Sayadi et al, 2013)

$$\mathbf{u}(t) = \sum_{n=1}^N b_n \exp(\mu_n t) \Psi_n \quad (3.26)$$

where Ψ_n is the n th DMD mode, b_n the corresponding amplitude and μ_n the corresponding frequency, and N the number of snapshots used in the calculation.

Different to the fluctuation velocity fields used in POD analysis, raw velocity field V_1^N , are used as an input to the DMD procedure. It is defined as

$$V_1^N = \begin{pmatrix} u_1^1 & \cdots & u_1^N \\ v_1^1 & \cdots & v_1^N \\ \vdots & \vdots & \vdots \\ u_M^1 & \cdots & u_M^N \\ v_M^1 & \cdots & v_M^N \end{pmatrix} \quad (3.27)$$

where, u and v are the raw velocity components, N is the maximum number of snapshots and M is the number of grid points. Given a sequence of N snapshots Δt apart in time,

two data matrices V_1^{N-1} and V_2^N are formed that contain the first $N - 1$ snapshots and the same sequence shifted by Δt , respectively. If a linear mapping B is assumed to connect V_1^{N-1} and V_2^N as

$$V_2^N = BV_1^{N-1} \quad (3.28)$$

Then, the goal here is to extract the dynamic characteristics, i.e. eigenvalues and eigenvectors of the dynamical process described by B . In order to avoid forming this large matrix B , a companion matrix G is formed instead. The eigenvalues of G then approximate some of the eigenvalues of B , which can easily be solved using a QR-decomposition of V_1^{N-1} as

$$[Q, R] = qr(V_1^{N-1}, 0) \quad (3.29)$$

$$G = R^{-1}Q^H V_2^N \quad (3.30)$$

Once G has been determined, its eigenvalues and eigenvectors can be computed as

$$[X, D] = eig(G) \quad (3.31)$$

which, in turn, result in the dynamic modes of the underlying snapshot sequence together with their temporal behavior (contained in the eigenvalues of G). The eigenvectors of G contain the coefficients of a specific dynamic mode expressed in the snapshot basis V_1^{N-1} .

For applications in fluid dynamics, it is common to transform the eigenvalues of G using a logarithmic mapping as,

$$\mu = \log(D)/\Delta t \quad (3.32)$$

after which the unstable (stable) eigenvalues have a positive (negative) real part μ_r , and frequency is obtained from imagine part as $\mu_i/2\pi$. The dynamic modes are then calculated as

$$\Psi_n = V_1^{N-1} X_n \quad (3.33)$$

with X_n as the i th eigenvector of G . And the corresponding amplitude b_n is obtained from 2-norm of Ψ_n (Rowley et al., 2009; Zeinab, 2013). In this thesis, the 2D DMD is conducted using the computing language MATLAB, the detail steps can be found in the publications of Schmid (2010, 2011) and Zeinab (2013).

3.5 Remarks

In this chapter, experimental and CFD approaches used in this thesis are presented. In experiments, stereoscopic color dye visualization and 2D digital PIV are used to obtain qualitative flow patterns and quantitative information respectively. The general principles, set up and procedures of the experiments are presented. LES model is used to simulate SJs in a TBL. Validation and convergence studies are conducted confirming the capability of current CFD frameworks. Q -criterion and λ_{ci} are used to capture SJ-induced flow structures from 3D and 2D flow fields respectively. Particle tracking simulation using DPM is also conducted to further examine the details of these flow structures. POD and DMD are conducted to extract representative coherent structures from energy and dynamics aspects, respectively.

Chapter 4

Single SJs in Crossflows

In this chapter, a numerical study is conducted to compare the similarity and difference of the hairpin vortices induced by single SJs in a LBL and in a TBL, and to compare their influence on these two boundary layers in the context of flow separation control. Two simulation cases are investigated. In one case single SJs are perpendicularly issued from a circular orifice into a flat-plate LBL, and in the other case the same SJs are issued into a flat-plate TBL.

4.1 Test conditions

As described in Chapter 3, the SJ actuator has a circular diaphragm with a diameter of $D_d = 45\text{mm}$, and a cylinder cavity with a height of $H_c = 25\text{mm}$. Its orifice has a circular shape with diameter $D_o = 5\text{mm}$ and a depth of $h = 5\text{mm}$, locates at the centerline of the cavity. Its piston-type diaphragm oscillates in a sinusoidal manner. The diaphragm oscillates with a peak-to-peak displacement of $\Delta = 0.106\text{ mm}$ at a frequency of $f = 2\text{ Hz}$. In both boundary layers, the freestream velocities are set as the same value, i.e. $U_\infty = 0.1\text{ m/s}$. In the SJ-LBL case, the momentum thickness based Reynolds number is $Re_\theta = 180$ at the SJ actuator orifice exit, and the corresponding boundary layer thickness is about $3D_o$. In the SJ-TBL case, the Reynolds number is set as $Re_\theta = 420$, and the boundary layer thickness is about $6D_o$. Hence these operating conditions give $VR = 0.17$ and $L = 1.7$. According to Jabbal et al. (2006), hairpin vortices will be generated under such conditions.

4.2 SJ-induced hairpin vortices in boundary layers

Figure 4.1: Phase-averaged hairpin vortices in the LBL (left) and in the TBL (right) at $t = 3T/4$ at $VR = 0.17$ and $L = 1.7$. The vortex structures are identified by iso-surfaces of $Q = 10$. The contours represent streamwise vorticity.

In this section, the production and evolution of SJ-induced hairpin vortices in both the LBL and TBL are presented and compared through the visualization of coherent flow structures at different phases from combined isotropic, side cross-section and plan views. In addition, the velocity and vorticity information in selected cross-flow planes is showed to reveal more flow details. The similarity and difference between the SJ-induced hairpin vortices in the LBL and in the TBL are discussed. For the visualization of coherent flow structures, only instantaneous flow structures at different phases are presented in the SJ-LBL case, whereas in the SJ-TBL case both the phase-averaged and instantaneous flow structures are showed. The Q -criterion (Hunt et al., 1988) is used to identify vortex structures. In the present study, initially the same Q value of 10 is chosen to show coherent structures in both the SJ-LBL and SJ-TBL cases for fair comparison. However, as shown in Figure 4.1, the SJ-induced flow structures in the TBL are surrounded by many similar- size turbulence structures, making the observation difficult. To let the coherent

structures stand out of the background turbulence structures, iso-surfaces of higher Q values are adopted, i.e. $Q = 25$ and 80 for the phase-averaged and instantaneous flow structures, respectively. On the contrary, in order to capture as much flow details as possible, a lower Q value of 0.5 is used in the SJ-LBL case. For this reason, however, the vortex structures shown for the SJ-TBL case have smaller sizes than those shown for the SJ-LBL case.

4.2.1 Hairpin vortices in the LBL

Figure 4.2 and 4.3 show the flow structures induced by the SJ-LBL interaction at four consecutive phases, i.e. the maximum blowing ($t = T/4$), the beginning of ingestion ($t = T/2$), the maximum ingestion ($t = 3T/4$) and the beginning of blowing ($t = 0$ or T). Under the current flow and SJ actuator operating conditions, four types of flow structures can be observed. In the region near the mid-span plane, hairpin vortices are the dominant structures that evolve downstream and stay in the boundary layer for a distance up to $12Do$ from the SJ actuator orifice exit. A pair of secondary vortices is located outboard of the hairpin legs with opposite-signed streamwise vorticity. In the most outboard region, a pair of tertiary vortices is induced, which has the same streamwise vorticity sign as that of the hairpin legs. And during the SJ actuator blowing cycle, a horseshoe vortex forms right upstream of the orifice exit due to the blockage of the SJ.

At the maximum blowing ($t = T/4$), a new vortex ring appears right above the SJ actuator orifice exit as shown in Figure 4.2a. As time evolves, the upstream branch of this vortex ring is weakened by the resident vorticity in the LBL that has the opposite-signed vorticity. As shown in Figure 4.2b, the vortex ring gradually tilts due to the Magnus effect (Zhong & Wood, 2005). Its upstream branch becomes closer to the wall than its downstream branch. At $t = 3T/4$, the upstream branch vanishes, and the downstream branch starts getting stretched by the shear stress in the LBL in Figure 4.3a. It is at this moment that the vortex ring becomes a hairpin vortex. At $t = T$ in Figure 4.3b, the hairpin vortex keeps stretching with its leg retarded at the orifice exit. In the next SJ actuator actuation cycle ($t = T$ or $2T$), since the head of this hairpin vortex reaches the edge of the boundary layer, its head portion tends to be upright due to smaller shear out there, while its leg portion keeps stretching, as shown in Figure 4.3b. Because of the

Figure 4.2: Instantaneous flow structures plotted with $Q = 0.5$ and wall shear stress in LBL at (a) maximum blowing ($t = T/4$), (b) beginning of ingestion ($t = T/2$) at $VR = 0.17$ and $L = 1.7$.

Figure 4.3: Instantaneous flow structures plotted with $Q = 0.5$ and wall shear stress in LBL at (a) maximum ingestion ($t = 3T/4$), and (b) beginning of blowing ($t = T$) at $VR = 0.17$ and $L = 1.7$.

generation of another new vortex ring, the upstream edge of the hairpin leg starts moving downstream. At $t = 3T/2$, the head of this hairpin vortex goes beyond the boundary layer, and hence its moving speed becomes much higher than its leg, causing the entire vortex structure to further elongate in the streamwise direction.

When the vortex ring emerges and blocks the incoming flow, a horseshoe vortex in a crescent shape forms just upstream of the orifice exit, as shown in Figure 4.2a. This horseshoe vortex has also been captured in previous simulations (Zhou et al., 2009; Zhou & Zhong, 2010). At the beginning of ingestion ($t = T/2$), this horseshoe vortex increases its size significantly and connects with its predecessor, forming a folded toroid-like vortex structure. As it develops, however, the horseshoe vortex soon disconnects with its predecessor and reaches its maximum size at the maximum ingestion ($t = 3T/4$). Its shape from the top view also changes from crescent to ellipsoidal-cap shape. During the SJ actuator ingestion process, a portion of the horseshoe vortex has been sucked into the SJ actuator cavity. At the end of ingestion ($t = T$), it moves downstream together with the hairpin vortex that blocks it. Two protrusions form at its downstream side right outboard of the hairpin legs, which are induced by the streamwise rotation of a pair of secondary vortices underneath. During the blowing process of the next SJ actuator actuating cycle ($t = T \sim 3T/2$), since it is right on top of the orifice exit, this horseshoe vortex is lifted up by the newly formed vortex ring, as shown in Figure 4.2a. The shape of its main body changes to oblate, with the two protrusions becoming more obvious. The two protrusions then separate from the horseshoe vortex, riding on the respective secondary vortices. When the newly formed vortex ring evolves into a hairpin vortex, the middle portion of the horseshoe vortex sits on the head of the hairpin vortex like a “hat”, reduces its strength, and fades out eventually.

Although hardly seen due to the view obstruction, a pair of secondary vortices forms underneath the two protrusions of the horseshoe vortex at the end of ingestion ($t = T$), as indicated in the side view of Figure 4.3b. These two secondary vortices are slightly outboard of the hairpin legs, each carrying streamwise vorticity of opposite sign to that of its nearby leg. As shown in Figure 4.2 and Figure 4.3, once formed, the secondary vortices stretch in the streamwise direction due to the shear stress and gradually lift their heads up during the next SJ actuator actuation cycle, experiencing a similar evolution

process to most of quasi-streamwise vortices in TBLs (Adrian, 2007). When a new hairpin vortex forms and develops upstream, the residual horseshoe vortex riding on the upstream portion of the secondary vortex is influenced by the head of the new hairpin vortex, starting lumping and deforming, and giving its way to the new hairpin vortex, as shown in Figure 4.3b. The lumped vortex structure sits and slides towards the head of the secondary vortex due to the movement of the new hairpin vortex, increasing its size significantly.

The generation of the two secondary vortices was also observed in other hairpin-vortex-in-LBL studies (Zhou et al., 2009; Acarlar & Smith, 1987). It is generally believed that the secondary vortices are induced and strengthened by the rotation of the hairpin legs. As explained by Acarlar & Smith (1987), the downwash flow toward the wall that is induced outboard of the counter-rotating hairpin legs generates velocity gradients that develop secondary streamwise vortices adjacent to the hairpin legs with opposite rotation. In the present study, however, the timing and location of the secondary vortices indicate that the SJ ingestion also contributes to generation of the secondary vortices. As an inverse process of the blowing stroke, the ingestion is able to produce vorticity of opposite signs to that produced during the blowing cycle, which can strengthen the pair of secondary vortices.

When forming, the secondary vortices are strong enough to further induce a pair of tertiary vortices that is further outboard and underneath the head of the secondary vortices. The sign of the streamwise vorticity carried by the pair of tertiary vortices is opposite to that of the secondary vortices and the same as that of the hairpin legs. Since the secondary vortices produced in two consecutive actuating cycles are close to each other in the streamwise direction as shown in Figure 4.3a, both of them help strengthen the tertiary vortices. Once produced, the tertiary vortices stay close to the wall and experience high shear stress, and hence keep stretching. In the meantime, they slightly raise their heads similarly to the secondary vortices. In Figure 4.2a, it is found that they connect with the lumped vortex structure riding on the head of the secondary vortices that are developed in the previous actuating cycle, forming a pair of “n” shape vortex structures.

The current simulation can also provide detailed flow information near the hairpin vortex. As an example, the velocity vectors in the $x = 3Do$ spanwise-wall-normal plane

Figure 4.4: (a) Instantaneous flow structures plotted with $Q = 0.5$, (b) velocity vectors with contour of spanwise vorticity in the mid-span plane at $t = T/4$ in LBL, and (c) deduction of the translating velocity of the hairpin head at $VR = 0.17$ and $L = 1.7$.

at $t = T/4$ are presented in Figure 4.4a, in which the cross-section of the two hairpin legs are captured by the streamwise vorticity contours. A strong upwash flow is observed between the two legs, which drives the near-wall low-momentum flow to the outer flow field. Meanwhile, the streamwise rotation of the two legs also induces downwash flows outboard, which are able to bring the outer high-momentum flow into the near wall region. The velocity vectors superimposed by spanwise vorticity contours in the mid-span plane are also showed in Figure 4.4b and c. A hairpin vortex is captured by the vorticity contours, especially its head at about $x = 4.5Do$ and $y = 2Do$. It seems the flow above the hairpin vortex is not affected too much by the SJ, whereas the flow beneath shows pronounced wall-normal velocity component, again indicating an upwash flow field. Deduction of the translating velocity of the hairpin head from the velocity field gives a relative velocity field. It clearly shows the hairpin vortex signature (Adrian et al., 2000): a vorticity focus region in the head, a upward reversed flow underneath and

approximately perpendicular to the hairpin leg, a downward flow above the hairpin leg, and a stagnation point between these two flows.

4.2.2 Hairpin vortices in the TBL

Similar to in the LBL, hairpin vortices are also induced by single SJs in a TBL under the same flow and SJ actuator operating conditions. Since in the current SJ-TBL case turbulence is involved in the boundary layer, coherent structures produced by the SJ actuator are shown based on phase-averaged velocity fields. In addition, instantaneous flow structures at the same phase from a selected actuation cycle are also shown to provide more information. In Figure 4.5, at $t = T/4$, a tilted vortex ring appears just downstream of the orifice. It then travels downstream, gets stretched and evolves into a hairpin vortex at $t = 3T/4$ as shown in Figure 4.7. The newly formed hairpin vortex is very similar to the auto-generated hairpin vortex at the initial phase in TBLs (Adrian & Liu, 2002). At $t = T$ as shown in Figure 4.8, the hairpin head becomes upright after reaching $y = 1Do$ due to the much lower velocity gradient beyond that height. This bending process is not obvious for the phase-averaged structures due to the averaging process, but it can be clearly observed in the side view of the instantaneous structures shown in Figure 4.8. From the instantaneous images, one can see that the turbulence structures are comparable or even larger both in size and in vortex strength than the vortex structure produced by the SJ actuator. Due to the disturbance from these turbulence structures, the hairpin vortex once formed keeps losing its coherence. As shown in the top view of the instantaneous structures in Figure 4.8, the newly formed hairpin vortex loses its left leg, making itself asymmetric about the mid-span plane. Similar asymmetry can also be observed in autogenerated hairpin vortices in TBLs (Zhou et al., 1999). This asymmetry is less observable in the corresponding phase-averaged structures due to the averaging process. Because of this asymmetry, the hairpin vortex deviates from its centerline and loses its coherence further. After about one actuating cycle, therefore, the hairpin vortex structure becomes less recognizable. In Figure 4.6 to 4.8, the hairpin vortex downstream of $x = 4Do$ only shows its two legs in the phase-averaged structures, and its head disappears very rapidly. By observing its travelling sequence, the deviation on both sides from the centerline indicates that the hairpin vortex oscillates laterally. For example,

Figure 4.5: Flow structures at maximum blowing ($t = T/4$) in TBL at $VR = 0.17$ and $L = 1.7$.

Figure 4.6: Flow structures at beginning of ingestion ($t = T/2$) in TBL at $VR = 0.17$ and $L = 1.7$. Refer to Figure 4.5 for the color map.

Figure 4.7: Flow structures at maximum ingestion ($t = 3T/4$) in TBL at $VR = 0.17$ and $L = 1.7$. Refer to Figure 4.5 for the color map.

Figure 4.8: Flow structures at beginning of blowing ($t = T$) in TBL at $VR = 0.17$ and $L = 1.7$. Refer to Figure 4.5 for the color map.

from the top view of the instantaneous structures, the head of the hairpin vortex at about $x = 7Do$ is off the centerline and in the positive z region at $t = T/2$, while it shifts to the negative z region in the next phase. This kind of oscillation is found within the angle range of 5° measured from the SJ actuator orifice exit, as indicated in the top view of the instantaneous structures in Figure 4.8.

Figure 4.9: (a) Phase-averaged flow structures plotted with $Q = 25$, (b) velocity vectors with contour of spanwise vorticity in the mid-span plane at $t = T$ in TBL, (c) deduction of the translating velocity of the hairpin head, at $VR = 0.17$ and $L = 1.7$.

Other flow structures similar to those in the SJ-LBL case can also be observed. A horseshoe vortex forms during the blowing cycle of the SJ actuator. Unlike in the SJ-LBL case, however, it vanishes very fast once the ingestion cycle starts. A pair of secondary streamwise vortices is also captured at the beginning and maximum of blowing ($t = T$ and $5T/4$, as shown in Figures 4.8 and 4.5, respectively) and soon disappears. Compared to the secondary vortices in the SJ-LBL case, the current secondary vortices are closer to the wall. The pronounced distance between these vortices and the hairpin legs indicates the dominant contribution from the SJ actuator ingestion process in the generation of

the secondary vortices. Different from in the SJ-LBL case, wall vortices can be observed underneath the hairpin legs from the side views in the present SJ-TBL case, as shown in Figure 4.7 and 4.8, which are induced by the near-wall hairpin legs and are commonly observed to accompany SJ-induced hairpin vortices in TBL (Dandois & Garner, 2006; Wu & Leschziner, 2009). Note for consistency, these vortices are named as wall vortices in this thesis according to previous publications (Dandois & Garner, 2006).

The velocity vectors in the $x = 3Do$ spanwise-wall-normal plane at $t = T$ are presented in Figure 4.9a, in which the cross-section of the two hairpin legs are captured by the streamwise vorticity contours. Compared to in the SJ-LBL case, the vorticity in the legs are much weaker. A strong upwash flow between the hairpin legs and downwash flows outboard are also observed. The velocity vectors superimposed by spanwise vorticity contours in the mid-span plane shows the position the hairpin head in Figure 4.9b and c. It seems the phase-averaged flow is not affected too much by the hairpin vortex. Although very weak, however, in the relative velocity field the hairpin vortex signature (Adrian et al., 2000) can still be observed.

4.2.3 Comparisons in LBL and TBL

Along the wall normal direction in the boundary layers, the shear stress varies, causing different portions of the hairpin vortex to stretch at different rates. This results in continuous evolution of the shape of the hairpin vortex. Depending on the type of boundary layers, the evolution could be quite different, as revealed in the previous sections. In this section, the backbones of vortex structures observed from the side view at different instants are sketched to compare the evolution of hairpin vortices in the LBL and TBL. The backbone indicates the length and orientation of a vortex structure and is sketched in the way described by Zhou et al. (1999).

To describe the shape of a hairpin vortex, four characteristic angles are defined for different portions of a typical hairpin vortex (Haidari & Smith, 1994). As shown in Figure 4.10a, angles α_1 and α_2 describe the orientation of the hairpin leg, and angles β_1 and β_2 describe the orientation of the head. Using these angles Haidari & Smith (1994) found that, for a fully developed hairpin vortex induced by continuous flow injection in a LBL, the orientation varies from about $\alpha_1 = 6^\circ$ at the upstream portion of the leg to about

$\beta_2 = 67^\circ$ at the head, which is independent of the injection Reynolds number and plate Reynolds number. In the present study, to simplify the analysis, only two of the four angles, α_2 and β_2 , are examined, which represent the orientation of the hairpin leg and head, respectively.

