Turbulence Control in Wall Jets

Jonathan Latim

Follow this and additional works at: https://commons.erau.edu/edt

Part of the Aerospace Engineering Commons

Scholarly Commons Citation

https://commons.erau.edu/edt/335
TURBULENCE CONTROL IN WALL JETS

A Thesis
Submitted to the Faculty
Of Embry-Riddle Aeronautical University
By
Jonathan Latim

In Partial Fulfillment of the
Requirements for the Degree
of
Master of Science in Aerospace Engineering

December 2016
Embry-Riddle Aeronautical University
Daytona Beach, Florida
TURBULENCE CONTROL IN WALL JETS

By

Jonathan Latim

A Thesis prepared under the direction of the candidate’s committee chairman, Dr. Ebenezer Gnanamanickam, Department of Aerospace Engineering, and has been approved by the members of the thesis committee. It was submitted to the School of Graduate Studies and Research and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

THESIS COMMITTEE

[Signatures and signatures]

Chairman, Dr. Ebenezer Gnanamanickam

Member, Dr. J. Gordon Leishman

Member, Dr. Reda Mankbadi

Graduate Program Coordinator, Dr. Magdy Attia

Dean of College of Engineering, Dr. Maj Mirmirani

Vice Chancellor, Academic Support, Dr. Christopher Grant

2.8.2017

Date

2/8/2018

Date

2/8/17

Date
ACKNOWLEDGEMENTS

I would like to begin by thanking the Lord who has been the source of my strength throughout this journey. Many nights I found strength in quoting and reciting Philippians 4:13 which says, “I can do all things through Christ which strengtheneth me.” I have no doubt he has been guiding my steps and will continue doing so for the rest of my life.

I would also like to express my gratitude to my advisor Dr. Ebenezer Gnanamanickam for his support, guidance, motivation, and the vast amount of knowledge he shared with me. His guidance was a useful tool throughout this journey.

Besides my advisor, I would like to thank the rest of my thesis committee: Dr. J. Gordon Leishman and Dr. Reda Mankbadi, for their high expectations and insightful comments, both of which helped me become a better research student.

My sincere thanks also goes to William Russo, Mike Potash, Shibani Bhatt, and Sravan Artham. Their assistance made it possible to conduct this research and without their precious support, it would not be have been possible to complete.

Lastly, I want to thank my family whose prayers and support have made it possible for me to chase my dreams.

Big thanks.

Jonathan Latim
TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ iv
TABLE OF CONTENTS ........................................................................................................... iv
LIST OF FIGURES ................................................................................................................ v
SYMBOLS .......................................................................................................................... vii
ABBREVIATIONS ............................................................................................................... ix
ABSTRACT ......................................................................................................................... x
1. INTRODUCTION ........................................................................................................... 1
2. BACKGROUND ............................................................................................................... 4
   2.1. Interaction Between Large-scales and Small-scales ............................................... 4
   2.2. Literature review of Wall Jet .................................................................................. 9
   2.3. Excited Plane Wall Jet ......................................................................................... 14
3. EXPERIMENTAL SETUP ............................................................................................. 18
   3.1. Experimental Facility ............................................................................................ 18
   3.2. Hot-wire Anemometry and Calibration ............................................................... 20
   3.3. Perturbation Configurations ................................................................................ 21
   3.4. Data Collection and Reduction Flow Chart ....................................................... 24
4. RESULTS AND DISCUSSION ..................................................................................... 26
   4.1. Unforced Wall Jet: Baseline ................................................................................. 26
   4.2. Effects of a Rod Trip on the Wall Jet Development .......................................... 33
   4.3. Effects of Sandpaper Trip on the Wall Jet Development .................................... 39
   4.4. Effects of Sandpaper and String Trips on the Wall Jet Development ............. 45
5. CONCLUSIONS AND FUTURE WORK .................................................................... 52
   5.1. Effects of Perturbation ......................................................................................... 52
   5.2. Future Work ......................................................................................................... 53
REFERENCES .................................................................................................................... 55
LIST OF FIGURES