Figure 4.10: (a) Schematic diagram illustrating the four characteristic angles for a typical hairpin vortex (Haidari & Smith, 1994); (b) geometrical evolution of hairpin vortices in the LBL (solid lines) and TBL (dashed lines) at $VR = 0.17$ and $L = 1.7$; (c) mean velocity profiles; (d) shear stress in the LBL and TBL.

Sketched in Figure 4.10b are two sequences of backbones of the hairpin vortices, one in the LBL and the other in the TBL. The time interval between two consecutive backbones of the same type is $T/4$. For the SJ-TBL case, the backbones are obtained from the side view of instantaneous structures, and are sketched only for the first five phases due to the fast dissipation. It shows that the hairpin vortex in the TBL travels faster than that in the LBL. This is because the near wall velocity in the TBL ($y < 1.4D_o$) is much higher than that in the LBL, as depicted in Figure 4.10c.

In the SJ-LBL case, it is found that the orientation of the hairpin leg decreases from $\alpha_2 = 32^\circ$ to 14° , and the orientation of the hairpin head increases from $\beta_2 = 63^\circ$ to 73° ,

indicating a continuous bending motion of the hairpin vortex. In addition, the hairpin head moves away from the wall along an inclined line with an angle of 10° , as indicated by the dotted line in Figure 4.10b. In the SJ-TBL case, it is found that the orientation of the hairpin leg decreases from $\alpha_2 = 30^\circ$ at the first phase to 10° at the fifth phase, and the orientation of the hairpin head increases from $\beta_2 = 58^\circ$ to 71° . In comparison, during the same period (the first five phases), the angle of the hairpin leg in the LBL decreases from $\alpha_2 = 32^\circ$ to 23° , and the angle of the hairpin head increases from $\beta_2 = 63^\circ$ to 69° , both changing less than in the TBL.

The difference in the shape of the hairpin vortices in the LBL and TBL mainly stems from the difference of shear stress distribution along the wall normal direction. As shown in Figure 4.10d, in the near wall region ($y < 0.4Do$), the shear stress in the TBL is significantly larger than that in the LBL, whereas in the region away from the wall ($y > 0.4Do$) the trend reverses. Larger shear stress results in larger stretching and hence smaller-angle orientation, and smaller shear stress results in more upright flow structures and hence larger-angle orientation. Therefore, the hairpin vortex in the TBL is more bended and has a longer hairpin head compared to its counterpart in the LBL.

It is well known that TBLs are able to generate hairpin vortices through auto-generation. As a key coherent structure in developing and sustaining turbulence in the near-wall region of TBLs, the formation and evolution of auto-generated hairpin vortices have been studied in many investigations (Adrian, 2007). The hairpin vortices produced by this mechanism and by the current SJ show similar asymmetry and off-the-mid-span plane oscillation. The spanwise growth angle of the oscillation in the current SJ-TBL case is about 10° , while it is reported to be about 12° for the auto-generated hairpin vortex (Adrian & Liu, 2002). The shape observed from the side view shown in Figure 4.10b indicates the orientation of the vortex leg is $\alpha_2 = 30^\circ$ at the first phase in the current case, whereas it is reported to be within $\alpha_2 = 20^\circ$ to 30° at the initial phase for the auto-generated structures (Zhou et al., 1996). At the last phase in Figure 4.10b, the orientation of the vortex leg is about $\alpha_2 = 10^\circ$ and the head is about $\beta_2 = 71^\circ$. For the auto-generated hairpin vortex, the angles are about $\alpha_2 = 8^\circ$ for the leg and about $\beta_2 = 75^\circ$ for the head (Zhou et al., 1999). For the phase-averaged structure, the hairpin head reaches $y^+ = 45$ at $t = 3T/4$, whereas the auto-generated hairpin head locates at

$y^+ = 49$ at the initial phase (Adrian & Liu, 2002). The above comparison reveals that the hairpin vortices induced by the SJ and by the auto-generation mechanism in TBLs show many similarities in terms of shapes and evolution process. This implies that findings obtained from the studies of auto-generated hairpin vortices can be used to describe the behavior of the SJ-induced hairpin vortices in TBLs.

Based on the above simulation and comparison results, conceptual sketches of the coherent structures induced by the SJ in both the LBL and TBL are proposed in Figure 4.11. Compared to its counterpart in the LBL, the hairpin vortex in the TBL is more bent and has obvious asymmetric legs, and its head and leg are more distinctive. In addition, the hairpin vortex travels and develops faster in the TBL, and also dissipates faster. The hairpin vortex in both boundary layers induces secondary vortices, which locate outboard of the hairpin legs. A pair of wall vortices forms just underneath the hairpin legs in the TBL, which is not observed in the LBL.

Figure 4.11: Conceptual sketches of vortical structures (a) in LBLs and (b) in TBLs at $VR = 0.17$ and $L = 1.7$.

4.3 Role of SJ-induced hairpin vortices in flow separation control

The interaction between SJs and boundary layers includes two aspects. On one hand the SJ is significantly affected by the boundary layer, forming hairpin vortices, and on the other hand the boundary layer is also disturbed by the SJ. In this section, the changes of the LBL and TBL due to the introduction of the SJ are presented, and the role of these changes in flow separation control is discussed.

4.3.1 Effects on velocity fields

The streamwise velocity profiles at four spanwise locations $z = 0, 0.5Do, 1Do$ and $1.5Do$ in the $x = 3Do$ plane are plotted and compared to show the lateral extent of the SJ influence in both boundary layers. The distribution of the corresponding velocity gradients is also plotted to help assess the change of shear stress in the near wall region due to the introduction of the SJ.

For the SJ-LBL case, it is found that the streamwise velocity along the centerline $z = 0$ is reduced in the region of $y = 0.5Do$ to $2Do$, compared to that in the no-SJ case. As shown in Figure 4.12a, the deficit is especially prominent at $t = T/4$ and T . At these two instants, the two counter-rotating hairpin legs pass through the $x = 3Do$ plane and significant upwash happens along the centerline, as depicted in Figure 4.4. This upwash brings up the low-momentum near-wall flow, causing the deficit of the streamwise velocity. Along the line $z = 0.5Do$ that roughly goes through the center of the hairpin leg cross section, because of the upwash effect in the upper portion of the leg cross section and the downwash effect in the lower portion, the streamwise velocity reduces in the upper region and increases in the lower region compared to the no-SJ case. In the outboard region of the hairpin leg, downwash flow dominates, hence only velocity surplus is observed along lines $z = 1Do$ and $1.5Do$, with stronger surplus occurring at $z = 1Do$. When the hairpin legs are off the current $x = 3Do$ plane, e.g. at $t = 3T/4$, the velocity profiles along the four lines are all very close to that of the no-SJ case. The time-averaged velocity profiles also show similar trends, i.e. obvious deficit along the centerline $z = 0$, surplus along $z = 1Do$ and $1.5Do$, and partial deficit and surplus along $z = 0.5Do$.

Figure 4.12: Profiles of (a) streamwise velocity and (b) velocity gradient at various spanwise locations in a cross-flow plane of $x = 3D_o$ in the LBL at SJ working conditions of $VR = 0.17$ and $L = 1.7$.

The profiles of the streamwise velocity gradient are shown in Figure 4.12b. It is found that in the $y < 0.2D_o$ near-wall region the velocity gradients along $z = 0.5D_o$ and $1D_o$ are greater than that of the baseline case at all four phases. The gradient along $z = 0.5D_o$ is generally the greatest among the four stations. Its largest wall-adjacent velocity gradient value is about 1.6 at $t = 3T/4$, which is about a 167% increment compared to the value of the no-SJ case. Along $z = 1D_o$, the largest increment of about 100% occurs at $t = T/4$, when the downwash caused by the hairpin legs brings in high momentum flows as shown

in Figure 4.4. At the other two stations, i.e. $z = 0$ and $1.5D_o$, the influence of the hairpin vortex is less significant since they are away from the hairpin legs in the spanwise direction. The time-averaged results also give similar conclusions, i.e. a wall-adjacent velocity gradient increment of about 133% along $z = 0.5D_o$, an increment of about 67% along $z = 1D_o$, and slight improvement along $z = 0$ and $1.5D_o$.

Figure 4.13: Profiles of (a) streamwise velocity and (b) velocity gradient at various spanwise locations in a cross-flow plane of $x = 3D_o$ in the TBL at SJ working conditions of $VR = 0.17$ and $L = 1.7$.

For the SJ-TBL case, the streamwise velocity profiles at the same four locations are plotted based on the phase-averaged results. Similar to in the SJ-LBL case, due to the

upwash flow caused by the passage of the hairpin vortex, the velocity along the centerline $z = 0$ in the region of $y = 0.5Do$ to $2Do$ is less or close to that in the no-SJ case. As shown in Figure 4.13a, the deficit is especially pronounced at the phases of $t = 3T/4$ and T , appearing earlier than in the SJ-LBL case. The velocity along $z = 0.5Do$ follows the similar trend, but with smaller deficit. At the other two outboard stations, i.e. $z = 1Do$ and $1.5Do$, velocity in the near-wall region is greater or close to that in the no-SJ case. The surplus is quite obvious at $t = T$. When the hairpin legs are off the current $x = 3Do$ plane, i.e. at $t = T/4$ and $T/2$ as indicated in Figure 4.9, the velocity profiles along the four lines are all very close to that of the no-SJ case. The time averaged velocity profiles only show slight deficits along $z = 0$ and $0.5Do$ in the region of $y = 0.5Do$ to $2Do$.

The profiles of the streamwise velocity gradient for the SJ-TBL case are plotted in Figure 4.13b. In the $y < 0.1Do$ near-wall region (corresponding to $y^+ = 3$) the velocity gradient in the no-SJ case is about 1.8, which is about 3 times of the value in the LBL. At $t = T/4$, with the influence of the hairpin vortex, the wall-adjacent velocity gradients at the four stations are all greater than that in the no-SJ case. The maximum value of 2.8 occurs at $z = 1Do$ which is about a 56% increment. At the next phase, i.e. $t = T/2$, the wall-adjacent value at $z = 1Do$ decreases, while the value of about 2.7 at the centerline $z = 0$ becomes the maximum, which is about a 50% increment. This is quite different from what happens in the SJ-LBL case, where the centerline values are never the largest. The streamwise vorticity contours and velocity vectors in the $x = 3Do$ plane as shown in Figure 4.14 reveal that the enhancement of the wall-adjacent gradient at $z = 0$ is due to the passage of the two secondary vortices, which rotate in the opposite direction to that of the hairpin legs. These two secondary vortices are able to induce a downwash flow that brings in outer high-momentum flow, and hence increase the near-wall flow speed in the centerline region. Although the wall-adjacent velocity gradient along $z = 0.5Do$ is not the maximum in the aforementioned two phases, it is close to the maximum value and becomes the maximum at $t = 3T/4$. For the station $z = 1.5Do$, the gradient is generally small, but it is enhanced significantly at $t = T/4$. The time-averaged profiles show that the effects of the SJ on the wall-adjacent velocity gradient at $z = 0, 0.5Do$, and $1Do$ are very close with an increment of about 28%, whereas it is marginal for the station $z = 1.5Do$ due to its far distance from the hairpin legs.

Figure 4.14: Streamwise vorticity and velocity vector in a cross-flow plane of $x = 3Do$ at beginning of ingestion ($t = T/2$) in the TBL at SJ working conditions of $VR = 0.17$ and $L = 1.7$.

By comparing the time-averaged results from both the SJ-LBL and SJ-TBL cases, it can be concluded that, in the region just downstream of the SJ actuator orifice exit, although the SJ influence in the TBL is wider (from $z = 0$ to $1Do$ compared to from $z = 0.5Do$ to $1Do$ in the LBL), the strength of the influence is much weaker than that in the LBL in terms of both the absolute and relative increments of the wall-adjacent velocity gradient.

4.3.2 Effects on wall shear stress

Wall shear stress is a useful indicator of the capability of a boundary layer in overcoming flow separation. The phase-averaged excess wall shear stress at the four phases has been plotted in Figure 4.2 to 4.3 and Figure 4.5 to 4.8, which is the difference of the wall shear stress between with and without the SJ. In the SJ-LBL case, very high stress values appear in the vicinity of the SJ actuator orifice exit all the time due to the SJ production. Downstream of the orifice exit, a pair of high stress strips is observed, which moves along with the hairpin vortices. Close inspection reveals that this pair of high stress strips locates right underneath the outboard side of the hairpin legs, where the downwash flow induced by the hairpin legs brings in high-momentum flows. In addition,

the wider section of the high stress strip is found in the area between the hairpin leg and the upstream portion of the secondary vortex. The downwash flow will be strengthened by the counter-rotating secondary vortex, which further enhances the wall shear stress. On the contrary, the upwash flow between the two hairpin legs tends to reduce the wall shear stress, especially at the upstream edge of the legs which is very close to the wall. In the SJ-TBL case, the pair of high stress strips is also observed as shown in Figure 4.5 to Figure 4.8, but it is asymmetric due to the influence of turbulent fluctuations. The distance between these two strips is a little bit larger than that in the SJ-LBL case.

Figure 4.15: Time-averaged excess wall shear stress: (a) contours on the wall and (b) spanwise distribution at $x = 3Do$ and $x = 12Do$. The SJ-LBL case is on the left and the SJ-TBL case on the right at $VR = 0.17$ and $L = 1.7$.

The patterns of time-averaged excess wall shear stress are also obtained in Figure 4.15a. In the LBL, the high stress strips concentrate in a $0.5Do$ band (from $0.5Do$ to $1Do$), last beyond $12Do$ without significant reduction of magnitude, and show perfect symmetry about the mid-span plane. In the TBL, the high stress strips are wider, which

is caused by the lateral oscillation of hairpin vortices. Because of the fast dissipation, they last for a much shorter distance, with one side less than $5Do$ and the other less than $12Do$. In addition, the excess wall shear stress in the vicinity of the orifice is much higher than that in the LBL. The reason is because the hairpin legs are closer to the wall in the TBL when the hairpin vortex just comes out of the orifice.

Figure 4.15b shows the spanwise distribution of the excess wall shear stress at two streamwise locations, i.e. $x = 3Do$ and $12Do$, for both the SJ-LBL and SJ-TBL cases. The maximum increment of the wall shear stress at $x = 3Do$ in the TBL is slightly higher than that in the LBL. It gradually increases along the streamwise direction in the LBL but decreases in the TBL. The excess wall shear stress reaches zero at about $z = 1.5Do$ in the LBL case, indicating the spanwise influence area is only $3Do$. For the TBL case, however, it is still greater than zero beyond $z = 2Do$, indicating a wider influence area.

4.3.3 Effects on boundary-layer shape factor

Shape factor H , defined as the ratio of the displacement thickness to the momentum thickness, is a common factor used for assessing integral effect of flow control methods in boundary layer flows (Gissen et al., 2010; Airiau, 2003). The decrease of shape factor is a favorable indicator of enhanced ability in overcoming flow separation. Figure 4.16a shows the distribution of shape factors along the streamwise direction for the current LBL and TBL without actuating the SJ actuator. As expected, the shape factors in both zero-pressure-gradient boundary layers are almost constant, and these two constant values fall in a region bounded by two values calculated from the Blasius and power law solutions. They are also close to the values obtained from the limited PIV data at two specific locations (Zhong, 2012).

In Figure 4.16b and c, the shape factor is calculated from the velocity filed in the mid-span and other various offset planes. It is found that the shape factor increases just downstream of the SJ actuator orifice exit in the mid-span plane for both the SJ-LBL and SJ-TBL cases. This is caused by the blockage of the emerging hairpin vortex, which results in the decrease of the streamwise velocity in the vicinity just downstream of the orifice exit. However, in the LBL, the shape factor along the centerline becomes less than that of the incoming flow at about $x = 8Do$ due to expansion of the influence area in the

Figure 4.16: Shape factor along streamwise direction at various spanwise locations: (a) without SJs at mid-span plane, (b) in the LBL with SJs, (c) in the TBL with SJs, at $VR = 0.17$ and $L = 1.7$.

spanwise direction. Pronounced decrease of the shape factor is observed at $z = 0.5Do$ and $1Do$. At $z = 1.5Do$, the decrease becomes marginal indicating the SJ influence in the LBL is limited in the spanwise direction. However, the influence can last beyond $x = 30Do$ in the streamwise direction. On the contrary, in the TBL the SJ influence on the shape factor is not obvious, except for that the favorable decrease happens just downstream of the orifice exit in offset planes. The reason is now obvious: compared to the background turbulence, the current SJ is not strong enough to affect the TBL flow. Therefore, a stronger SJ is required in order to achieve similar flow separation control effect to that in the SJ-LBL case.

4.4 Remarks

In this chapter, hairpin vortices induced by a single circular SJ in a LBL and in a TBL over a flat plate are investigated using CFD simulations. The similarities and differences in the production and evolution of the SJ-induced hairpin vortices and their accompanying vortex structures in both boundary layers are compared and discussed. Meanwhile the influence of the hairpin vortex structures on both boundary layers is also examined in the context of flow separation control, through the investigation of the boundary layers' velocity profile, wall shear stress, and shape factor. The main findings from this study are summarized as follows:

- (i) Under the same freestream and SJ actuator actuating conditions, hairpin vortices are generated in both the LBL and TBL. The hairpin vortex travels faster and is in a more bent shape in the TBL than in the LBL, due to the high velocity in the near wall region in TBL. For example, the velocity at $y/D_o = 0.5$ in TBL is about 1.5 times of that in LBL. In addition, because of the influence of turbulence structures, the hairpin vortex in the TBL is apparently asymmetric, oscillates laterally, and dissipates fast, whereas it is symmetric and persistent in the LBL.
- (ii) The generation of secondary vortices is observed in both cases. Close inspection of their position and emerging timing reveals that the SJ actuator ingestion also contributes to the production of secondary vortices. In the SJ-TBL case, this contribution is dominant. It is also found that in the SJ-LBL case a portion of the horseshoe vortex that is induced by the blockage of SJ merges into the secondary vortex, forming a complicated vortex structure.
- (iii) The change of velocity profiles and velocity gradient profiles due to the passage of hairpin vortices at $x = 3D_o$ reveals that the influence of the hairpin vortex in the TBL is wider but weaker than that in the LBL. The time-averaged increment of the wall-adjacent velocity gradient is significant at $z = 0, 0.5D_o$ and $1D_o$ in the TBL, while it is significant only at $z = 0.5D_o$ and $1D_o$ in the LBL. The maximum increment in the TBL is about 28% at $z = 0.5D_o$, whereas it is 133% at the same spanwise station in the LBL.

- (iv) The wall shear stress enhancement is related to the downwash flows induced at the outboard of the hairpin legs and the inboard of the secondary vortices. It is found that although in the TBL the excess wall shear stress in a short distance downstream of the SJ actuator orifice is wider than that in the LBL, it is asymmetric and lack of persistence. As for the shape factors, obvious decrease is observed at $z = 0.5Do$ and $1Do$ in the LBL, whereas very little reduction is found in the TBL.

From the above findings, it can be concluded that although similar hairpin vortices are produced under the same freestream and SJ actuator actuating conditions in both boundary layers, significant difference is still observed, which is mainly caused by the difference of velocity profiles and the background turbulence structures in the TBL. Although the influence of the SJ in the TBL is wider than that in the LBL, it is much weaker. To achieve similar flow separation control effect to that in the LBL, a much stronger SJ is required for the current SJ-TBL case.

Chapter 5

SJ Arrays in Attached Crossflows

This chapter presents the study on the interaction of twin circular SJs that are in line with attached laminar crossflows over a flat plate. The resulting vortex structures under different actuation and flow conditions are firstly investigated qualitatively using stereoscopic color dye and simulated particle trace visualizations. Then, the quantitative information of these structures and their impact on the boundary layer in the context of flow separation control are examined by PIV measurement. Both POD and DMD analysis are used to process PIV results, to obtain deeper understanding of these interactions from energy and dynamics standpoints.

5.1 Test conditions

From the analysis in section 3.1 Chapter 3, there are in total six non-dimensional parameters that can be used to characterize the behavior of in-line twin SJs in crossflows with fixed jet-streamwise-distance ($d/D_o = 2$): the non-dimensional stroke length L , the stroke length based Reynolds number Re_L , the Stokes number S , the Strouhal number St , the velocity ratio VR and the operational phase difference $\Delta\phi$. Note among the first five parameters that govern the behavior of the single SJ, only three are independent, that is, if Re_L , St and VR are chosen as the independent parameters, L and S can be expressed based on them as discussed in Chapter 3. Hence the behavior of the in-line twin SJs in crossflows can be characterized by four independent non-dimensional parameters, i.e. Re_L , St , VR , and $\Delta\phi$.

Table 5.1: Case summary

Case	Methodology	U_∞ (m/s)	Δ (mm)	f (Hz)	L	S	Re_L	St	VR
1	Dye	0.028	0.148	0.5	2.4	8.9	72	0.091	0.22
2	Dye	0.055	0.148	0.5	2.4	8.9	72	0.045	0.11
3	Simulation	0.055	0.158	0.5	2.6	8.9	82	0.045	0.12
4	Dye & Simulation	0.055	0.105	1	1.7	12.5	72	0.091	0.16
5	Dye & Simulation	0.055	0.158	1	2.6	12.5	164	0.091	0.23
6	Dye	0.055	0.210	1	3.4	12.5	289	0.091	0.31
7	Dye	0.110	0.158	1	2.6	12.5	164	0.045	0.12
8	Dye	0.110	0.210	1	3.4	12.5	289	0.045	0.16
9	Dye	0.110	0.074	2	1.2	17.7	72	0.091	0.11
10	Dye & PIV	0.110	0.105	2	1.7	17.7	145	0.091	0.16
11	Dye	0.110	0.158	2	2.6	17.7	328	0.091	0.23

Eleven cases are investigated in this chapter as summarized in table 5.1, at which hairpin vortices and stretched vortex rings are generated by single SJs in crossflows. Stereoscopic color dye visualization is used as a major method to capture the flow patterns, while three typical cases are also visualized by simulated particle traces to reveal the details of twin-SJ-induced flow structures. Then, PIV measurement is focused on case 10, at which hairpin vortices are generated by single SJs, to obtain quantitative information of the flow structures as well as their impact on a boundary layer. Three different crossflow speeds are utilized, i.e. $U_\infty = 0.028$, 0.055 , and 0.110 m/s. According to the boundary layer theory, the momentum-thickness based Reynolds numbers at the mid-point of the two orifice centers are $Re_\theta = 76$, 106 , and 150 , respectively. As demonstrated by the PIV data from the crossflow with highest $Re_\theta = 150$ in Figure 5.16, it confirms that current crossflow comes with a Blasius velocity profile, meaning it is laminar flow.

Previous studies have revealed that the non-dimensional stroke length L needs to be greater than about 0.5 to ensure SJ formation (Holman et al., 2005; Milanovic & Zaman, 2005) and less than about 4 to avoid the saturation of primary vortex rings and generation of secondary vortex rings (Gharib et al., 1998; Jabbal et al., 2006). In this L range, the Stokes number S is suggested to be greater than 8.5 to ensure the occurrence of vortex ring rollup (Zhou et al., 2009), which is important for SJ-based flow control. In addition,

depending on different combinations of Re_L , St , and VR values, three types of vortex structures can be induced by single SJs issued into a crossflow, i.e. hairpin vortices, stretched vortex rings, and tilted vortex rings (Jabbal & Zhong, 2008). Both hairpin vortices and stretched vortex rings are capable of delaying flow separation. For these two types of vortex structures, Jabbal & Zhong (2008) found an upper limit of $VR \approx 0.4$ ($0.1 < VR < 0.32$ for hairpin vortex; $0.2 < VR < 0.38$ for stretched vortex rings). Therefore, the SJ actuator diaphragm oscillates at selected amplitudes and frequencies such that all the test cases have non-dimensional parameters in the range of $0.5 < L < 4$, $S > 8.5$, and $VR < 0.4$. Note for each case there are one single SJ case plus four sub-cases with different phase difference, i.e. $\Delta\phi = 0, \pi/2, \pi$, and $3\pi/2$, hence the total number of cases under investigation is 55. Here the phase difference is defined as $\Delta\phi = \phi_u - \phi_d$, where ϕ_u and ϕ_d are the operational phase angles of the upstream SJ actuator and of the downstream SJ actuator, respectively.

To better describe the twin SJ interaction, single SJs issued from the upstream SJ actuator for the listed eleven cases are also studied as benchmark. A simple test has confirmed that the influence on the single SJ due to the existence of the non-operating downstream SJ actuator is negligible. Therefore the orifice of the downstream SJ actuator is not covered during the experiments.

5.2 Qualitative study

In this section, qualitative study is presented for the twin-SJ induced fluid structures in crossflows. Stereoscopic color dye and simulated particle trace visualizations are used to capture the flow patterns. To visualize and differentiate the twin SJs in dye visualization, food dye of two different colors is used to fill the SJ actuators. The upstream SJ actuator is filled with red dye and the downstream SJ actuator filled with green dye to make sharp contrast between twin SJs with a white color background. The flow patterns are captured at different phases from side and plan views. Simulated particle traces are released from the orifices to reveal more details of the flow structures presented from side cross-section, plan and span cross-section views. The influence of four independent non-dimensional parameters, i.e. the Reynolds number Re_L , Strouhal number St , velocity ratio VR , and

phase difference $\Delta\phi$, on the behavior of the twin SJs is studied, with special focus placed on $\Delta\phi$. The timing in the study is defined such that $t/T = 0$ corresponds to the beginning of blowing phase of upstream SJ actuator, and T is the time of an actuation cycle.

5.2.1 SJs visualized by particle-tracking and Q -criterion

Figure 5.1: Particle traces of single SJs at $t = 0$ using side cross-section view (upper row) and plan view (bottom row) at (a) case 5 with $Re_L = 164$, $St = 0.091$ and $VR = 0.23$, (b) case 4 with $Re_L = 72$, $St = 0.091$ and $VR = 0.16$, (c) case 3 with $Re_L = 82$, $St = 0.0045$ and $VR = 0.12$.

To examine the characteristics of particles traces for visualizing flow structures, simulated particle traces of single SJs are presented and compared to Q -criterion at different actuating conditions in Figure 5.1 and Figure 5.2 at $t = 0$. Note for better presentations, all the side cross-section and side view images hereinafter are adjusted such that the crossflow comes from left and the SJs are issued upwards. In case 5, hairpin vortices are generated as expected, with a clear head followed by a pair of hairpin legs as shown in the two views in Figure 5.1a. In addition, the vortex at the hairpin head is clearly presented by the spiral shape of particle traces in the side cross-section view. When the diaphragm oscillation amplitude Δ is reduced by 33% at case 4 compared to case 5, Re_L and VR are reduced by 56% and 30% accordingly. As shown in Figure 5.1b for case 4, the size of the induced hairpin vortices is smaller and the penetration in the boundary layer is lower. In addition, not like in case 5 where particles are concentrated at the hairpin head, particles in case 4 are more evenly distributed within the hairpin vortex. Actuating frequency f in case 3 is set as 0.5Hz which is half of the value in case 5. As such, Re_L ,

VR and St are reduced by 50% accordingly. Weak hairpin vortices are found in case 3 as shown in Figure 5.1c. Besides, the decreased St number results in the increase of spacing between consecutive hairpin vortices and makes the hairpin legs significantly stretched. In addition to the particles that are tracking the primary hairpin structures in case 3, amount of particle traces concentrate in the near wall region outboard of the hairpin legs in the plan view of Figure 5.1c. They were believed to form at low VR and are created by the inrush during the suction phase of actuator movement (Jabbal et al., 2006).

Figure 5.2: Particle traces and iso-surface of $Q = 5$ of single SJs at $t = 0$ using side cross-section view (upper row) and plan view (bottom row).

Furthermore, iso-surface of $Q = 5$ is also plotted along with simulated particle traces for comparison, as shown in Figure 5.2. Generally, in all three cases, particle traces coincide well with the iso-surface of Q -criterion for the primary hairpin vortices. For instance, at case 5, hairpin vortices captured by Q -criterion show similar shape to particle traces. However, there are still some differences between particle traces and iso-surface of Q value. For example, a strong fluid structure may not be tracked by particles, and amount of particles can still settle at places where no obvious vortex is found. In the plan view of case 5 as shown in Figure 5.2a, induced secondary vortices are captured by Q -criterion beneath and outboard of primary hairpin vortices within the first two actuation cycle. However, there is no particle tracking these vortices. This is because particles are released only from orifices, and are restricted in the strong primary hairpin vortices, therefore, no more left to track the induced secondary vortices which are formed by ambient fluid instead of fluid from actuator. In addition, in case 3 as shown in Figure 5.2c, amount of particles are distributed outboard of the hairpin legs in the near wall

region. But, no related vortex is captured by current Q value around there. This is because the primary hairpin vortices in case 3 are too weak and stretched to restrict all the particles within their coherent structures and leave amount of particles in the near wall region.

As the simulated particle traces show similar behavior as that of the colour dye in current experiment as validated in Chapter 3, in the following discussions, the color dye and CFD based particle trace visualizations are used alternatively to present the primary vortices induced by SJs.

5.2.2 Evolution of single and twin SJs

Figure 5.3: Evolution of vortex structures in a crossflow in case 5. Upper two rows: stereoviews of a single SJ. Bottom two rows: stereoviews of twin SJs with zero phase difference. The horizontal line represents the edge of the boundary layer.

A sequence of snapshots showing the evolution of single and twin SJs in case 5 is presented in Figure 5.3 using dye visualization. In Figure 5.3, the evolution of the single SJ issued from the upstream SJ actuator is shown in the upper two rows. It is shown

that, after emerging at the orifice exit, the vortex ring gradually tilts towards downstream ($t = 0.41T$). Its upstream branch is weakened by the resident vorticity in the boundary layer that has the opposite-signed vorticity. As time evolves to $t = 0.71T$, the upstream branch vanishes, and the downstream branch starts getting stretched by the shear stress in the boundary layer, forming two legs that are retarded at the orifice exit (see the plan view). At $t = 0.97T$, the upstream ends of the two vortex legs move downstream, and the vortex head reaches the edge of the boundary layer (the horizontal line). As time evolves to $t = 1.19T$, the vortex head moves faster outside the boundary layer and tends to be upright due to smaller shear out there, while the legs keep stretching, making the entire vortex structure elongate further in the streamwise direction.

When the in-line twin SJs are issued into the crossflow with zero phase difference, the SJ produced by the upstream SJ actuator evolves in the same way as the single SJ does as shown in first three snapshots of the lower two rows, whereas the SJ produced by the downstream SJ actuator behaves slightly differently. Due to the shielding effect of its upstream counterpart, the vortex structure generated from the downstream SJ actuator appears less tilted. When both vortex structures start stretching at $t = 0.71T$, the mid portion of the downstream vortex legs is entrained into the head of the upstream vortex, resulting in the touching of the two vortex structures. This entrainment is a combined result of clockwise rotation of the upstream vortex head and the upwash flow between the two legs of the upstream vortex that is induced by the counter-rotating of the two legs. As time evolves to $t = 0.97T$, the entire legs of the downstream vortex are lifted up by the upwash flow and entrained between the two legs of the upstream vortex, starting rotating around those legs. As such, the interaction between the twin SJs produces a more complex vortex structure than that produced by a single SJ, as shown at $t = 1.19T$. Furthermore, it is found that the upstream vortex of the twin SJs travels a little bit slower than that of the single SJ, and its penetration into the crossflow is slightly weaker. Obviously this is because of the influence of the downstream vortex.

Simulated particle traces are also presented to show the evolution of single SJ and twin SJs with zero phase difference at case 5 in Figure 5.4 from side cross-section view and plan view. Same to that in dye visualization, after emerging from the orifice exit, the single SJ gradually tilts towards downstream ($t = 0.375T$). Its upstream branch

Figure 5.4: Evolution of particle trace of single SJ and twin SJs at $\Delta\phi = 0$ at case 5 using side cross-section and plan views. Upper two rows: a single SJ. Bottom two rows: twin SJs with zero phase difference. The horizontal dash line represents the edge of the boundary layer.

is weakened by the resident vorticity in the boundary layer, while the downstream one is strengthened. In addition, from the side cross-section view of particle traces, it can be seen that particles that are released at early phase period are transported to lower downstream branch at $t = 0.375T$ and $t = 0.5T$. Due to the clockwise rotation within the vortex head, these particles are then driven back to upstream portion from $t = 0.625T$ to $1.25T$, contributing to the formation of vortex legs. After the first actuating cycle ($t = 1.25T$), a clear vortex head is formed trailing with stretched legs.

For twin SJs at $\Delta\phi = 0$ as presented by color particles in Figure 5.4, the SJ issued from the upstream SJ actuator evolves in almost the same way as the single SJ in the first two snapshots before $t = 0.5T$. However, the SJ from downstream actuator is affected

by the legs of its preceding vortex issued in the previous cycle, and shows a little lower penetration depth than its counterpart. After $t = 0.625T$ when two SJs meet each other, the legs of downstream vortex is gradually entrained into the upstream vortex, passing through the legs of upstream vortex and then scattered outside of them from $t = 0.75T$ to $t = 1.25T$. Similar to what is revealed at dye visualization, the upstream vortex travels a little slower than single SJ, and both vortices penetrate the boundary layer with lower distance.

5.2.3 Influence of $\Delta\phi$

As discussed in section 5.1, the fourth independent non-dimensional parameters, i.e. phase difference $\Delta\phi$, characterizes the interaction of the in-line twin SJs in crossflows. By varying the phase difference between the upstream and downstream SJ actuators, the interaction of the twin SJs is investigated in this section. Four representative phase differences are investigated, i.e. $\Delta\phi = 0, \pi/2, \pi$ and $3\pi/2$ (or $-\pi/2$). The dye visualization results are shown in Figure 5.5 for case 5. Three different types of flow structures are observed, i.e. one combined vortex at $\Delta\phi = \pi/2$, two completely separated vortices at $\Delta\phi = 3\pi/2$, and partially interacting vortex structures at $\Delta\phi = 0$ and π .

At $\Delta\phi = \pi/2$, the vortex produced by the downstream SJ actuator emerges when its counterpart from the upstream SJ actuator just passes by. As shown in Figure 5.5b, these two vortices perfectly merge together, forming a new vortex structure with a larger head and more strength. This new vortex structure penetrates the boundary layer with more ease than the vortex produced by a single SJ actuator shown in Figure 5.3. Hence at this $\Delta\phi$, the twin SJs interact in a constructive manner in terms of the vortex size, strength and celerity.

At $\Delta\phi = 3\pi/2$ (or $-\pi/2$) in Figure 5.5d, as the vortex produced by the downstream SJ actuator appears, its counterpart from the upstream SJ actuator has already passed the downstream SJ actuator orifice exit for about half an actuation cycle, i.e. $T/2$. As such, the newly emerging vortex is not affected too much compared to the vortex produced by a single SJ actuator shown in Figure 5.3. The resulting flow structures are then a sequence of vortices with the same color appearing alternatively. It seems like doubling the frequency of the single SJ. However, the vortex produced by the upstream SJ

Figure 5.5: Stereoscopic dye images of the twin SJs at various phase differences for case 5. The horizontal line represents the edge of the boundary layer.

actuator penetrates the boundary layer a little bit faster than its downstream counterpart, indicating it has slightly more momentum in the wall-normal direction. It is because during the formation the downstream vortex (in green) entrains and lifts up the legs of its upstream counterpart (in red), which in return reduces its own wall-normal momentum, whereas the formation of the upstream vortex is almost not affected by its downstream counterpart.

At $\Delta\phi = 0$ and π , the two vortices produced by the twin SJ actuators are very close, with the head of one vortex coupled with the legs of the other, forming complex vortex structures as shown in Figures 5.5a and 5.5c. The time difference between these two vortices in the vortex sequence is about a quarter of an actuation cycle, i.e. $T/4$. As shown in Figure 5.5a, at $\Delta\phi = 0$ the combination of clockwise rotation of the head of trailing vortex (in red) and strong upwash flow between its two legs lift up the mid portion of the leading vortex legs (in green). The tail portion of leading vortex legs merges with the trailing vortex legs. As the trailing vortex entrains the leading vortex legs, its vortex head grows bigger than single SJ. Oppositely, the head size of leading

vortex decreases during the interaction. Things become different at $\Delta\phi = \pi$. As shown in Figure 5.5c, on one hand the twin SJ interaction lifts up the legs of the leading vortex (in red), and on the other hand these lifted-up legs significantly change the trailing vortex (in green). Unlike that in the $\Delta\phi = 0$ case, the mid-portion of the trailing vortex legs in the present case is also lifted up, forming an “S” shape if observed from the side view. In addition, from the observation of the vortex size, the leading vortex head at $\Delta\phi = \pi$ seems more able to hold its flow structure than that at $\Delta\phi = 0$. The reason for this discrepancy stems from the formation phase of the twin SJs. Since during its formation the vortex produced by the upstream SJ actuator (in red) is not affected too much by the downstream vortices, it is well developed and hence is able to sustain its coherence in the following evolution. On the contrary, the vortex produced by the downstream SJ actuator (in green) is significantly affected by the vortices immediately upstream/downstream/right-on-top during its formation, especially in the $\Delta\phi = \pi$ case. For this reason, it has no time to fully develop its own coherence and hence becomes less sustainable. Similar phenomenon is also observed by Honami & Motosuke (2012) in their PIV measurement results.

The three different types of vortex structures observed in the present dye visualization study can be used to explain previous hotwire results obtained by Liddle & Wood (2005). They measured the velocity field of in-line twin SJs in a TBL at various phase differences. The PSD analysis of the velocity history at a near-wall point in the mid-span plane showed that the spectral peak coincides with the operating frequency of the SJ actuator at most of the investigated phase differences. Although their crossflow and SJ actuator operating conditions are different from those in the present study, at a specific phase difference that happens to be $\Delta\phi = \pi/2$, the highest spectral peak is obtained as shown Figure 2.18a Chapter 2, indicating the merge of vortex structures produced by the two SJ actuators similar to that in Figure 5.5b. Furthermore, at another specific phase difference that happens to be $\Delta\phi = 3\pi/2$, the spectral peak occurs at twice the value of the SJ actuator operating frequency as shown Figure 2.18b in Chapter 2, indicating the completely separated vortices produced by the two SJ actuators similar to that in Figure 5.5d.

Similar induced flow structures are represented by simulated particle traces in Figure 5.6 from which more detailed interactions can be revealed. It is found that, when there are

Figure 5.6: Particle trace of twin SJs at four phase difference at $t = 0$ in case 5 using side cross-section and plan views.

obvious interactions as shown in Figure 5.6a, b and c, particles issued from downstream SJ actuator (in green) are more likely to be transported to the outer layer of the interacting structures. This is more obvious at the plan views when the interacting structures are maturely developed to the 2nd cycle period. The possible reason is that SJs issued from upstream actuator is more likely to hold their coherent structures than their counterpart issued from downstream actuator as discussed above. Therefore, particles issued from upstream actuators (in red) are more easily to be grouped together by the coherent flow structures while particles from downstream actuator (in green) are easily scattered and

transported to the outer layer.

Figure 5.7: Particle trace of twin SJs at $\Delta\phi = \pi/2$ in case 5 at $t = 0$ using span cross-section view at three streamwise locations.

To further examine such interactions at different evolution periods, spanwise cross section views of the particle traces on different streamwise locations at $\Delta\phi = \pi/2$ in case 5 at $t = 0$, i.e. at same time to Figure 5.6b, are presented in Figure 5.7. Within the first actuating cycle ($x = 2.5D_o$), it can be seen that particles issued from two actuators are clearly separated in Figure 5.7a, while the particles issued from downstream actuator (in green) are lifted to upper level with particles from upstream actuator (in red) stay at lower level. As flow structures evolves to the second cycle ($x = 11D_o$), two groups of particles are combined together in Figure 5.7b. Particles from upstream actuator stay in side and form the core of the interacting structure. And, particles from downstream actuator are transported and scattered outside. As the flow structures further develop to third cycle period ($x = 20.5D_o$), these two color types of particles are more mixing together without clear boundary as shown in Figure 5.7c.

CFD particle trace results can also provide evolution information for specific particles. Figure 5.8 shows the trajectories of several typical particles released from SJ actuators for case 5, which are superimposed by SJ vortices (semi-transparent flow structures) identified using the Q criterion. To focus the discussion, only three sub-cases are presented, i.e. single SJ, and twin SJs at $\Delta\phi = \pi/2$ and $3\pi/2$. In the subplots of the top row, a particle is released from the center of each SJ actuator orifice exit (for the single SJ case, the particle is released from the upstream SJ actuator as shown in the upper

left subplot). Because of the symmetry of the flow, these particles stay in the mid-span plane. Since at $\Delta\phi = \pi/2$ the twin SJs merge together into a single vortex structure that is much stronger than the corresponding single SJ, the particle released from the upstream SJ actuator (in red) is lifted up starting at $x = 3D_o$ to a level higher than that in the single SJ case, and the particle released from the downstream SJ actuator (in green) directly rises to a height of about $y = 3D_o$ (shown in the upper middle subplot). These two particles then rotate about the center of the vortex head, resulting in multiple intersections of the two trajectories. At $\Delta\phi = 3\pi/2$ where the resulting vortex structures are completely separated vortices, both the particles re-produce the trajectory as in the single SJ case, with the green one shifting a distance of $2D_o$ downstream (shown in the upper right subplot).

Figure 5.8: Trajectory of fluid particles released from the twin SJ actuators for case 5. From left to right: single SJ, twin SJs with $\Delta\phi = \pi/2$, twin SJs with $\Delta\phi = 3\pi/2$. From top to bottom: particle released at center of the SJ actuator orifice exit, particle released at $z/D_o = 0.4$ (side view), particle released at $z/D_o = 0.4$ (plan view). The trajectories are superimposed by SJ vortex structures (semitransparent structures) at $t/T = 0.25$. The larger dots represent the points on the corresponding vortex structures. The horizontal dashed line represents the edge of the boundary layer.