Figure 1: Wall shear stress.............................................................................................................. 3
Figure 2: Amplitude and frequency modulation effect as seen at a wall normal location $z+ \approx 6$ [26].............................................................................................................................................. 5
Figure 3: Riblet film viewed under a scanning electron microscope: a) 44-lm riblet film, and b) 62-lm riblet film [12].......................................................................................................................................... 6
Figure 4: Interaction of small-scales structures and large-scale structures at low friction Reynolds number [26]...................................................................................................................................................... 8
Figure 5: Interaction of small-scales structures and large-scale structures at high friction Reynolds number [26]...................................................................................................................................................... 8
Figure 6: Typically developed mean streamwise velocity profile of a wall jet............................ 11
Figure 7: Modern high-pressure turbine blade [17]......................................................................... 13
Figure 8: Schematic of a Coanda jet over a semi-circular trailing region of a circulation control airfoil with external flow [18]................................................................................................................................................... 13
Figure 9: A schematic of the wall jet apparatus used by Katz et al [19]......................................... 15
Figure 10: Experimental facility used by Schober and Fernholz [20].......................................... 17
Figure 11: Schematic of the experimental setup showing salient features.................................. 19
Figure 12: Representative pre-calibration and post-Calibration curves........................................ 21
Figure 13: Unforced wall jet ........................................................................................................ 22
Figure 14: Rod configuration......................................................................................................... 23
Figure 15: Sandpaper configuration............................................................................................ 23
Figure 16: Sandpaper and string configuration............................................................................ 24
Figure 17: Experiment flow chart................................................................................................ 25
Figure 18: Velocity profile in the unforced wall jet ...................................................................... 27
Figure 19: Turbulence Intensity development in the unforced wall jet........................................ 29
Figure 20: Spectrogram of an unforced wall-jet at $x/b = 300$.................................................... 30
Figure 21: Turbulence Intensity Development in an unforced ....................................................... 30
Figure 22: Calculating the Wall shear stress................................................................................. 31
Figure 23: Spectrogram of the unforced wall jet at $x/b = 100$..................................................... 32
Figure 24: Spectrogram of the unforced wall jet at $x/b = 200$..................................................... 32
Figure 25: Spectrogram of the unforced wall jet at $x/b = 300$..................................................... 33
Figure 26: Velocity development in the wall jet with a rod......................................................... 35
Figure 27: Turbulence Intensity Development in wall jet with a rod........................................... 36
Figure 28: Spectrogram of a wall jet with a rod at $x/b = 100$...................................................... 36
Figure 29: Spectrogram of a wall jet with a rod at $x/b = 200$...................................................... 37
Figure 30: Spectrogram of an unforced wall-jet at $x/b = 300$...................................................... 38
Figure 31: Spectrogram of a wall-jet with a rod at $x/b = 300$...................................................... 38
Figure 32: Velocity development in wall jet with sandpaper...................................................... 41
Figure 33: Turbulence Intensity development in the wall jet with sandpaper............................ 42
Figure 34: Spectrogram of the wall jet with sandpaper at $x/b = 100$........................................... 42
Figure 35: Spectrogram of the wall jet with sandpaper at $x/b = 200$........................................... 43
Figure 36: Spectrogram of the unforced wall-jet at $x/b = 300$...................................................... 44
Figure 37: Spectrogram of the wall-jet with sandpaper at $x/b = 300$........................................... 44
Figure 38: Velocity development in wall jet with Sandpaper and String...................................... 47
Figure 39: Turbulence Intensity development in wall jet with sandpaper and string.................. 48
Figure 40: Spectrogram of a wall jet with Sandpaper and String at $x/b = 100$............................ 48
Figure 41: Spectrogram of a wall jet with sandpaper and string at $x/b = 200$. .............................. 49
Figure 42: Spectrogram of an unforced wall-jet at $x/b = 300$. ....................................................... 50
Figure 43: Spectrogram of a wall-jet with sandpaper at $x/b = 300$. ............................................... 50
Figure 44: Spectrogram of a wall-jet with sandpaper and string at $x/b = 300$. .............................. 50
**SYMBOLS**