The particle trajectories shown in the second- and third-row subplots of Figure 5.8 start from a point that is $0.4D_o$ away from the SJ actuator orifice exit center in the span-wise direction. In the single-SJ case, this particle translates downstream while rotating around one of the vortex legs, following a helix path. At $\Delta\phi = \pi/2$ the stronger vortex

structure formed by the twin SJs causes a little faster rotation of both particles about the vortex leg, which is estimated from the slightly short “wave length” of the trajectory oscillation observed in the plan view (the bottom middle subplot). At $\Delta\phi = 3\pi/2$ this rotation acceleration is not observed. The red particle follows similar trajectory as in the single-SJ case, but the green particle is trapped in the near-wall region and follows a nearly straight trajectory towards downstream. Close inspection reveals that the green particle is on the tail of a vortex leg and hence it mainly translates in the crossflow.

The velocity history at multiple stations is also recorded during the CFD simulations. Figure 5.9 shows the phase diagrams at three selected stations in the mid-span plane for case 5. These three stations fall along a vertical line $x = 5D_o$, with one located at $y = 2.4D_o$ through which the vortex head of the single SJ passes, and the other two located at $1D_o$ above and below. From left to right the phase diagrams for the single SJ, the twin SJs at $\Delta\phi = \pi/2$, and at $\Delta\phi = 3\pi/2$ are presented. When the crossflow is not disturbed by SJs, all the phase diagrams show only a single point (represented by an asterisk symbol) that represents a constant velocity at the corresponding station inside or outside the boundary layer. As shown in the left column, with the passage of a vortex structure induced by single SJs, the wall-normal velocity component (v/U_∞) at the mid station (the middle left subplot) increases from about 0 to about 0.3, and the streamwise velocity component (u/U_∞) reduces from a value about 1.0 to a value close to 0.4. After that the phase point returns to the vicinity of its undisturbed position. This process takes about $T/2$ and in the following $T/2$ the phase point stays near the undisturbed position. As such, the phase diagram appears a slant oblate shape, orientating from upper left to lower right. The increase of wall-normal velocity component and decrease of streamwise velocity component are the direct result of the upwash flow behind the vortex head and between the two vortex legs when the vortex passes by (Wen & Tang, 2014). At the station closest to the wall (the bottom left subplot), the oblate shape of the phase diagram becomes slimmer and more bent. Compared to the previous phase diagram, the increment of the wall-normal velocity component does not change too much, but the reduction of the streamwise velocity component decreases a lot. The reason is due to the bending of the vortex legs, which results in a more upright upwash flow near the tail portion of the legs. In addition, the duration for this upwash process is about $3T/4$,

Figure 5.9: Phase diagram at three stations in the mid-span plane for case 5. From left to right: single SJ, twin SJs with $\Delta\phi = \pi/2$, twin SJs with $\Delta\phi = 3\pi/2$. From top to bottom: Station 1 ($x = 5D_o, y = 3.4D_o$), Station 2 ($x = 5D_o, y = 2.4D_o$) and Station 3 ($x = 5D_o, y = 1.4D_o$).

longer than that in the previous phase diagram. This is consistent with the observation of the vortex structure passage in both dye and CFD visualizations, where the vortex leg has a larger streamwise projection than the vortex head. At the station furthest from the wall (the top left subplot), the area enclosed by the phase diagram becomes much smaller compared to at the mid station. Both the streamwise and wall-normal velocity components vary in the vicinity of the undisturbed point. Since from the visualization

results this station is well above the center of the vortex head, unlike at the other two lower stations where the phase point loops clockwise, in this phase diagram the phase point loops counterclockwise. This indicates that the flow at this station is the secondary flow induced by the passage of the vortex head.

When the twin SJs are introduced with a phase difference $\Delta\phi = \pi/2$, the combined vortex structure is much stronger than that in the single SJ case, so that the center of the combined vortex head is even higher than the top station. Therefore, the phase diagrams at both the top and mid stations (in the second column) show similar shapes, i.e. clockwise looping slant oblates. Compared to in the single SJ case, the variations in both the streamwise and wall-normal velocity components are substantially larger. At $\Delta\phi = 3\pi/2$, since the passage frequency of the vortex structures is doubled, all the three phase diagrams in the right column show double loops. However, the two loops at each station are not identical as imagined, and the discrepancy is substantial. This indicates that, although we categorized the resulting vortex structures at this phase difference as two completely separated vortices, the flow induced by each of these two vortices is not identical at this streamwise location ($x = 5D_o$). In addition, these three phase diagrams also reveal that the strength of individual vortex structures at this phase difference is slightly weaker than that in the single SJ case, in terms of the area enclosed by the loops and the variation of velocity components. This is consistent with the observation in the present dye visualization and simulated particle traces.

5.2.4 Influence of Re_L , VR , and St

The influence of the first three non-dimensional parameters introduced in section 5.1, i.e. Re_L , St , and VR , on the vortex structures induced by both single and twin SJs is studied and presented in Figures 5.10-5.12. From previous findings on single SJs (Tang & Zhong, 2006; Jabbal & Zhong, 2008), the stroke length based Reynolds number Re_L determines the strength of circulation carried by SJ-induced vortices, the velocity ratio VR indicates the relative jet velocity and is associated with the orientation of emerging vortex structures as well as the trajectory of SJs in the crossflow, and the Strouhal number St characterizes the streamwise distance between the consecutive vortices. Figures 5.10-5.12 not only confirm these findings for single SJs, but also reveal the influence of these

Figure 5.10: Steroscopic dye visualization of (left) case 5 and (right) case 11 showing the influence of Re_L on single- and twin-SJ induced vortex structures. The twin SJs are introduced with zero phase difference. The horizontal line represents the edge of the boundary layer.

three parameters on the interaction of the in-line twin SJs. Figure 5.10 compares case 5 and case 11, the former having the same St and VR values but a half of the Re_L value of the latter's. The increase of Re_L results in the increase of circulation carried by each vortex. It also induces instability, making the vortex structures seem more turbulent. As a result, the interaction between the twin SJs is less smooth (see case 11 in Figure 5.10). In addition, in case 5, a clear tendency is found that the leading vortex is entrained by the trailing vortex, since the leading vortex is believed to be weaker than the trailing one as discussed above. But, the increased individual vortex strength at case 11 makes the leading vortex resist from being entrained, and two vortex heads stay separated obviously even develop to downstream. Figure 5.11 compares case 1 and case 9, the former having the same Re_L and St values but twice of the VR value of the latter's. The increase of VR results in the increase of the orientation angle between the emerging vortex structures and the flat plate. In addition, the trajectories of the vortex heads are further away from the wall as VR increases. As such, the interaction of the twin SJs occurs in a higher region. As the VR value increases, strength difference between the vortices from two actuators

Figure 5.11: Steroscopic dye visualization of (left) case 1 and (right) case 9 showing the influence of VR on single- and twin-SJ induced vortex structures. The twin SJs are introduced with zero phase difference.

Figure 5.12: Steroscopic dye visualization of (left) case 2 and (right) case 9 showing the influence of St on single- and twin-SJ induced vortex structures. The twin SJs are introduced with zero phase difference.

seems to be less significant. At case 9, vortex issued from upstream actuator is much stronger than its counterpart and stays as dominant vortex at the following interaction. However, at case 1 where VR value is high, vortices from twin actuators show same level of strength especially within the first cycle. Note in case 9, since the non-dimensional stroke length $L = 1.2$ does not exceed the SJ formation criterion ($L > 0.5$) too much, the generated SJs appear much weaker than those in case 1 where $L = 2.4$. Figure 5.12 compares case 2 and case 9, the former having the same Re_L and VR values but a half of the St value of the latter's. It confirms that the decrease of St results in the increase of the streamwise spacing between two consecutive vortex structures. Therefore, the distance between two heads of vortices compared to the length of stretched vortices is relatively shorter in case 2 than that in case 9.

To further examine the influence of Re_L , VR and St on the interacting flow structures, simulated particle traces of twin SJs at case 4 and case 3 are presented in Figure 5.13 and Figure 5.14 respectively. Compared to case 5, the diaphragm movement amplitude Δ is reduced by 33% in case 4 resulting in a deduction of Re_L and VR by 56% and 30% respectively. Although three types of flow structures are generated by twin SJs at case 4 (Figure 5.13), similar to case 5 (Figure 5.6) especially in near orifice region, deduction of Re_L and VR still cause differences. For example as shown in Figure 5.13a and c, the partially interacting structures at $\Delta\phi = 0$ and π in case 4 are more close to one combined vortex compared to that in case 5 when the interacting structures develop to downstream. The reason is because boundary layer plays a more important role in the twin-SJs interaction when Re_L and VR are at low values. It is found that the resident vorticity in the boundary layer can strengthen the head of SJ-induced hairpin vortex (Jabbal et al., 2006). Since during its formation, the vortex produced by the upstream SJ actuator (in red) in case 4 is not affected too much by its counterpart, it is well developed and gains more strength from the boundary layer before the interaction than its counterpart. On the contrary, the vortex produced by the downstream SJ actuator (in green) is significantly affected by its counterpart immediately during its formation, being shielded by its counterpart from the boundary layer at $\Delta\phi = 0$ and $\Delta\phi = \pi$. Therefore, the strength difference between these two vortices is more obvious when the impact of boundary layer is increased at low Re_L and VR . As such, vortices issued from

Figure 5.13: Particle trace of twin SJs at four phase difference at $t = 0$ in case 4 with $Re_L = 72$, $St = 0.091$ and $VR = 0.16$ using side cross-section and plan views.

upstream actuator play a more dominant role during the interaction and can entrain their counterparts, resulting in combined vortices. For example, by comparing the partially interacting structures at $\Delta\phi = 0$ in case 4 (Figure 5.13a) and case 5 (Figure 5.6a), it can be seen that particles issued from downstream actuator are more quickly entrained and scattered outside the particles issued from upstream actuator in case 4 than in case 5.

In case 3 where actuating frequency is reduced by 50% compared to that in case 5, not only Re_L and VR is reduced by 50%, St number is also only half value of that in case 5. Due to the relative short distance between two orifices according to length of the

Figure 5.14: Particle trace of twin SJs at four phase difference at $t = 0$ in case 3 with $Re_L = 82$, $St = 0.045$ and $VR = 0.12$ using side cross-section and plan views.

stretched vortices, vortices from two actuators quickly combined together at $\Delta\phi = 0$ and $\pi/2$ as shown in Figure 5.14a and Figure 5.14b. As the distance between two vortices are significantly increased at $\Delta\phi = \pi$ in case 3, interaction is much weak, resulting in vortices that are similar to partially interacting vortices as shown in Figure 5.14c. At $\Delta\phi = 3\pi/2$ or $-\pi/2$ as shown in Figure 5.14d, vortices from downstream actuator are ahead of their counterparts with weak interaction between them.

5.2.5 A model for prediction of vortex patterns

The visualizations using dye and simulated particle traces have revealed that, at different phase difference of the twin SJs, the resulting vortex structures are quite different. Three different vortex structures are identified, i.e. one combined vortex, two completely separated vortices, and a partially interacting vortex structure. Based on these observations, a formula can be proposed to predict the non-dimensional spacing between the two vortices which majorly governs the vortex patterns produced by in-line twin SJs.

The spacing between the two vortices produced by in-line twin SJs is a function of the crossflow speed U_∞ , SJ actuator operating frequency f , center-to-center distance between the two orifices d , and phase difference $\Delta\phi$. During one actuation cycle T , the head of a vortex structure travels a streamwise distance $\alpha U_\infty T = \alpha U_\infty / f$, where $\alpha \leq 1$ is a coefficient describing the ratio of the mean translating speed of the vortex structure over one actuation cycle to the crossflow speed. Since at the initial stage the vortex structure has to travel in the boundary layer, α is a value not greater than unity, i.e. $\alpha \leq 1$. By introducing the phase difference $\Delta\phi$, the non-dimensional spacing between the two SJ vortices, s , can be estimated as

$$s = \frac{d - (\alpha U_\infty / f)(\Delta\phi / 2\pi)}{\alpha U_\infty / f} = \frac{d}{D_o} \frac{St}{\alpha} - \frac{\Delta\phi}{2\pi} \quad (5.1)$$

Equation 5.1 indicates that s is a function of the non-dimensional orifice spacing d/D_o , Strouhal number St , vortex-crossflow speed ratio α , and phase difference $\Delta\phi$. A value close to zero means the two vortices merge together, a positive value indicates the vortex produced by the upstream SJ actuator follows its counterpart produced by the downstream SJ actuator, and a negative value indicates the opposite pattern. In addition, a value close to 0.5 or -0.5 indicates that the two vortices are completely separated. To use this formula, one has to determine the α value first, which can be estimated from the single SJ visualization results. From the present study, it is found that α varies with the Strouhal number St , e.g. $\alpha = 0.65$ at $St = 0.091$, and $\alpha = 0.75$ at $St = 0.045$.

The calculated s values for all the investigated cases using dye visualizations are listed in Table 5.2, and the corresponding flow structures are shown in Figure 5.15. Note that only dye visualizations are presented for simplicity when both dye and particle trace visualizations are used. For cases with $St = 0.091$, the normalized spacing at $\Delta\phi = \pi/2$

Table 5.2: Estimation of s value at different St and $\Delta\phi$

Case	d/D_o	St	α	s			
				$\Delta\phi = 0$	$\Delta\phi = \pi/2$	$\Delta\phi = \pi$	$\Delta\phi = 3\pi/2$
1, 4-6, 9-11	2	0.091	0.65	0.28	0.03	-0.22	-0.47
2-3, 7-8	2	0.045	0.75	0.12	-0.13	-0.38	-0.63

Figure 5.15: Summary of side view visualization at different phase difference for all cases, showing the spacing and resulting interaction between the vortices produced by the twin SJ actuators. The horizontal line represents the edge of the boundary layer.

is $s = 0.03$ that is close to zero. The resulting flow structure is identified as one combined vortex. The normalized spacing at $\Delta\phi = 0$ is $s = 0.28$, meaning the vortex produced by the upstream SJ actuator follows its counterpart produced by the downstream SJ actuator, and they are partially interacted. The resulting flow structure is then a partially

interacting vortex structure. At $\Delta\phi = \pi$ the normalized spacing is $s = -0.22$, meaning the vortex produced by the upstream SJ actuator leads its counterpart. The resulting flow structure is also a partially interacting vortex structure. At $\Delta\phi = 3\pi/2$ the normalized spacing is $s = -0.47$ that is close to -0.5 , and the resulting flow structure is identified as two completely separated vortices.

Things become different for cases with $St = 0.045$. It is found that the zero s value falls between $\Delta\phi = 0$ and $\Delta\phi = \pi/2$, meaning the resulting vortex structure at these two phase differences slightly deviates from one combined vortex. This can be confirmed by the visualization results of cases 2, 3, 7 and 8 as shown in Figure 5.15. At $\Delta\phi = \pi$ the normalized spacing is $s = -0.38$. The resulting vortex structure appears two completed separated vortices, because the larger vortex spacing involved at the present Strouhal number. At $\Delta\phi = 3\pi/2$, the normalized spacing is $s = -0.63$. As a result, instead of being close to its counterpart, the vortex produced by the upstream SJ actuator is even closer to the vortex produced in the preceding actuation cycle.

Although promising, it must be admitted that some issues have to be addressed before the proposed formula, Eqs. 5.1, can be used with confidence. First, this formula is more applicable to predict the interacting structures at their early stage. After these structures develop in crossflow with sufficient time, boundary layer can play an important role in the interactions especially when the values of Re_L and VR are low. From example, at case 4 and 9, partially interacting flow structures develop to be similar to combined vortex dominated by the vortices issued from upstream SJ actuator at downstream even at $s = 0.28$ and $s = -0.22$. Second, the term d/D_o that quantifies the spacing between the twin SJs is fixed in the present study. Since it influences the extent of interaction between the twin SJs and hence their spacing s , investigation on its effect is also important and recommended for further research.

5.3 Quantitative study

Although a qualitative investigation has been conducted, a quantitative study is ultimately required to understand the interactions between twin SJs as well as their impact on a boundary layer in term of flow separation control. Using PIV measurement and

dye visualization as complementary approach, a quantitative investigation is conducted on the interaction of twin in-line SJs at various relative phase differences in a attached LBL.

5.3.1 Experimental settings

To make the present quantitative research more focused, working conditions of SJs in case 10 as described in Table 5.1 are used at which hairpin vortices are produced by single SJs in the crossflow. The crossflow velocity is kept at $U_\infty = 0.11$ m/s, and the diaphragm peak-to-peak displacement and oscillating frequency are set at $\Delta = 0.105$ mm and $f = 2$ Hz for both SJ actuators. These settings yield $L = 1.7$ and $VR = 0.16$, which fall in the region of hairpin vortex production suggested by Jabbal & Zhong (2008). Under such conditions, the total circulation or vorticity flux produced across a single SJ actuator orifice exit in quiescent conditions can be estimated as (Tang & Zhong, 2006)

$$\Gamma = \frac{\Gamma_o}{U_\infty D_o} \approx \left(\frac{\pi^2}{8}\right) \left(\frac{\nu}{U_\infty D_o}\right) Re_L = 0.32 \quad (5.2)$$

For twin SJs under such conditions, as revealed by case 10 in Figure 5.15, three types of flow structures are induced at four phase differences, i.e., one combined vortex at $\Delta\phi = \pi/2$, two completely separated vortices at $\Delta\phi = 3\pi/2$, and partially interacting vortex structures at $\Delta\phi = 0$ and π .

5.3.1.1 Experimental procedures

The PIV measurements are conducted in the mid-span plane, which bisects the twin SJ actuators, as well as in a selected spanwise-wall-normal plane, i.e. $x = 8D_o$, as shown in Figure 3.6 in Chapter 3. A laser sheet of approximately 1 mm thickness is generated by a 200 mJ double pulsed Nd:YAG laser generator to illuminate the seeding particles. A FlowSense 2M CCD camera with a Nikon 105mm lens is used to capture a field of view of $x = 4 \sim 11D_o$ and $y = 0 \sim 5D_o$ in the mid-span plane. The resulting velocity vectors are resolved using a two-frame cross-correlation algorithm, in which a 32×32 pixel IA with an overlap ratio of 50% is chosen, giving a 0.76 mm spatial resolution. In the spanwise-wall-normal plane, the field of view is $y = 0 \sim 5D_o$ and $z = 4 \sim 4D_o$. Considering a large minimum-required distance between this plane and the camera due

to the actual water tunnel dimensions, a smaller IA of 16×16 pixel is adopted in the two-frame cross-correlation algorithm, hence yielding a 0.51 mm spatial resolution. The selection of this IA has been proved adequate by comparing the resulting velocity fields obtained with a 32×32 pixel IA.

Herein the phase is defined by the diaphragm movement of the upstream SJ actuator: $t/T = 0$ (and 1), $1/4$, $1/2$, and $3/4$ correspond to the beginning of blowing, maximum blowing, beginning of ingestion, and maximum ingestion, respectively, where T is the SJ actuator operation period. To better present the results, velocity vector images at eight equispaced phases, i.e. $t/T = 0.075, 0.2, 0.325, 0.45, 0.575, 0.7, 0.825$ and 0.95 , within one actuation cycle are obtained. At each phase, 60 vector images are used to calculate phase-averaged quantities, which, based on (Jabbal & Zhong, 2010), is adequate for SJ-induced flow structures in LBLs. As discussed in Chapter 3, the PIV measurement uncertainties determined from the recursive image interrogation procedure are approximately 1% in the streamwise and wall-normal velocity components and 2% in the spanwise velocity component. The uncertainty for the resulting vorticity is estimated to be up to 5.6%.

The mean velocity profile of the developed boundary layer flow without SJs is first obtained using 300 consecutive PIV images taken at a frequency of 10 Hz in the mid-span plane. According to the boundary layer theory, given the crossflow velocity of $U_\infty = 0.11$ m/s, a LBL developed along the test plate shall have a thickness of about 10 mm and a momentum thickness based Reynolds number of about $Re_\theta = 150$ at the origin of the current coordinate system (midpoint of twin orifices). As shown in Figure 5.16, the measured mean velocity profile in the boundary layer agrees with the Blasius solution very well, confirming the zero-pressure-gradient laminar nature of the current boundary layer.

In addition, to provide a intuitive impression of twin-SJs induced flow structures measured by PIV, stereoscopic color dye visualizations are also presented to provide complementary information of the flow patterns.

5.3.1.2 Quantitative analysis methods

With the velocity information obtained from the PIV measurements, the SJ-induced coherent structures are identified using local swirling strength λ_{ci} , as discussed in Chapter

Figure 5.16: Comparison of PIV-measured mean velocity profile and the Blasius solution at $x = 4D_o$ in the mid-span plane.

3. In the present study, an iso-value of $\lambda_{ci} = 0.25$ is used to determine the edge of vortex structures so as to show the shape of vortex structures while filtering out low λ_{ci} value noise. Vortex centers are then determined using local maximum λ_{ci} values.

In the 2D PIV data planes, the strength of identified vortex structures is quantified using vortex circulation Γ

$$\Gamma = \int_{\Sigma} \omega dA \quad (5.3)$$

where Σ is the identified vortex edge, ω the vorticity contained in the vortex, and A the area of the vortex.

In this PIV study, all the results showed are non-dimensional, with the length scale normalized using the SJ actuator orifice diameter D_o , the time scale using the SJ actuator operating period T , the velocity using the crossflow velocity U_{∞} , the vorticity using U_{∞}/D_o , and the vortex circulation using $U_{\infty}D_o$.

5.3.1.3 POD and DMD analysis methods

To extract coherent flow structures from this unsteady flow, POD (Lumley, 1967; Sirovich & Kirby, 1987) and DMD (Schmid, 2010) are used to analysis the PIV results obtained from mid-span plane. In the present study, $N = 240$ is chosen and the analysis focus

is only on up to the first four modes. For the POD analysis, previous studies on SJs in turbulent separated flows have revealed that $N = 200$ is sufficient to provide statistically converged results for at least the first eight modes (Ben Chiekh et al., 2013). In addition, it is expected to observe pairs of POD modes that are of similar energy level and include structures of similar sizes but opposite velocity and vorticity values (Ben Chiekh et al., 2013; Lengani et al., 2014). For the DMD analysis, the same set of PIV data as for the POD analysis is used. Since there are 16 equispaced snapshots of flow field data per second, the present DMD analysis can only capture the flow dynamics up to 8 Hz, four times of the SJ actuation frequency (2 Hz).

5.3.2 Single SJs in a LBL

Figure 5.17: (a) Stereoscopic dye images of a single SJ in a LBL. The horizontal line in the side view indicates the edge of the boundary layer. (b) Snapshots of streamwise vorticity contour in spanwise wall-normal plane $x = 8D_o$ during an actuating cycle, (c) Contour of wall-normal velocity and velocity vectors and (d) structure and spanwise vorticity contour at the streamwise mid-span plane at $t = 0.2T$.

Before the interaction of the twin SJs is investigated, the flow pattern of a single SJ in the LBL is discussed as a baseline case. As expected, hairpin vortices are generated

under the present test conditions, with a clear hairpin head followed by a pair of hairpin legs as shown in Figure 5.17a. The formation of these hairpin vortices is the direct result of the interaction between the SJ and the boundary layer (Wen & Tang, 2014). The well-defined vortex tubes that form the hairpin vortex are captured in the side view of the dye visualization, indicating the laminar nature of the flow structures.

The time sequence of PIV measurements in the spanwise wall-normal plane at $x = 8D_o$ also captures the passage of the hairpin vortex. By arranging snapshots of vorticity contour in that plane at eight equally divided phases along a time axis, the hairpin vortex can be re-constructed as demonstrated in Figure 5.17b. With this method, the hairpin leg is well captured, defined by concentrations of positive and negative streamwise vorticity values. The shape of the “captured” hairpin vortex generally matches that shown in the dye visualization. Additional flow structures that are not captured in the dye visualization in the no-dye region are also captured in the current PIV results. As shown in Figure 5.17b, a pair of secondary vortices underneath the hairpin legs is captured, which carries vorticity opposite in sign to the hairpin legs. As explained in Chapter 4, these secondary vortices are partially induced by the hairpin legs and partially induced by the ingestion stroke of the SJ actuator.

Figure 5.18: Time history of hairpin vortex circulation.

PIV measurements along streamwise mid-span plane also captures the hairpin vortex using contours of wall-normal velocities. A hairpin vortex is well captured by an inverted-hook-shaped, positive wall-normal velocity area that follows a smaller negative wall-normal velocity area shown in Figure 5.17c. The streamwise gap at about $x = 5D_o$

defines the hairpin head, and the slant near-wall portion of the positive velocity area defines the upwash flow region between the two hairpin legs. The hairpin head is also captured by an enclosed area identified with an iso-value of $\lambda_{ci} = 0.25$ as shown in Figure 5.17d. With this enclosed area, the circulation around the hairpin head can be evaluated using Eqs. 5.3. Figure 5.18 plots a time history of non-dimensional circulation Γ around the hairpin head. This curve indicates that Γ grows in the beginning, achieves its maximum value at about $t/T = 0.45$ that is near the end of blowing stroke, and then gradually decreases due to viscous dissipation. Its peak value is $\Gamma \approx 0.82$, which is about 2.6 times of the analytical value $\Gamma = 0.32$ estimated by Eqs. 5.2. The significantly larger value obtained from the PIV data is likely caused by two main reasons: First, since the analytical value estimated in Eqs. 5.2 is based on a uniform (or top-hat) jet velocity profile assumption, non-uniformity of the velocity profile will result in greater circulation values; Second, the analytical value 0.32 estimated in Eqs. 5.2 is for vortices just coming out of the SJ actuator exit, while the value 0.82 is the peak value that develops for a while and carries additional circulation entrained during the vortex development.

5.3.3 In-line twin SJs in a LBL

5.3.3.1 Behavior of in-line twin SJs at various phase differences

By controlling the phase difference between the two SJ actuators, the interaction of the in-line twin SJs are investigated in the same LBL. Four different phase differences are investigated, i.e. $\Delta\phi = 0, \pi/2, \pi$ and $3\pi/2$ or $-\pi/2$. Note that although similar interacting flow structures visualized by dye traces in case 5 are already shown Figure 5.5, the flow patterns in current case 10 are also presented in Figure 5.19 for a fair comparison with the PIV measurements. The corresponding contours of vorticity at spanwise wall-normal plane at $x = 8Do$ and contours of wall-normal velocity superimposed with velocity vectors at mid-span plane are presented in Figure 5.20 and Figure 5.21 and respectively, which are obtained from the PIV measurements. It can be seen that the flow structures captured by the PIV measurements generally match the structures in the dye visualization in terms of the vortex size and shape.

Three different types of flow structures are observed, i.e. one combined vortex at $\Delta\phi = \pi/2$, two completely separated hairpin vortices at $\Delta\phi = 3\pi/2$, and the partially

Figure 5.19: Stereoscopic dye images of the twin SJs at four phase differences in case 10, i.e. $L = 1.7$, $Re_L = 145$, $St = 0.091$ and $VR = 0.16$.

interacting flow structures at $\Delta\phi = 0$ and $\Delta\phi = \pi$. At $\Delta\phi = \pi/2$, the hairpin vortex produced by the downstream SJ actuator emerges when its counterpart from the upstream SJ actuator just passes by. As shown in Figure 5.19b, these two hairpin vortices perfectly merge together, forming a new vortex structure with a larger head, stronger legs and more strength than the hairpin vortex generated by single SJs (Figure 5.17). The PIV measurements also prove the merging of the two hairpin vortices. In Figure 5.20b, a single, large vortex is captured, which stays highest among all of the four cases. In Figure 5.21b, the size of a single inverted-hook-shaped contour and its accompanying negative wall-normal velocity contour is significantly larger than that in the single SJ case (Figure 5.17c), confirming the increased strength of the combined vortex. Hence at this phase difference, the two hairpin vortices interact in a very constructive way in terms of the vortex size, strength, and celerity.

At $\Delta\phi = 3\pi/2$, as the hairpin vortex produced by the downstream SJ actuator appears,

Figure 5.20: Contour of streamwise vorticity in the $x = 8D_o$ plane during one actuating cycle. Refer to Figure 5.17b for the color map.

Figure 5.21: Contour of wall-normal velocity and velocity vectors at four phase differences at streamwise mid-span plane. Refer to Figure 5.17c for the color map.

its counterpart from the upstream SJ actuator has already passed the downstream SJ actuator for about half an actuation cycle, i.e. $T/2$. As such, the newly emerging hairpin

vortex is not affected too much as shown in Figure 5.19d. The PIV measurements also capture these two completely separated hairpin vortices as shown in Figure 5.20d and Figure 5.21d. The contour size as shown in Figure 5.21d further reveal that the hairpin vortex issued from the downstream SJ actuator is weaker than its counterpart issued from the upstream SJ actuator.

At $\Delta\phi = 0$ and $\Delta\phi = \pi$, the two hairpin vortices produced by the twin SJ actuators are close, with the head of one hairpin vortex coupled with the leg of the other, forming complex vortex structures as shown in Figure 5.19a and Figure 5.19c. The time difference between these two hairpin vortices is about a quarter of an actuation cycle, i.e. $T/4$. As shown in Figure 5.19a, at $\Delta\phi = 0$ the strong upwash flow induced between the two legs of the trailing hairpin vortex (in red) lifts up the mid portion of the leading hairpin legs (in green), part of which is even entrained into the head of the trailing hairpin vortex making it keeps growing in size.

The story changes at $\Delta\phi = \pi$. As shown in Figure 5.19c, the interaction of the trailing hairpin head (in green) with the leading hairpin legs (in red) results in the trailing hairpin head breaking up into multiple smaller “vortex head”. This is because that during its formation process the hairpin vortex issued from the downstream SJ actuator is significantly disturbed by its counterpart, and hence has no time to fully develop its own coherence. By such intense disturbance, the flow pattern of the trailing hairpin vortex is not perfectly laminar but a little bit turbulent. In addition, by comparing Figure 5.19a and 5.19c, the leading hairpin vortex issued from the upstream SJ actuator at $\Delta\phi = \pi$ seems more sustainable than the leading hairpin vortex issued from the downstream SJ actuator at $\Delta\phi = 0$. These features are further confirmed by the PIV measurements. As shown in Figure 5.20a and Figure 5.20c as well as Figure 5.21a and Figure 5.21c, at $\Delta\phi = 0$ the trailing hairpin vortex is much stronger than the leading hairpin vortex, whereas at $\Delta\phi = \pi$ the trailing hairpin vortex merges into the legs of the leading hairpin vortex, forming a larger combined vortex structure. On top of this combined vortex structure lie two weak vortex heads as shown in Figure 5.21c, this is consistent to what is observed in the dye visualization as shown in Figure 5.19c.

The PIV measurements along spanwise wall-normal plane not only can capture the primary vortices but also the induced secondary vortices underneath the primary vortex

legs as shown in Figure 5.20b, which however cannot be captured by the dye visualization. It is believed that the secondary vortices together with the hairpin legs are able to bring high-momentum fluid into the near-wall region, and hence delay flow separation. As shown in Figure 5.20b, a pair of smaller areas of vorticity concentration in the near-wall region, with vorticity opposite in sign to the hairpin vortex, defines the secondary vortices. Located underneath and outboard of the hairpin legs, they are induced by the hairpin vortex. It is seen that combined vortices at $\Delta\phi = \pi/2$ and partially interacting vortices at $\Delta\phi = \pi$ induce obviously strongest secondary vortices in all four phase differences.

Figure 5.22: Evolution of value of vortex strength of twin SJs at $\Delta\phi = \pi/2$ and $\Delta\phi = 3\pi/2$ and single SJs at (a) mid-span plane and (b) spanwise wall-normal plane. ‘UP’ and ‘DS’ in figure indicates the SJ issued from upstream and downstream actuator.

With the PIV data from streamwise mid-span plane, the evolution of spanwise circulation carried by hairpin heads can be calculated and compared as shown in Figure 5.22a. At $\Delta\phi = \pi/2$, in its initial developing phase, the hairpin vortex issued from the upstream SJ actuator shares a strength evolution process similar to that in the single SJ case. After the vortex meets and merges with its counterpart issued from the downstream SJ actuator, the circulation of combined vortex continues increasing and reaches a peak value $\Gamma = 1.15$ at $t/T = 0.7$, which is a 40% increment compared to the peak value in the single SJ case. Similar to that in single hairpin vortices, after the peak a plateau

appears between $t/T = 1.2$ and 1.7 . At $\Delta\phi = 3\pi/2$, with the weakest interaction, it is not surprising to see that the hairpin vortex from the upstream SJ actuator shares the entire strength evolution process similar to that in the single SJ case, except that it has a slightly higher peak value, which is most likely caused by the downwash flow induced through the suction of the downstream SJ actuator when the vortex passes by. Since in this case the hairpin vortex issued from the downstream SJ actuator emerges $3\pi/2$ later (or $\pi/2$ earlier), its circulation evolution curve is shifted to the left by about $0.25T$. Due to the disturbance of its preceding vortex issued in the previous cycle during its emerging process, this hairpin vortex has a significant lower circulation peak value ($\Gamma = 0.65$) compared to that of its counterpart ($\Gamma = 0.90$) as well as of the single hairpin vortex ($\Gamma = 0.82$). Interestingly, its strength increases again after a graduate decrease. This rebound is caused by the absorption of its preceding hairpin legs, a phenomenon clearly shown in the dye visualization as in Figure 5.19d.

The evolution of streamwise vortex circulation in a spanwise-wall-normal plane $x = 8D_o$ is also compared as shown in Figure 5.22b. To obtain this plot, the circulation of primary streamwise vortices in that plane is calculated at the eight evenly distributed instants during one actuation cycle. In this way the vortex strength at different portions of the interacting vortex structure is presented and compared. As expected, the variation of vortex circulation at $\Delta\phi = \pi/2$ shares a trend similar to that in the single SJ case, and shows the highest peak at the instant when the vortex head passes the plane. Oppositely, at $\Delta\phi = 3\pi/2$ two peaks of lower-amplitude circulation appear, confirming the passage of two separated hairpin vortices.

In the same plane, i.e. $x = 8D_o$, time-averaged streamwise vorticity contours superimposed by velocity vectors are shown in Figure 5.23. The counter-rotating hairpin legs and their associated secondary are well captured, which are represented by pairs of streamwise vorticity concentration areas that are symmetric about the mid-span plane. Compared to the single SJ, the twin SJs regardless of their phase difference are able to produce either stronger or larger primary and secondary vortices. Among the four twin-SJ cases, the primary vortices reach farthest from the wall at $\Delta\phi = \pi/2$ as a result of formation of the combined hairpin vortex. However, they are relatively weaker in the time-average sense due to their low occurrence rate and slant hairpin legs. At $\Delta\phi = 3\pi/2$,

Figure 5.23: Contour of time-averaged streamwise vorticity and velocity vectors in the $x = 8D_o$ plane

the primary vortices stay lowest and are even lower than those in the single SJ case, but are much concentrated and stronger in the time-averaged sense because of their doubled occurrence rate. For the two cases showing time-averaged partially interacting vortex structures, it is found that the vortices are very strong at $\Delta\phi = \pi$ but weak at $\Delta\phi = 0$. The reason for the strong vortices at $\Delta\phi = \pi$ is because, as shown in Figure 5.19c, Figures 5.21c and 5.20c, the partially interacting vortex structures are almost parallel to the wall, hence resulting in strong time-averaged vorticity in the spanwise-wall-normal plane. In addition to the vorticity fields, the velocity vectors shown in all the cases reveal that, in the time-average sense, SJs introduce an upwash flow between the two counter-rotating hairpin legs, and downwash flows outboard and underneath the legs. These downwash

flows can bring outer high-momentum fluid into the near-wall region, and hence are very helpful in flow separation control (Pauley & Eaton, 1988).

Figure 5.24: Contour lines of time averaged wall-normal velocity (without colour, using the same contour levels as in Figure 5.17c) superimposed by contours of streamwise velocity difference between SJ influenced flows and the background boundary layer flow (with colour) and velocity vectors. The vectors are for time-averaged absolute velocities.

As revealed in the above discussions, the boundary layer flow plays an important role in the twin SJ interaction. In return, the twin SJs also influences the boundary layer flow. Figure 5.24 shows two overlapped contours: one is the time-averaged wall-normal velocity (contours without colour) and the other is the time-averaged streamwise velocity that subtracts the background boundary layer velocity field (contours with colour). It is seen that the introduction of SJs into the boundary layer increases the wall-normal velocity

downstream of the SJ actuators. In this aspect, all twin SJs exert much greater influence than the single SJ, as demonstrated by the continuity of the contour lines. Among the four twin SJ cases, the influence of the case at $\Delta\phi = \pi/2$ most penetrates into the crossflow because of the aforementioned constructive interaction of the two hairpin vortices. From the color contours of streamwise velocity, it is seen that the introduction of SJs produces a slant strip of velocity deficit (in blue) along the trajectories of hairpin heads, as well as a strip of velocity surplus (in red) near the wall. The emergence of near-wall velocity surplus well demonstrates the capability of SJs in energizing near-wall flow, which is a favorable feature of flow separation control. It is found that the twin SJs at all $\Delta\phi$ values show larger near-wall velocity surplus than the single SJ. Among the four twin SJs cases, it is the case at $\Delta\phi = \pi$ instead of at $\Delta\phi = 3\pi/2$ that shows the greatest near-wall velocity surplus. Although it seems not reasonable, as shown in Figure 5.23c, the high position of the two counter-rotating vortices makes the downwash flow dominant in the mid-span plane that energize the near-wall flow, whereas in Figure 5.23d the low position of the vortex pair causes mainly the upwash flow in the mid-span plane.

5.3.4 POD analysis

POD analysis on mid-span plane is conducted to extract coherent structures produced by the in-line twin SJs from the energy point of view. For the single SJ case, the fractional contributions of the first ten POD modes to the total fluctuation kinetic energy, $\lambda_n/\Sigma\lambda_n$, are plotted in Figure 5.25a. It shows that the energy levels of the first two modes are similar (21% and 18%, respectively) and much higher than that of other modes. The next two modes also have similar energy levels, i.e. 6% and 5%, respectively. This indicates that in the present flow large-scale energetic flow structures appear in pairs, which was revealed by Ben Chiekh et al. (2013) and Lengani et al. (2014). By scatter plotting all 240 snapshots in a space spanned by the two coefficients of each mode pair as shown in Figure 5.25b, it is found that the scatters for mode Φ_1 and Φ_2 roughly fall on a circle centered at the origin, indicating a 90° phase difference between modes Φ_1 and Φ_2 (Meyer et al, 2007). The appearance of eight scatter clusters reflects the fact that one SJ actuation cycle contains eight equispaced phases in the present PIV measurements. For the second pair, i.e. mode Φ_3 and Φ_4 , Figure 5.25b only shows four scatter clusters falling on a circle

Figure 5.25: POD analysis for the single SJ case: (a) POD energy levels of the first 10 modes, (b) scatters of coefficients a_1 vs a_2 (black solid circle) and a_3 vs a_4 (green hollow square), (c) FFT spectra of a_1 and a_2 , and (d) a_3 and a_4 .

of a smaller diameter, which not only confirms the lower energy levels but also indicates higher frequencies associated with these two modes. This finding is further confirmed by a FFT analysis of all 240 coefficients of a specific mode, each coefficient corresponding to one snapshot. As clearly revealed in Figure 5.25c and 5.25d, both modes Φ_1 and Φ_2 show peaks of similar amplitudes at 2 Hz, i.e. the SJ actuation frequency, whereas both modes Φ_3 and Φ_4 show peaks of smaller amplitudes at 4 Hz, twice of the SJ actuation frequency. This is consistent to what was observed by Ben Chiekh et al. (2013), in which

Figure 5.26: Wall-normal velocity contour of first 4 POD modes for single SJ case at mid-span plane.

the first pair of POD modes dominates in the energy level, and the second mode pair is associated with higher harmonics but lower energy.

The first four POD modes for the single SJ are plotted in Figure 5.26. It confirms that the two modes in either of the mode pairs (Φ_1 and Φ_2 , or Φ_3 and Φ_4) are closely correlated, which share similar flow patterns. There is also a spatial shift of about 90° between the two mode patterns, revealing the convective nature of these large-scale flow structures. Since as revealed their dominant frequency coincides with the SJ actuating frequency, the first pair of POD modes is associated with the convection of hairpin vortices induced by the SJ. The second pair of POD modes, as shown in Figure 5.26c and Figure 5.26d, corresponds to the flow pattern of second harmonic demonstrating the nonlinearity of the SJ-boundary-layer interaction flow.

As the twin SJs operate at $\Delta\phi = \pi/2$ and generate combined hairpin vortices, the energy level and coefficient distribution of POD modes follow similar trends to those in the single SJ case, but with significantly larger values especially for the first mode pair as shown in Figure 5.27: the summation of the energy levels of the first two modes increases

Figure 5.27: POD analysis for $\Delta\phi = \pi/2$ case: (a) POD energy levels of the first 10 modes, (b) scatters of coefficients a_1 vs a_2 (black solid circle) and a_3 vs a_4 (green hollow square), (c) FFT spectra of a_1 and a_2 , and (d) a_3 and a_4 .

from 39% as for the single SJ to 53% at $\Delta\phi = \pi/2$, and the radius of the scatter circle increases from about 0.3 to about 0.6. In addition, as shown in Figure 5.28, the first four POD modes also appear similar to those in the single SJ case, but with obviously increased strength. These POD modes depict the convection of the combined hairpin vortex and its second harmonic, and are associated with enhanced single frequency components as demonstrated in the FFT analysis shown in Figure 5.27c and 5.27d.

However, as the twin SJs operate at $\Delta\phi = 3\pi/2$ and generate two completely sepa-

Figure 5.28: Wall-normal velocity contour of first 4 POD modes for $\Delta\phi = \pi/2$ case at mid-span plane. Refer to Figure 5.26 for the color map.

rated hairpin vortices, things become different. First, as depicted in Figure 5.29a, the energy levels of the first four POD modes fall in a narrow band between 10% and 16%, and are not as distinguishable for pairing as in the previous cases. As a result, the correlation among the coefficients of these four modes is not as obvious as in the previous cases, as shown in Figure 5.29b. By carefully checking the mode shapes shown in Figure 5.30, it is found that the first and fourth modes are actually a pair, and the second and third are another. Furthermore, the dominant structures in the pair of modes Φ_1 and Φ_4 are located near the SJ actuators ($x < 3Do$), which seem similar to the structures associated with the SJ actuation frequency as in the previous cases (Figures 5.26a and 5.26b, Figures 5.28a and 5.28b), whereas the dominant structures in the pair of modes Φ_2 and Φ_3 are located in the downstream of the SJ actuators ($x > 3Do$), which are similar to the structures associated with the second harmonic of the SJ actuation frequency (Figures 5.26c and 5.26d, Figures 5.28c and 5.28d). This finding indicates that in each model multiple frequency components may co-exist. This hypothesis is confirmed by the FFT analysis. As shown in Figures 5.29c and 5.29d, all the four modes have two comparable

Figure 5.29: POD analysis for $\Delta\phi = 3\pi/2$ case: (a) POD energy levels of the first 10 modes, (b) scatters of coefficients a_1 vs a_2 (black solid circle) and a_3 vs a_4 (green hollow square), (c) FFT spectra of a_1 and a_2 , and (d) a_3 and a_4 .

frequencies, one is 2 Hz, the SJ actuation frequency, and the other is 4 Hz, the second harmonic.

5.3.5 DMD analysis

The above POD analyses especially the analysis for the $\Delta\phi = 3\pi/2$ case reveal that POD modes may contain information of multiple time scales, which makes it quite challenging to analyze dynamics of a complex flow system like in the present study. Therefore,

Figure 5.30: Wall-normal velocity contour of first 4 POD modes for $\Delta\phi = 3\pi/2$ case at mid-span plane. Refer to Figure 5.26 for the color map.

in addition to the POD analysis, DMD analysis is also conducted on the same cases, which is able to extract the most representative modes from the dynamic point of view. Figure 5.31a shows the distribution of DMD eigenvalues for the single SJ case, in which each eigenvalue is represented by a circular marker in a space spanned by the real and imaginary parts of the eigenvalue μ_n (see Chapter 3 Eqs. 3.26). All the eigenvalues appear in complex conjugate pairs, as expected due to the convective nature of the boundary layer flow, and their real parts are all negative, indicating the stable nature of this SJ-boundary-layer system. The size of markers is proportional to the DMD mode amplitude b_n (see Eqs. 3.26), which indicates the spatial coherence of associated dynamic modes, i.e. larger symbols correspond to large-scale structures. It shows that the largest two marker pairs are located at $\mu_i/2\pi = 2$ Hz and 4 Hz, respectively, i.e. the fundamental and second harmonics of the SJ actuation frequency. The DMD modes corresponding to these two marker pairs, Ψ_1 and Ψ_3 , are presented in Figures 5.31b and 5.31c. It is found that Ψ_1 and Ψ_3 match the POD modes Φ_1 and Φ_3 (shown in Figures 5.26a and 5.26c) very well, indicating that for this single SJ case, the POD analysis and the DMD analysis have no

Figure 5.31: DMD analysis for the single SJ case: (a) scatters of DMD eigenvalue, and contours of wall-normal velocity of (b) mode Ψ_1 and (c) mode Ψ_3 (using the same contour levels as in POD modes).

Figure 5.32: DMD analysis for the $\Delta\phi = \pi/2$ case: (a) scatters of DMD eigenvalue, and contours of wall-normal velocity of (b) mode Ψ_1 and (c) mode Ψ_3 .

Figure 5.33: DMD analysis for the $\Delta\phi = 3\pi/2$ case: (a) scatters of DMD eigenvalue, and contours of wall-normal velocity of (b) mode Ψ_1 and (c) mode Ψ_3 .

much difference in terms of the mode shapes and corresponding frequency components. This similarity also extends to the twin SJ case with phase difference $\Delta\phi = \pi/2$, in which the combined hairpin vortices are produced. The DMD modes Ψ_1 and Ψ_3 shown in Figures 5.32b and 5.32c match the POD modes Φ_2 and Φ_4 (shown in Figures 5.28b and 5.28d), respectively, in terms of both the topologies and corresponding frequencies. In addition, as shown in Figure 5.32a, the increased sizes of the largest two marker pairs compared to those in the single SJ case confirm the constructive interaction of the twin SJs, which is also supported by the increased size and strength of the coherent structures depicted in the two modes.

As the twin SJs operate at $\Delta\phi = 3\pi/2$ and generate two completely separated hairpin vortices, it is seen from the distribution of DMD eigenvalues shown in Figure 5.33a that the size of the largest marker pair remains almost unchanged compared to that in the single SJ case, whereas the size of the second largest marker pair increases significantly to a size almost equal to that of the largest marker pair. This change indicates that both the first two DMD mode pairs have almost equal contributions to the dynamics of the flow system. Furthermore, the DMD modes obtained for this case look quite different

from the corresponding POD modes. The coherent structures of mode Ψ_1 (shown in Figure 5.33b) are mainly located near the two SJ actuators ($x/D_o = \pm 1$), which are solely associated with the SJ actuation frequency 2 Hz. Not like in the corresponding POD mode Φ_1 and Φ_4 , in this DMD mode no coherent structures appear in the far downstream of the SJ actuators. Therefore, one can conclude that mode Ψ_1 captures the flow dynamics associated with the SJ generation. On the other hand, the coherent structures of mode Ψ_3 (shown in Figure 5.33c) appear throughout the near-wall region downstream of the SJ actuator. The sole frequency they are associated with, i.e. 4 Hz, clearly demonstrates the doubling effect of hairpin vortex appearance rate in this case. The analysis of the present case also demonstrates that sometimes DMD analysis can better extract coherent structures that represent flow dynamics than POD analysis.

5.4 Remarks

In this chapter, interactions of twin circular SJs that are in line with laminar attached crossflows over a flat plate are presented. The resulting vortex structures at four phase differences between twin SJs are investigated using stereoscopic color dye visualization in a water tunnel, simulated particle traces and PIV measurements. The main findings from this study are summarized as follows:

- (i) Three different types of flow structures induced by twin-SJs are observed under different actuation and flow conditions, i.e. one combined vortex, two completely separated vortices, and partially interacting vortex structures. It is found the resulting flow structures are largely depend on the non-dimensional orifice spacing s , and a simple model is proposed to predict it.
- (ii) The vortices issued from the upstream SJ actuator sustain their coherence more easily than their counterparts issued from the downstream SJ actuator, because they have enough time to develop themselves while their counterparts are disturbed during their formation process. This gap is more obvious at low VR and Re_L , making the vortices from upstream SJ actuator as dominant vortices during the interaction. Therefore, vortices from upstream actuator form the inner cores of the interacting structures while their counterparts are scattered at outside layer.

- (iii) Interactions of twin hairpin vortices are then focused for quantitative study using PIV measurement in the mid-span plane and in a selected spanwise-wall-normal plane ($x = 8D_o$) at different time instants. It is found that the combined vortex at $\Delta\phi = \pi/2$ penetrates the boundary layer quickest and deepest in all cases, which is beyond $y/D_o = 3$. Oppositely, two completely separated hairpin vortices at $\Delta\phi = 3\pi/2$ are weakest as individual structures and stay closest to the wall. The evolutions of spanwise circulation in the mid-span plane carried by relevant vortex heads reveal that the strength of combined hairpin vortex is the greatest, about 40% larger than that in the single SJ case. At $\Delta\phi = 3\pi/2$, the hairpin vortex from the upstream SJ actuator shares very similar circulation evolution process to that in the single SJ case, except that it has a slightly higher peak, whereas the hairpin vortex issued from the downstream SJ actuator shows two significantly lower peaks.
- (iv) From PIV results, it also is found that introduction of SJs into the boundary layer increases the wall-normal velocity in the region downstream of the SJ actuators. It also produces a slant strip of streamwise velocity deficit along the trajectories of hairpin heads and a strip of streamwise velocity surplus near the wall. Generally twin SJs induce larger wall-normal velocity and larger near-wall streamwise velocity surplus compared to the single SJ. Among the four twin SJs cases, it is the case at $\Delta\phi = \pi$ instead of at $\Delta\phi = 3\pi/2$ that shows the greatest near-wall velocity surplus.
- (v) From the PIV measurement of present twin SJ problem, it is found that in the single SJ case and the twin SJ case with $\Delta\phi = \pi/2$ the first four DMD modes seem very similar to the first four POD modes, but they are quite different for the twin SJ case with $\Delta\phi = 3\pi/2$. POD extract four flow patterns with no clear correlation between them, and with multiple frequencies in individual mode. However, DMD can clearly extract two types of distinct flow patterns with each flow pattern corresponding to a single frequency. This indicates that although the POD analysis is able to capture the most energetic modes, sometimes it fails to capture the flow dynamics. In this aspect, the DMD analysis performs better.

Chapter 6

SJ Arrays in a Separated Crossflow

On the basic understanding of the interactions between in-line twin circular SJs with attached boundary layers, the work reported in this chapter goes one step further by applying these in-line twin SJs to a separated LBL over inclined flat plates. Both dye visualization and PIV measurement are used to reveal the flow patterns for a better observation and examine the flow control effect of the induced flow structures, respectively. To examine the control effectiveness of the induced flow structures on the separated flow, POD is used to decompose the complex flow field. Note that due to the complicity of the corresponding setup of CFD simulation and limited time frame, the CFD simulation is undergoing and is listed for further work.

6.1 Test conditions

As a first step to study the interaction between twin-SJs and a separated flow, the present work is undertaken in a separated LBL. Working conditions of SJs are set same to case 10 in Chapter 5, i.e. $U_\infty = 0.11$ m/s, $\Delta = 0.105$ mm and $f = 2$ Hz. As such, hairpin vortices are produced by single SJs under conditions of $L = 1.7$ and $VR = 0.16$. As revealed in Figure 5.15 and Figure 5.19 in Chapter 5, three types of flow structures are induced by twin SJs at four phase differences, i.e. one combined vortex at $\Delta\phi = \pi/2$, two completely separated vortices at $\Delta\phi = 3\pi/2$, and partially interacting vortex structures at $\Delta\phi = 0$ and π .

6.2 PIV measurement and dye visualization

Same test rig is used in this study as that in the attached flow study in Chapter 5, except a slop is introduced downstream. The LBL is expected to separate from the slop as described in Figure 3.2 Chapter 3. A transitional plate is added to the horizontal plate with a small upward angle of 3° to introduce a smooth inclined angle. The transitional plate is specially designed to bend upwards with a 5° angle at 10 mm downstream from its upstream edge to introduce obvious flow separation. After then, a flat plate with 150mm length is connected to the downstream edge of the transitional plate, and therefore is inclined to the horizontal plate with 8° upward angle. The origin of the coordinate system is set at middle point on the joint of the transitional plate (where 5° happens) and is about $28D_o$ downstream from the midpoint of twin orifices as shown in Figure 3.2. PIV measurements are taken in two planes, i.e. at the mid-span wall-normal plane and spanwise plane parallel to the inclined plate downstream from the origin of the coordination. The field of view on mid-span wall-normal plane covers $x = -2 \sim 22D_o$, and $y = -3D_o \sim 6D_o$. The corresponding vectors are resolved using a two-frame cross-correlation algorithm, in which a 32×32 pixel IA with an overlap ratio of 50% is chosen, giving a 1.30 mm spacing separation between adjacent vectors. For PIV measurement on spanwise wall-parallel plane, the lightsheet is located at a distance of about 5 mm, i.e. $1D_o$, below the inclined plate so as to keep the surface reflection to an acceptable level. By using an IA of 32×32 pixel in two-frame cross-correlation algorithm, 1.50 mm spatial resolution in spanwise PIV measurement can be obtained. The time is setup according to the movement of the upstream SJ actuator diaphragm, $t = 0$ (and T) corresponds to the beginning of blowing. There are total 8 consecutive phases captured during one actuating cycle T and each phase is averaged from 120 image pairs.

For a clear presentation and explanation of the complex interactions between twin SJs in the separated flow, stereoscope color dye visualizations are used to provide complementary information about the induced flow patterns.

6.3 Uncontrolled separated boundary layer

Dye is injected from the SJ actuator orifice to reveal the location of separation in the baseline case without the actuation of the SJs. Note for better presentations, all the

side view images hereinafter are adjusted such that the crossflow comes from left and the SJs are issued upwards. The LBL is developed along the test plate, the boundary layer thickness is about 12 mm, i.e. $2.4D_o$, and the momentum thickness based Reynolds number is $Re_\theta \approx 170$ at the original point. Due to the smooth curved joints between the plates and relatively small inclined angle, the flow does not separate at the curved joints; instead, it separates at some distances further downstream. From the dye visualization image shown in Figure 6.1, it can be seen that the dye becomes detached from the test surface at about $x = 2D_o$ from the original point. In addition, due to the low value of Reynolds number, there is no obvious turbulence observed in the separated dye trace.

Figure 6.1: Dye visualization of the flow separation over the inclined plate without active control.

300 consecutive frames of PIV images taken at 10 Hz are used to get the time-averaged results of uncontrolled separated flow from both mid-span wall-normal plane (Figure 6.2a) and spanwise wall-parallel plane (Figure 6.2b), respectively. In Figure 6.2a, to clearly show the separated LBL, contour of streamwise velocity is plotted as that the white color strip represents the reverse flow region beneath the separation line, i.e. $u/U_\infty \leq 0$. Together with the streamlines, it shows that the baseline LBL separates from the wall at about $x = 3D_o$. The small discrepancy of the separation point observed from PIV measurement compared to dye visualization may come from the reflection of the laser light from the test surface making separation point difficult to be accurately captured. The separated boundary layer then slowly inclines to the wall with a reverse flow region (white colore) located beneath it. As the laser plane at spanwise wall-parallel direction is about 5mm, i.e. $1D_o$, offset away from the wall, spanwise separation line is captured

at about $x = 11D_o$ both by the time-averaged streamwise velocity and the streamlines at Figure 6.2b. Note that the plane view is adjusted so as that the crossflow comes from bottom to top. The location of spanwise separation line can be identified as the region where the crossflow meets the reversed flow (white colore) and so as the streamlines from upstream begin to divert sideways. In order to quantify the control effect, the streamwise location of the space-averaged spanwise separation line S_L is calculated along a range $z = -5D_o \sim 5D_o$ within which the maximum spanwise control effect of twin SJs can be covered. In the uncontrolled flow, S_L is located at $11D_o$ as shown in Figure 6.2b.

Figure 6.2: Time-averaged baseline flow of streamwise velocity contour and streamlines (a) at mid-span wall-normal plane and (b) at a spanwise wall-parallel plane, S_L/D_o indicates the averaged separated line within $z = -5D_o$ to $z = 5D_o$.

6.4 SJ-controlled separated flow

6.4.1 SJ-induced flow structures in separated flow

Figure 6.3 to Figure 6.5 show the stereo colour dye visualizations of the single SJs as well as twin SJs with a separated flow. Although they show that both the flow structures induced by single SJs as well as twin SJs are similar to that in attached crossflows at the near orifice region as presented in Chapter 5, differences are still introduced when these flow structures develop to downstream in the separated boundary layer. First, hairpin

Figure 6.3: Dye visualization of the flow structure induced by single SJs over the inclined plate. (Red dashed line indicates the edge of boundary layer)

vortices generated by single SJ penetrate the boundary layer edge at downstream as shown in Figure 6.3, making hairpin head more upright. Their legs are highly stretched which are overlapped by the trailing hairpin vortices. In addition, due to the inclined separated flow, these flow structures slowly move downward to the wall, especially for the hairpin legs.

As strong stretched vortex rings are induced by twin SJs at $\Delta\phi = \pi/2$, flow dye is mainly concentrated at the vortex heads when these flow structures develop to downstream as shown at Figure 6.4b. In addition, due to the strong rotation at the center of vortex heads and weak rotation at the head boundaries, dye trace is rotated faster in the center than at boundary, resulting in “S” shape dye traces as shown in side view of Figure 6.4b. For two completely separated hairpin vortices at $\Delta\phi = 3\pi/2$ in Figure 6.5b, they do not show many differences when travel to the downstream separated flow compared to at near orifice region in the attached crossflow. Only the hairpin legs significantly lose their coherent structures because they are close to the separated flow region. By comparing them to single SJs in Figure 6.3, it is found that completely separated hairpin vortices are more close to the inclined plate. For the partially interacting vortices, the leading hairpin vortices at $\Delta\phi = 0$ are already found to be very weak at near orifice region in Chapter 5 due to the disturbance caused by the trailing hairpin vortices. As further

Figure 6.4: Dye visualization of the flow structure induced by twin SJs at (a) $\Delta\phi = 0$ and (b) $\Delta\phi = \pi/2$ over the inclined plate.

develop, the leading vortices are continually weaken, and are hardly to be recognized in Figure 6.4a. On the contrary, the trailing vortices entrain much part of the leading vortices, becoming dominant flow structures. At $\Delta\phi = \pi$, although the leading vortices still hold their coherent structures when they travel to downstream, the trailing vortices are much stronger than the leading vortices, and show turbulent flow patterns as shown in Figure 6.5a.

To further examine the induced flow structures and their effect on the separated flow, Figure 6.6 presents the contours of phase-averaged streamwise velocity on the mid-span wall-normal plane at $t/T = 0.2$ from PIV measurements. In Figure 6.6b, the passages

Figure 6.5: Dye visualization of the flow structure induced by twin SJs at (a) $\Delta\phi = \pi$ and (b) $\Delta\phi = 3\pi/2$ over the inclined plate.

of the hairpin vortices induced by single SJs can be seen as lumps of low-speed fluid that propagate downstream from left to right (Zhong & Zhang, 2013). By comparing to the uncontrolled flow in Figure 6.6a, separation point is clearly delayed by single SJs to about $x = 6D_o$ and the separation line is suppressed to the wall. When twin SJs are actuated, in general, flow separation at four phase differences are further delayed or suppressed than single SJs. This indicates the constructive interaction of the twin in-line SJs. The reverse flow region (white color region) seems to be most suppressed at $\Delta\phi = \pi$ as shown in Figure 6.6e. This is consistent to the findings in Chapter 5: it is found that case at $\Delta\phi = \pi$, instead of at $\Delta\phi = 3\pi/2$, shows the greatest near-wall

Figure 6.6: Contours of phase-averaged streamwise velocity at $t/T = 0.2$ at mid-span wall-normal plane. (Refer to Figure 6.2a for color map)

velocity surplus in an attached flow on mid-span plane. However, this control effect seems not robust indicated by the thickest buffer area (shown by the light blue area) between the reverse flow and the separated crossflow in all four phase differences. Consistent to the observation of dye visualizations, combined vortices are generated at $\Delta\phi = \pi/2$ and penetrate the boundary layer most deeply to about $y = 4D_o$ in Figure 6.6d. Compared to single SJs, completely separated hairpin vortices are recognized by double numbered low-speed bulges at $\Delta\phi = 3\pi/2$ in Figure 6.6f. Consistent to the observation from dye visualization, the partially interacting flow structures captured by PIV show only the dominate vortices at $\Delta\phi = 0$ and $\Delta\phi = \pi$ in Figures 6.6c and 6.6e. Besides these actuating vortices, wave patterns on the edge of reverse flow region are observed in all twin-SJ controlled flows especially obvious at $\Delta\phi = 0$ and $\Delta\phi = \pi/2$. This is believed to

be caused by the passing periodic flow structures (Zhang & Zhong, 2011).

6.4.2 Time-averaged flow control effect

Figure 6.7: Contour of time-averaged streamwise velocity and streamlines at mid-span wall-normal plane. Refer to Figure 6.2a for the color map.

The flow control effects of twin SJs in time-averaged sense at various phase differences as well as single SJs are examined and compared to uncontrolled flow at mid-span wall-normal plane in Figure 6.7. By comparing Figure 6.7b to Figure 6.7a, it is seen that the separated boundary layer is suppressed downward to the inclined plate a little bit when the single SJs is actuated. When twin SJs are issued, separated flow is obviously delayed or suppressed in all four phase differences especially at $x = 3D_o \sim 8D_o$. However, control effect at these four phase differences still shows distinct difference. Impact of two typical

fluid structures induced at $\Delta\phi = \pi/2$ and $\Delta\phi = 3\pi/2$ are firstly discussed by comparing Figures 6.7d and 6.7f, it can be seen that the separated boundary layer is more suppressed to the inclined plate with longer streamwise distance at $\Delta\phi = 3\pi/2$ compared to that at $\Delta\phi = \pi/2$. As revealed by PIV measurement in Chapter 5, this is because completely separated hairpin vortices induced at $\Delta\phi = 3\pi/2$ are more close to the wall, and therefore can imply strong and consist impact on the separated flow. Oppositely, the combined vortex at $\Delta\phi = \pi/2$ penetrates the boundary layer quickly, resulting in weak and quick decayed impact on the near wall region at mid-span plane. As shown in Figures 6.7c and 6.7e, flow separation is more suppressed by partially interacting vortices at $\Delta\phi = \pi$ than at $\Delta\phi = 0$, and even than at $\phi = 3\pi/2$.

Figure 6.8 shows control effect of induced flow structures on the spanwise wall-parallel plane by plotting the time-averaged streamwise velocity contour and streamlines. As the single hairpin vortices are issued, a delayed separation area near the middle region can be observed in Figure 6.8b. Delayed flow separation becomes much more obvious when twin SJs are actuated. Consistent to the observations at mid-span wall-normal plane, flow separation delayed by combined vortices at $\Delta\phi = \pi/2$ is shorter in streamwise direction in Figure 6.8d than completely separation hairpin vortices at $\Delta\phi = 3\pi/2$ in Figure 6.8f. However, the impact area of combined vortices $\Delta\phi = \pi/2$ is much wider in spanwise direction ranging between $z = \pm 5D_o$ compared to completely separated vortices at $\Delta\phi = 3\pi/2$ limited within $z = \pm 2.5D_o$. The reason is proposed in Chapter 5 from Figure 5.23: one combined vortex and its secondary vortices impact large area in spanwise direction, oppositely, two completely separated hairpin vortices and the weak secondary vortices are concentrated to the mid-span area. By space averaging, it can be seen that delaying separation line reaches to about $S_L = 23.7D_o$ at $\Delta\phi = \pi/2$. And the averaged separation line at $\Delta\phi = 3\pi/2$ is at $S_L = 17.3D_o$ due to its narrow influenced area. Also, the averaged separation lines delayed by partially interacting vortices at $\Delta\phi = 0$ and $\Delta\phi = \pi$ fall between this range.

6.5 POD analysis

As discussed above in temporal and time-averaged sense, interactions of vortices induced at $\Delta\phi = \pi/2$ and $\Delta\phi = 3\pi/2$ with a separated boundary layer show distinct difference,

Figure 6.8: Contour of time-averaged streamwise velocity with streamlines in the plane parallel to the inclined plate. Refer to Figure 6.2b for the color map.

Figure 6.9: POD analysis for the single SJ case at mid-span wall-normal plane: (a) POD energy levels of the first 10 modes, (b - d) contour of streamwise velocity of first 3 POD modes. (Black dashed line: boundary layer edge, Red solid line: separation line)

and different flow control effect. POD provides a suitable scheme to extracting flow structures according to their fluctuation energy, and therefore can be used to decompose current complex flow field and examine the flow control efficiency of the distinct induced flow structures. As there is almost no obvious coherent structures captured by POD modes at the spanwise wall-parallel plane, POD results from mid-span wall-normal plane are only presented here. To make current discussion focus, only three typical sub-cases are discussed, i.e. single SJs, combined vortices at $\Delta\phi = \pi/2$ and completely separated vortices $\Delta\phi = 3\pi/2$. Although not shown here, POD modes extracted from uncontrolled flow reveal that there is not obvious fluctuation in the uncontrolled separated LBL due to the low Reynolds number.

In the most energetic mode Φ_1 extracted from single-SJ-controlled flow, a jet-like flow pattern induced by the passing hairpin vortices near to the separation line (extracted from

Figure 6.10: POD analysis for the $\Delta\phi = \pi/2$ case at mid-span wall-normal plane: (a) POD energy levels of the first 10 modes, (b - d) contour of streamwise velocity of first 3 POD modes. Refer to Figure 6.9 for the color map.

time-averaged PIV data) is captured as shown in Figure 6.9b. Due to the close location, this jet-flow can directly impact on the reverse flow region. Similar to the POD modes associated with the hairpin vortices in an attached crossflow as shown in Chapter 5, one pair of modes $[\Phi_2, \Phi_3]$, with similar energy level as shown in Figure 6.9a, is then extracted with similar pattern shape and a phase shift indicating the convective nature of the hairpin vortices as shown in Figures 6.9c and 6.9d. From Figure 6.9a, it can be seen that the most energetic mode Φ_1 takes about 4.4% of the total fluctuation energy, then modes pair of $[\Phi_2, \Phi_3]$ captures about 5.6% in total. Note that the low energy captured by the POD modes is believed to be caused by the strong background noise.

For twin SJs at $\Delta\phi = \pi/2$ at which combined vortices are generated, opposite to the POD mode energy sequence of single SJs, the pair of modes $[\Phi_1, \Phi_2]$ (Figures 6.10b and 6.10c) associated with the combined vortices is more energetic than jet-like mode

Figure 6.11: POD analysis for the $\Delta\phi = 3\pi/2$ case at mid-span wall-normal plane: (a) POD energy levels of the first 10 modes, (b - d) contour of streamwise velocity of first 3 POD modes. Refer to Figure 6.9 for the color map.

Φ_3 (Figure 6.10d) as shown in Figure 6.10a. In addition, jet-like flow pattern captured in POD mode is not continuous streak in just one single mode any more, but is divided into several modes. As shown in Figure 6.10d, the most energetic jet-like pattern is captured at the downstream location of the separated flow region. This indicates that the separated flow is more unstable when it travels far from the separation point. As shown in Figure 6.10a, the pair of modes $[\Phi_1, \Phi_2]$ takes about 11% of total fluctuation energy which is about twice of that for single SJs. However, jet-like flow mode Φ_3 only takes about 3.8% even lower than single SJs.

For twin SJs at $\Delta\phi = 3\pi/2$ where completely separated hairpin vortices are induced, same to single SJs case, POD mode Φ_1 (Figure 6.11b) associated with the jet-like flow is the most energetic mode as shown in Figure 6.11a. It is then followed by the pair of modes $[\Phi_2, \Phi_3]$ which is related to the heads of completely separated hairpin vortices

as shown in Figures 6.11c and 6.11d. Hairpin legs are barely captured because they lose their coherent flow structures significantly as shown from the dye visualization in Figure 6.5b. Due to the strong control effect implied by these vortices, mode Φ_1 takes 6.6% of the total fluctuation energy far higher than combined vortices and even single SJs. Oppositely, The energy of modes $[\Phi_2, \Phi_3]$ is even lower than that of single SJs, and takes only about 5.5%. The highest energy percentage taken by the jet-like flow pattern near to the separation line implies that flow separation is more efficiently affected by two completely separated hairpin vortices at $\Delta\phi = \pi/2$ than combined vortices at $\Delta\phi = 3\pi/2$ and single SJs at mid-span wall-normal plane.

6.6 Remarks

In this chapter, an experimental investigation is carried out to investigate the control effect of twin in-line SJs at four phase difference $\Delta\phi$ on a separated LBL flow over inclined flat plates. The flow and actuation conditions are set for the generation of hairpin vortices induced by single SJs. The extents of flow separation delayed by the flow structures induced by twin hairpin vortices are examined and compared using PIV measurement at relatively far downstream from SJ orifices. Complementary dye visualizations are also presented to reveal the interacting flow structures. The main findings from this study are summarized as follows:

- (i) Twin hairpin vortices produce stronger control effect on a separated LBL regardless of the phase difference than single hairpin vortices, indicating the constructive interaction of the twin in-line hairpin vortices.
- (ii) One combined vortex induced by twin SJs at $\Delta\phi = \pi/2$ produces widest separation delay in spanwise direction but with limited impact on wall-normal direction and streamwise direction. On the contrary, two completely separated hairpin vortices at $\Delta\phi = 3\pi/2$ induce narrowest separation delay in spanwise direction, but can suppress flow separation more significantly in wall-normal direction and last for longer distance along the mid-span wall-normal plane than combined vortices. On a plane parallel to the inclined plate, it is found that partially interacting flow

structures at $\Delta\phi = 0$ and at $\Delta\phi = \pi$ generally imply intermediate separation control effect. But flow separation is most suppressed at $\Delta\phi = \pi$ in all four phase differences at mid-span wall-normal plane.

- (iii) POD analysis of flow field on mid-span wall-normal plane shows two types of most energetic flow patterns: jet-like flow near the separation line and actuating flow structures induced by SJs. In addition, jet-like mode is most energetic at single SJ case and twin completely separated hairpin vortices at $\Delta\phi = 3\pi/2$ case, then is followed by the modes pair of corresponding actuating structures. Oppositely, modes pair of actuating flow structures is placed first at $\Delta\phi = \pi/2$ when combined vortices are formed. The mode associated with the jet-like flow pattern near to the separation line takes higher percentage of total fluctuation energy at $\Delta\phi = 3\pi/2$ than at $\Delta\phi = \pi/2$ and single SJ case. This implies that flow separation is more efficiently affected by two completely separated hairpin vortices at $\Delta\phi = 3\pi/2$ than combined vortices at $\Delta\phi = \pi/2$ and single SJs at mid-span wall-normal plane.

Chapter 7

Conclusions and Recommendation for Future Work

7.1 Conclusions

This PhD research mainly focuses on hairpin vortices induced by single SJs and SJ arrays in various boundary layers and their impact on the boundary layers in context of flow separation control. First, a CFD simulation framework is developed for this research, which is able to capture key features of SJs issued into crossflows. With this framework, the similarities and differences of SJ-induced hairpin vortices in a LBL and in a TBL are studied. Second, a water tunnel test rig is designed and developed to study the interaction of twin in-line SJs in an attached LBL. The resulting vortex structures under different actuation and flow conditions are observed and analyzed using stereoscopic color dye visualization, PIV measurements, and CFD simulations. Both POD and DMD analyses are used to extract dominant flow structures from energy and dynamics points of view, respectively. Finally, these twin in-line SJs are applied on a separated LBL over an inclined flat plate to examine the control effect of the resulting vortex structures. POD analysis is conducted to decompose the complex flow field, and to examine the control effectiveness of these vortex structures. The objectives introduced in Chapter 1 are achieved. Major conclusions are summarized as follows:

- (i) The impact of the nature of a crossflow, i.e., whether it is laminar or turbulent, on the performance of SJs in flow separation control is revealed. Under the same crossflow and SJ actuation conditions, hairpin vortices are generated and compared

in both the LBL and TBL. The hairpin vortex travels faster and is in a more bent shape in the TBL than in the LBL, due to the significant difference in the velocity profiles of the two boundary layers. In addition, because of the influence of turbulence structures, the hairpin vortex in the TBL is apparently asymmetric, oscillates laterally, and dissipates fast, whereas it is symmetric and persistent in the LBL. The changes of velocity profiles, wall shear stress and shape factor reveal that the influence of the hairpin vortex in the TBL is wider but weaker and lack of persistence compared to that in the LBL. Therefore, to achieve similar flow separation control effect to that in the LBL, a much stronger SJ is required for the TBL case.

- (ii) The influence of the array configuration and operating condition of an SJ array on the interacting vortex structures is revealed with the focus on phase difference. For twin SJs in line with an attached LBL, three types of flow structures are identified under various operating conditions, i.e., one combined vortex, two completely separated vortices, and partially interacting vortex structures. It is found the resulting flow structures largely depend on the operational phase difference $\Delta\phi$. Based on the dye visualization observation, a simple model is proposed to predict the resulting flow structures. It is also found that the vortices issued from the upstream SJ actuator can sustain their coherence more easily than their counterparts issued from the downstream SJ actuator. This observation is more obvious at low VR and Re_L values. The PIV measurements further reveal that the one combined vortex, at phase difference $\Delta\phi = \pi/2$, along with accompanying secondary vortices influences the boundary layer to the largest extent in the wall-normal and spanwise directions. On the other hand, the two completely separated hairpin vortices at $\Delta\phi = 3\pi/2$ exert the strongest impact to the narrowest near-wall region. The POD and DMD analyses indicate that the boundary layer flow disturbed by the single SJ and one combined vortex contains a dominant coherent structure that appears with one major frequency. On the contrary, the most energetic coherent structures in the disturbed boundary layer with the two completely separated vortices appear with two major frequencies.

- (iii) The control effect of the interacting flow structures induced by SJ arrays is examined. When the resulting flow structures induced by the in-line twin SJs are applied to a separated LBL, it can be seen that the twin SJs produce greater control effect regardless of the phase difference than the single SJ. In addition, one combined vortex at $\Delta\phi = \pi/2$ produces the widest separation delay region in the spanwise direction, but with a limited impact on the wall-normal and streamwise directions. On the contrary, the two completely separated vortices at $\Delta\phi = 3\pi/2$ induce a narrowest separation delay region, but suppress the flow separation more effectively in the wall-normal direction and last for the longest distance in streamwise direction. The partially interacting vortex structures exert intermediate control effects. By analyzing the separated shear layer using POD, it is found that the energy associated with the jet-like flow near the separation line is higher when the two completely separated vortices are generated, indicating that the two completely separated vortices are more effective in suppressing separation than the one combined vortex.

Through this research, a more thorough understanding in underlying physics associated with SJ-based flow separation control has been achieved, which can be extended to future SJ-technology applications.

7.2 Recommendations for Future Work

7.2.1 Single SJs in boundary layers

Although SJ-induced hairpin vortices are the focus in the present study, it is worth pursuing a detailed investigation on the performances of the other two SJ-induced vortex structures, i.e., stretched vortex rings and tilted vortex rings, at different flow and actuation conditions. These vortices are stronger than hairpin vortices and are able to sustain their coherence more easily especially in TBLs. Therefore, they may be able to deliver more lasting impacts on boundary layers. However, due to their farther distance from the wall, their impact on the near-wall region especially the separation point may be limited. To give an answer to this issue, further investigation is needed in both LBLs and TBLs.

7.2.2 SJ arrays in boundary layers

As the orifice distance d/D_o is fixed in current research on twin in-line SJs, the result is limited to further extend the proposed model for predicting interacting flow structures. In addition, more case studies with large range of St value need to be conducted in the future to extend this model. Besides the significant influence of phase difference $\Delta\phi$ demonstrated in the current research, the yaw angle γ , the velocity ratio VR_j and frequency ratio FR_j of SJ arrays are also important for the interactions of SJ arrays. When the yaw angle $\gamma \neq 0$ and the jet-axis-distance d/D_o is small enough to allow interactions, the counter-rotating streamwise vortices issued from two neighboring SJ actuators are expected to interact in a destructive manner if $\Delta\phi = 0$. However, if $\Delta\phi \neq 0$ and the neighboring SJs are issued alternatively, the destructive interactions may be relieved. The interactions will become even complicated if non-unity SJ velocity ratio and frequency ratio are further introduced, i.e., $VR_j \neq 0$ and $FR_j \neq 0$. Therefore, a more comprehensive parameter study on the interactions of SJ arrays can be planned to find the optimal SJ array configuration in the context of flow separation control. In addition, as only circular SJ arrays are focused in current research, SJ arrays issued from other types of orifices, such as thin slot (high-aspect-ratio rectangular orifice)(Smith & Glezer, 1998; Smith et al., 1999; Dandois et al., 2007) and finite-span rectangular orifice (Shani et al, 2011), worth further study.

Furthermore, the SJ arrays are studied only in LBLs in the current research, the next step can be applying the SJ array in TBLs that is more realistic in real-world applications. Due to background turbulence and quite different mean velocity profiles, the SJ-array-induced flow structures in TBLs are expected to vary from what is revealed in the current SJ-array-LBL interactions, which is worth investigating. In addition, CFD simulations are encouraged to reveal the details of such complex interaction.

Publications

- (i) WEN, X. & TANG, H. 2014 On hairpin vortex induced by circular synthetic jets in laminar and turbulent boundary layers. *Comput. Fluids* **95**, 1–18.
- (ii) WEN, X., TEO, K., & TANG, H. 2014 Experimental study of in-line twin synthetic jets in a laminar boundary layer. *16th International Symposium on Flow Visualization, Okinawa, Japan*.
- (iii) WEN, X. & TANG, H. 2012 Interaction of synthetic jets with laminar and turbulent boundary layers. *18th Australasian Fluid Mechanics Conference, Launceston, Australia*.
- (iv) WEN, X. & TANG, H. 2014 Effect of phase difference on the interaction of hairpin vortices induced by in-line twin synthetic jets. submitted.
- (v) WEN, X. & TANG, H. 2014 Interaction of in-line twin synthetic jets in cross flows - a qualitative study. submitted.
- (vi) WEN, X., TANG, H. & DUAN, F. 2014 Vortex dynamics of in-line twin synthetic jets in a laminar boundary layer. submitted.

References

- ADRIAN, R.J. 2007 Hairpin vortex organization in wall turbulence. *Phys. Fluids* **19**, 041301.
- ADRIAN, R.J. & LIU, Z.C. 2002 Observation of vortex packets in direct numerical simulation of fully turbulent channel flow. *J. Vis.* **5**, 9-19.
- ADRIAN, R.J., MEINHART, C.D. & TOMKINS, C.D. 2000 Vortex organization in the outer region of the turbulent boundary layer. *J. Fluid Mech.* **422**, 1-54.
- ACARLAR, M.S. & SMITH, C.R. 1987 A study of hairpin vortices in a laminar boundary layer. Part 1. Hairpin vortices generated by a hemisphere protuberance. *J. Fluid Mech.* **175**, 1-41.
- ACARLAR, M.S. & SMITH, C.R. 1987 A study of hairpin vortices in a laminar boundary layer. Part 2. Hairpin vortices generated by fluid injection. *J. Fluid Mech.* **175**, 43-83.
- AIRIAU, C., BOTTARO, A., WALTHER, S. & LEGENDRE, D.A. 2003 A methodology for optimal laminar flow control: application to the damping of tollmienschlichting waves in a boundary layer. *Phys. Fluids* **15**, 1131-1145.
- AMITAY, M., BARTON, L.S. & GLEZER, A. 1998 Aerodynamic flow control using synthetic jet technology. *AIAA Paper 98-0208*.
- AMITAY, M. & GLEZER, A. 2002 Role of actuation frequency in controlled flow reattachment over a stalled airfoil. *AIAA Paper 2000-4334*.
- AMITAY, M., HONOHAN, A., TRAUTMAN, M. & GLEZER, A. 1997 Modification of the aerodynamic characteristics of bluff bodies using fluidic actuators. *AIAA Paper 97-2004*.

REFERENCES

- AMITAY, M., SMITH, D. R., KIBENS, V., PAREKH, D. E. & GLEZER, A. 2001 Aerodynamic flow control over an unconventional airfoil using synthetic jet actuators. *AIAA J.* **39**, 361–370.
- ANDRIANNE, M., RAZAK, N.A. & DIMITRIADIS, G. 2011 Flow Visualization and Proper Orthogonal Decomposition of Aeroelastic Phenomena. *Wind Tunnels*.
- BEN CHIEKH, M., MICHARD, M., GUELLOUZ, M.S. & BRA, J.C. 2013 POD analysis of momentumless trailing edge wake using synthetic jet actuation. *Exp. Therm. Fluid Sci.* **46**, 89–102.
- BHATTACHARJEE, S., SCHEELKE, B. & BROUTT, T.R. 1986 Modification of vortex interactions in a reattaching separated flow. *AIAA J.* **24**, 623–629.
- CATER, J.E. & SORIA, J. 2002 The evolution of round zero-net-mass-flux jets. *J. Fluid Mech.* **472**, 167–200.
- CHAKRABORTY, P., BALACHANDAR, S. & ADRIAN, R. 2005 On the relationships between local vortex identification schemes. *J. Fluid Mech.* **535**, 189–214.
- CHEN, H., REUSS, D.L., HUNG, D.L.S. & SICK, V. 2013 A practical guide for using proper orthogonal decomposition in engine research. *Int. J. Engine Res.* **14**, 307–319.
- CHONG, M.S. 1990 A general classification of three-dimensional flow fields. *Phys. Fluids A* **2**, 765–777.
- CROOK, A 2002 The control of turbulent flows using synthetic jets. *PhD thesis* University of Manchester, UK.
- CROOK, A., SADRI, A.M. & WOOD, N.J. 1999 The development and implementation of synthetic jets for the control of separated flow. *AIAA Paper 99-3176*.
- CROOK, A. & WOOD, N. 2001 Measurements and visualisations of synthetic jets. *AIAA Paper 2001-0145*.
- CUI, J. GUO, D. & CARY, A.W. 2003 Numerical Simulation of behavior of synthetic jets in cross-flow. *AIAA Paper 2003-1264*.

REFERENCES

- DANDOIS, J. & GARNIER, E. 2006 Unsteady simulation of a synthetic jet in a crossflow. *AIAA J.* **44**, 225-238.
- DANDOIS, J., GARNIER, E. & SAGAUT, P. 2007 Numerical simulation of active separation control by a synthetic jet. *J. Fluid Mech.* **574**, 25-58.
- DEEN, W.M. 1998 Analysis of Transport Phenomena. *Oxford University Press*.
- DEJOAN, A. & LESCHZINER, M.A. 2004 Large eddy simulation of periodically perturbed separated flow over a backward-facing step. *Intl J. Heat Fluid Flow* **25**, 581-592.
- DELERY, J.M. 1985 Shock wave/turbulent boundary layer interaction and its control. *Prog. Aerosp. Sci.* **22**, 209-280.
- DUBIEF, Y. & DELCAYRE, F. 2000 On coherent-vortex identification in turbulence. *J. Turbulence* **1**, 1-22.
- ELIMELECH, Y., VASILE, J. & AMITAY, M. 2011 Secondary flow structures due to interaction between a finite-span synthetic jet and a 3-D cross flow. *Phys. Fluids*. **23**(9), 094104.
- ERLEBACHER, G., HUSSAINI, M.Y., SPEZIALE, C.G. & ZANG, T.A. 1992 Toward the large-eddy simulation of compressible turbulent flows. *J. Fluid Mech.* **238**, 155-185.
- EROGLU, A. & BREIDENTHAL, R.E. 2001 Structure, Penetration, and Mixing of Pulsed Jets in Crossflow. *AIAA J.* **39**, 417-423.
- FUGAL, S.R., SMITH, B.L., & SPALL, R.E. 2005 Displacement amplitude scaling of a two-dimensional synthetic jet. *Phys. Fluids* **17**, 045103-10.
- FUKUNAGA, K. 1990 Introduction to Statistical Pattern Recognition (2nd edition). *Academic Press*.
- GERMANO, M., PIOMELI, U., MOIN, P. & CABOT, W.H. 1996 Dynamic Subgrid-Scale Eddy Viscosity Model. In *Summer Workshop, Center for Turbulence Research*.
- GAD-EL-HAK, M. 2000 Flow control: passive, active, and reactive flow management. Cambridge University Press.

REFERENCES

- GAO, L. 2011 The pinch-off process of the leading vortex ring in a starting circular jet. *PhD thesis* Nanyang Technological University, Singapore.
- GHARIB, M., RAMBOD, E. & SHARIFF, K. 1998 A universal time scale for vortex ring formation. *J. Fluid Mech.* **360**, 121–140.
- GISSEN, A.N., VUKASINOVIC, B. & GLEZER, A. 2010 Manipulation of streamwise vorticity in an emulated diffuser boundary layer using hybrid flow control. *AIAA paper 2010-4586*.
- GORDARD, G. & STANISLAS, M. 2006 Control of a decelerating boundary layer. Part 1: Optimization of passive vortex generators. *Aerosp. Sci. Technol.* **10**, 181–191.
- GORDON, M., CATER, J.E. & SORIA, J. 2004 Investigation of the mean passive scalar field in zero-net-mass-flux jets in cross-flow using planar-laser-induced fluorescence. *Phys. Fluids* **16**, 794–808.
- GORDON, M. & SORIA, J. 2002 PIV measurements of a zero-net-mass-flux jet in cross flow. *Exp. Fluid* **33**, 863–872.
- GREENBLATT, D., DARABI, A., NISHRI, B., & WYGNANSKI, I.J. 1999 Some factors affecting stall control with particular emphasis on dynamic stall. *AIAA Paper 99-3504*.
- GREENBLATT, D., PASCHAL, K.B., YAO, C.S. & HARRIS, J. 1996 Experimental investigation of separation control. Part 2: zero mass-flux oscillatory blowing. *AIAA J.* **44**, 2831–2845.
- GREENBLATT, D. & WYGNANSKI, I.J. 2000 The control of flow separation by periodic excitation. *Prog. Aerosp. Sci.* **36**, 487–545.
- GLEZER, A. & AMITAY, M. 2002 Synthetic jets. *Annu. Rev. Fluid Mech.* **34**, 503–529.
- GRECO, C.S., IANIRO, A., ASTARITA, T. & CARDONE, G. 2013 On the near field of single and twin circular synthetic air jets. *Int. J. Heat Fluid Flow* **44**, 41–52.
- HAIDARI, A.H. & SMITH, C.R. 1994 The generation and regeneration of single hairpin vortices. *Int. J. Heat Fluid Flow* **277**, 135–162.

REFERENCES

- HASAN, M. & KHAN, A. 1992 On the instability characteristics of a reattaching shear layer with nonlaminar separation. *Int. J. Heat Fluid Flow* **13**, 224-231.
- HASNAIN, Z. & FLATAU, A.B. 2012 Numerical Study and Experimental Validation of the Interaction of Multiple Synthetic Jet Actuators with Cross Flow. *AIAA Paper 2012-1247*.
- HASSAN, A.A. & MUNTS, E.A. 2000 Traverse and near-tangent synthetic jets for aerodynamic flow control. *AIAA Paper 2000-4334*.
- HEAD, M.R. & BANDYOPADHYAY, P.R. 1981 New aspects of turbulent boundary-layer structure. *J. Fluid Mech.* **107**, 279.
- HINZE, J.O. 1975 Turbulence. *McGraw-Hill Publishing Co.*
- HJELMFELT, A. & MOCKROS, L. 1966 Motion of discrete particles in a turbulent fluid. *Appl. Sci. Res.* **16**, 149-161.
- HOLMAN, R., UTTURKAR, Y., MITTAL, R., SMITH, B. L. & CATTAFESTA, L. 2005 Formation criterion for synthetic jets. *AIAA J.* **43**, 2110–2116.
- HONAMI, S. & MOTOSUKE, M. 2012 Vortex interaction of in-line synthetic jets injected at different phase in low Reynolds number cross flow. *AIAA Paper 2012-3243*.
- HUANG, H., DABIRI, D. & GHARIB, M. 1997 On errors of digital particle image velocimetry. *Meas. Sci. Technol.* **8**, 1427-1440.
- HUERRE, P. & ROSSI, M. 1998 Hydrodynamic instabilities in open flows. In *Hydrodynamics and Nonlinear Instabilities*, **Cambridge University Press**.
- HUNT J. C. R., WRAY A. A. & MOIN P. 1988 Eddies, streams, and convergence zones in turbulent flows. In *Proceedings of the 1988 summer program, Center for Turbulence Research, Stanford University*, 193–208.
- IAI, T., IWABUCHI, K., MOTOSUKE M. & HONAMI, S. 2010 Vortex behavior of in-line synthetic jets in cross flow at low Reynolds number. *AIAA Paper 2010-4412*.

REFERENCES

- INGARD, U. & LABATE, S. 1950 Acoustic circulation effects and the nonlinear impedance of orifices. *J. Acoust. Soc. Am.* **22**, 211-218.
- JABBAL, M., WU, J. & ZHONG, S. 2006 The performance of round synthetic jets in quiescent flow. *Aeronaut. J.* **110**, 382-393.
- JABBAL, M. & ZHONG, S. 2008 The near wall effect of synthetic jets in a boundary layer. *Int. J. Heat Fluid Flow* **29**, 119-130.
- JABBAL, M. & ZHONG, S. 2010 Particle image velocimetry measurements of the interaction of synthetic jets with a zero-pressure gradient laminar boundary layer. *Phys. Fluids* **22**, 063603.
- JAVADI, A & EL-ASKARY, W.A. 2011 Numerical prediction of turbulent flow structure generated by a synthetic cross-jet into a turbulent boundary layer. *Inter. Int. J. Numer. Meth. Fluids* **69**, 1219-1236.
- JEONG, J. & HUSSAIN, F. 1995 On the identification of a vortex. *J. Fluid Mech.* **285**, 69-94.
- KEANE, R. & ADRIAN, R. 1992 Theory of cross-correlation analysis of PIV images. *Appl. Sci. Res.* **49**, 191-215.
- KIM, W., KIM, S., CHOI, K. & KIM, C. 2010 Experimental and computational study on flow characteristics by synthetic jets configuration. *AIAA Paper 2010-864*.
- KIM, W.W. & MENON, S. 1997 Application of the localized dynamic subgrid-scale model to turbulent wall-bounded flows. *AIAA Paper 97-0210*.
- KOTAPATI, R., MITTAL, R., MARXEN, O., HAM, F. & YOU, D. 2010 Nonlinear dynamics and synthetic-jet-based control of a canonical separated flow. *J. Fluid Mech.* **654**, 65-97.
- KUNDU, P.K. & COHEN, I.M. 2004 Fluid Mechanics (3rd edition). *Elsevier Academic Press*.

REFERENCES

- KRAL, L.D. 1999 Active Flow Control Technology. *ASME Fluids Engineering Technical Brief*.
- LACHMANN, G.V. 1961 Boundary Layer and Flow Control: Its Principles and Application. Vol. 1;. *Pergrmon Press*.
- LENGANI, D., SIMONI, D., UBALDI, M. & ZUNINO, P. 2014 POD analysis of the unsteady behavior of a laminar separation bubble. *Exp. Therm. Fluid Sci.* **58**, 70-79.
- LIDDLE, S. C. & WOOD, N. J. 2005 Investigation into clustering of synthetic jet actuators for flow separation control applications. *Aeronaut. J.* **109**, 35-44.
- LIN, J.C. 2002 Review of research on low-profile vortex generators to control boundary-layer separation. *Prog. Aerosp. Sci.* **38**, 389-420.
- LÖFDAHL, L. & GAD-EL-HAK, M. 1999 MEMS applications in turbulence and flow control. *Prog. Aerosp. Sci.* **35**, 101-203.
- LUMLEY, J.L. 1967 The structure of inhomogeneous turbulent flow. In *Atmospheric Turbulence and Radio Wave Propagation*. 166-178.
- MAGILL, J.C. & McMANUS, K.R. 2001 Exploring the feasibility of pulsed jet separation control for aircraft configurations. *Aeronaut. J.* 48-56.
- MALLINSON, S.G., HONG, G. & REIZES, J.A. 1999 Some characteristics of synthetic jets. *AIAA Paper 1999-3651*.
- MASKELL, E.C. 1955 Flow separation in three dimensions. *Royal Aircraft Establishment*.
- MATHEY, F., COKLJAT, D., BERTOGLIO, J.P. & SERGENT, E. 2006 Assessment of the vortex method for large eddy simulation inlet conditions. *Prog. Comput. Fluid Dy.* **6**, 58-64.
- MCCORMICK, D. 2000 Boundary layer separation control with directed synthetic jets. *AIAA Paper 2000-0519*.
- McMANUS, K. & MAGILL, J. 1996 Separation control in incompressible and compressible flows using pulsed jets. *AIAA Paper 1996-194*.

REFERENCES

- MCKENNA, S.P. & MCGILLIS, W.R. 2002 Performance of digital image velocimetry processing techniques. *Exp. Fluids* **32**, 106-115.
- MEI, R. 1996 Velocity fidelity of flow tracer particles. *Exp. Fluids* **22**, 1-13.
- MERZKIRCH, W. 1987 Flow visualization. *Academic Press* 48-56.
- MEYER, K.E., JAKOB, M.P. & ZCAN, O. 2007 A turbulent jet in crossflow analysed with proper orthogonal decomposition. *J. Fluid Mech.* **583**, 199-227.
- MILANOVIC, I. M. & ZAMAN, K. B. M. Q. 2005 Synthetic jets in cross-flow. *AIAA J.* **43**, 929-940.
- MITTAL, R. & RAMPUNGOON, P. 2001 Interaction of a synthetic jet with a flat plate boundary layer. *AIAA Paper 2001-2773*.
- NICOUD, F. & DUCRO, F. 1999 Subgrid-Scale Stress Modeling Based on the Square of the Velocity Gradient Tensor. *Flow Turbul. Combust.* **62**, 183-200.
- NISHRI, B. 1998 Effects of periodic excitation on turbulent separation from a flap. *AIAA J.* **36**, 547-556.
- NISHRI, B. & WYGNANSKI, I. 1995 On the dominant mechanisms governing active control of separation. PhD thesis, *Tel Aviv University*.
- OZAWA, T., LESBROS, S., & HONG, G. 2010 LES of synthetic jets in boundary layer with laminar separation caused by adverse pressure gradient. *Comput. Fluids* **39**, 845-858.
- PAULEY, W.R. & EATON, J.K. 1988 Experimental study of the development of longitudinal vortex pairs embedded in a turbulent boundary layer. *AIAA J.* **26**, 816-823.
- RAFFEL, M. & WILLERT, C.E. 2007 Particle image velocimetry - a practical guide. *Springer Verlag*.
- RAMASAMY, M., WILSON, J. S. & MARTIN, P. B. 2010 Interaction of synthetic jet with boundary layer using microscopic particle image velocimetry. *J. Aircraft* **47**, 404-422.

REFERENCES

- RATHNASINGHAM, R. & BREUER, K.S. 1997 Coupled fluid-structural characteristics of actuators for flow control. *AIAA J.* **35**, 823-837.
- RATHNASINGHAM, R. & BREUER, K. S. 2003 Active control of turbulent boundary layers. *J. Fluid Mech.* **495**, 209-233.
- REDINIOTIS, O.K., KO, J., YUE, X. & KURDILA, A.J. 1999 Synthetic jets, their reduced order modelling and applications to flow control. *AIAA 1999-1000*.
- ROWLEY, C.W., MEZIC, I., BAGHERI, S., SCHLATTER, P. & HENNINGSON, D.S. 2009 Spectral analysis of nonlinear flows. *J. Fluid Mech.* **641**, 115-127.
- ROWLEY, C.W., MEZIC, I., BAGHERI, S., SCHLATTER, P. & HENNINGSON, D.S. 2009 Spectral analysis of nonlinear flows. *J. Fluid Mech.* **641**, 115-127.
- RIZZETTA, D. P., VISBAL, M.R. & STANEK, M. J. 1999 Numerical Investigation of Sythetic-Jet Flowfields. *AIAA J.*, 1-10.
- PRANDTL, L. 1904 Uber Flussigkeitsbewegung bei sehr kleiner Reibung. In *Proceedings of the third international mathematics congress*, 484491, Heidelberg, Germany.
- SAGAUT, P. 2006 Large eddy simulation for incompressible flows (3rd Edition). *Springer*.
- SAHNI, O., WOOD, J., JANSEN, K. & AMITY, M. 2011 Three-dimensional interactions between a finite-span synthetic jet and a crossflow. *J. Fluid Mech.* **671**, 254-287.
- SAYADI, T., SCHMID, P., NICHOLS, J.W. & MOIN, P. 2013 Dynamic mode decomposition of controlled Hand K-type transitions. *Center for Turbulence Research, Annual Research Briefs 2013.*, 189-200.
- SCHMID, P.J. 2010 Dynamic mode decomposition of numerical and experimental data. *J. Fluid Mech.* **656**, 5-28.
- SCHMID, P.J. 2011 Application of the dynamic mode decomposition to experimental data. *Exp. Fluids* **50**, 1123-1130.
- SEIFER, A., DARABI, A., & WYGNANSKI, I. 1996 Delay of airfoil stall by periodic excitation. *AIAA J.* **33**, 691-698.

REFERENCES

- SEIFERT, A. & PACK, L. G. 1999 Oscillatory control of separation at high Reynolds numbers. *AIAA J.* **37**, 1062–1071.
- SERGENT E. 2002 Vers une methodologie de couplage entre la simulation des grandes echelles et les modeles statistiques. Ph.D. thesis, *LEcole Centrale de Lyon*.
- SIROVICH, L. & KIRBY, M. 1987 Low-dimensional procedure for the characterization of human faces. *J. Opt. Soc. Am.* **A4**, 519-524.
- SMAGORINSKY, J. 1963 General Circulation Experiments with the Primitive Equations. I. The basic Experiment. *Month. Wea. Rev.* **91**, 99-164.
- SMITH, B.L. & GLEZER, A. 1998 The formation and evolution of synthetic jets. *Phys. Fluids* **10**, 2281-2297.
- SMITH, B.L. & GLEZER, A. 2005 Vectoring of adjacent synthetic jets. *AIAA J.* **43**, 2117-2124.
- SMITH, B.L., TRAUTMAN M.A. & GLEZER, A. 1999 Controlled interactions of adjacent synthetic jets. *AIAA Paper 99-0669*.
- SMITH, D.R., AMITAY, M., KIBENS, V., PAREKH, D., & GLEZER, A. 1998 Modification of lifting body aerodynamics using synthetic jet actuators. *AIAA Paper 98-0209*.
- SMITH, D.R., KIBENS, V., PITT, D.M. & KOPKINS, M.A. 1999 Effect of synthetic jet arrays on boundary layer control. In *SPIE Conference on Industrial and Commercial Application of Smart Structure Technologies*.
- SPALART, P.R. 1988 Direct simulation of a turbulent boundary layer up to $Re_\theta = 1410$. In *J. Fluid Mech.* **187**, 61-98.
- TANG, H., SALUNKHE, P., ZHENG, Y., DU, J. & WU, Y. 2014 On the use of synthetic jet actuator arrays for active flow separation control. *Exp. Therm. Fluid Sci.* **57**, 1–10.
- TANG, H. & ZHONG, S. 2006 Incompressible flow model of synthetic jet actuators. *AIAA J.* **44**, 908–912.

REFERENCES

- TANG, H., ZHONG, S., JABBAL, M., GARCILLAN, L., GUO, F., WOOD, N. & WAR-SOP, C. 2007 Toward the design of synthetic-jet actuators for full-scale flight conditions. Part2: low-dimensional performance prediction models and actuator design method *Flow Turbul. Combust.* **78**, 283–307.
- TAYLOR, H.D. 1948 Application of vortex generator mixing principles to diffusers. *Research department concluding report No. R-15064-5*, United Aircraft Corporation, East Hartford, Connecticut.
- VASILE, J.D. & AMITAY, M. 2013 Interactions of an Array of Finite Span Synthetic Jets and a Crossflow. *AIAA J.*, 1-10.
- WATON, M., JAWORSKI, A.J. & WOOD, N.J. 2010 Contribution to the Understanding of Flow Interactions Between Multiple Synthetic Jets. *AIAA J.* **41**, 747-749.
- WEN, X. & TANG, H. 2014 On hairpin vortex induced by circular synthetic jets in laminar and turbulent boundary layers. *Comput. Fluids* **95**, 1–18.
- WENGLE, H., HUPPERTZ, A., BARWOLFF, G. & JANKE, G. 2001 The manipulated transitional backwardfacing step flow: an experimental and direct numerical simulation investigation. *Eur. J. Mech. B Fluids* **20**, 2546.
- WILLERT, C.E. & GHARIB, M. 1991 Digital particle image velocimetry. *Exp. Fluids* **10**, 181-193.
- WOOD, J., SAHNI, O., JANSEN, K. & AMITAY, M. 2009 Experimental and numerical investigation of active control of 3-D flows. *AIAA Paper 2009-4279*.
- WOOD, N., SADRI, A. & CROOK, A. 2000 Control of turbulent flow separation by synthetic jets. *AIAA Paper 2000-4331*.
- WU, D.K.L & LESCHZINER, M.A. 2009 Large-Eddy simulations of circular synthetic jets in quiescent surroundings and in turbulent cross-flow. *Int. J. Heat Fluid Flow* **30**, 421-434.
- YE, T, SONG,Q. & CATTAFESTA, L. 2006 Adaptive Feedback Control of Flow Separation. *AIAA Paper 2006-3016*.

REFERENCES

- ZEINAB, M.N. 2013 Simulation and modal analysis of instability and transition in a steady eccentric stenotic flow. *Master Thesis*, The Royal Institute of Technology, Stockholm.
- ZHANG, S. & ZHONG, S. 2010 Experimental investigation of flow separation control using an array of synthetic jets. *AIAA J.* **48**, 611–623.
- ZHANG, S. & ZHONG, S. 2011 Turbulent Flow Separation Control over a Two-Dimensional Ramp Using Synthetic Jets. *AIAA J.* **49**, 2637–2649.
- ZHONG S. 2012 Private communications.
- ZHONG, S., JABBAL, M., TANG, H., GARCILLAN, L., GUO, F., WOOD, N. & WAR-SOP, C. 2007 Toward the design of synthetic-jet actuators for full-scale flight conditions. *Flow Turbul. Combust.* **78**, 283–307.
- ZHONG, S. & WOOD, N.J. 2005 The behaviour of circular synthetic jets in a laminar boundary layer. *Aeronaut. J.* 461–470.
- ZHONG S. & ZHANG, S. 2013 Further examination of the mechanism of round synthetic jets in delaying turbulent flow separation. *Flow Turbul. Combust.* **91**, 177–208.
- ZHOU, J., ADRIAN, R.J. & BALACHANDAR, S. 1996 Autogeneration of near-wall vortical structures in channel flow. *Phys. Fluids* **8**, 228.
- ZHOU, J. ADRIAN, R.J., BALACHANDAR, S. & KENDALL, T. M. 1999 Mechanisms for generating coherent packets of hairpin vortices in channel flow. *J. Fluid Mech.* **387**, 353–396.
- ZHOU, J., TANG, H. & ZHONG, S. 2009 Vortex roll-up criterion for synthetic jets. *AIAA J.* **47**, 1252–1262.
- ZHOU, J. & ZHONG, S. 2010 Coherent structures produced by the interaction between synthetic jets and a laminar boundary layer and their surface shear stress patterns. *Comput. Fluids* **39**, 1296–1313.