$Re$  Reynolds number

$Re_f$  Friction Reynolds number

$U_f$  Friction velocity

$\tau_w$  Wall shear stress

$\lambda_x$  Streamwise wavelength

$k_x$  Streamwise wavenumber

$\varphi_{xx}$  Spectral density of the streamwise velocity fluctuations

$k_x \varphi_{xx}$  Pre-multiplied energy spectra

$\delta$  Boundary layer thickness (Integral length scale)

$z^+$  Wall normal location

$U_S$  Small-scale structures

$U_L$  Large-scale structures

$\nu$  Kinematic viscosity

$\rho$  Density

$u_m$  Maximum velocity

$z_m$  Position of maximum velocity

$z$  $z$-coordinate
x  x-coordinate

y  y-coordinate

w  Velocity component in the z direction

u  Velocity component in the x direction

v  Velocity component in the y direction

b  Slot width

Hz  Hertz
ABBREVIATIONS

HWA  Hot-wire anemometry

DAQ  Data acquisition system

CTA  Constant temperature anemometer
ABSTRACT

Latim, Jonathan MSAE, Embry-Riddle Aeronautical University, December 2016.

Turbulence Control in wall Jets.

The turbulent boundary layer has been the focus of many studies over the last century or so due to its engineering significance. Recent studies have shown that the turbulent boundary layer encapsulates extremely energetic large-scale structures which play a much more significant role in its dynamics than has been previously thought. Further, these large scales amplitude and frequency modulate the finer scales of turbulence. This offers a path to control wall turbulence by controlling the large-scales of the flow. The focus of this thesis is to establish ways to manipulate the energy of the large-scale structures in a model turbulent boundary layer and characterize its effect. The plane wall jet was chosen as the model flow field because it is possible to perturb/excite the large-scales at the onset of turbulence independent of the finer scales of turbulence. Hot-wire anemometry was used to carryout velocity measurements in at plane wall jet at streamwise locations up to three hundred times the jet exit slot height. Three different passive perturbation configurations were used to manipulate the energy of the large-scale structures of the plane wall jet. The different perturbation configurations used were a rod, sandpaper and sandpaper and a still wire. All the perturbations were carried out in the vicinity of the jet exit. The unforced wall jet was used as the baseline to compare the effect of these perturbations. All the perturbation cases were able to alter the energy of the large-scale structures in the flow. However, the large-scale structures were shown to be most energetic and reached closest to the wall in the flow that was perturbed using the rod than in all other flow cases at all streamwise positions considered. Last but not least,
the sandpaper and the sandpaper and string configurations showed less energetic large-scale structures at all streamwise locations than in an unforced wall jet. However, the large-scale structures in the sandpaper and string configuration were more energetic than the large scale structures in the sandpaper configuration at all streamwise locations.
1. INTRODUCTION

The total drag on an aircraft comprises several components namely, basic pressure drag, lift-induced drag, skin friction drag, wave drag, and other miscellaneous drag. Skin friction is the friction between a fluid and a solid surface moving through the fluid. It is caused by the fluid’s viscosity [1]. The skin friction drag on a body moving in a fluid is calculated by integrating the local wall shear stress, \( \tau_w \), over the body surface. The skin friction drag on an aircraft flying at cruise is about 40-50% of its total drag [2]. This is clearly a significant contribution to drag which if reduced, even slightly, could not only improve the aerodynamic efficiency of the aircraft but also have significant economic impact i.e. appreciable fuel savings. For example, according to the United States Department of Transportation, in 2015, both domestic and international air carriers used approximately 16730 million gallons of fuel at a cost of $1.84 per gallon [3]. A slight reduction of 0.1% in fuel consumption would have saved the industry approximately $30 million. Beyond the economic benefits, reducing fuel consumption has an environmental benefit as well, which is the reduction of pollutants.

The wall shear stress is the shear stress that arises from the layer of fluid next to a wall, which is the boundary layer as illustrated in Fig.1. The boundary layer is a very thin layer of fluid close to the body where the effects of viscosity are very important [9]. The boundary layer maybe either of laminar form or of turbulent form. The turbulent boundary layer typically observed at high Reynolds numbers, \( Re \), consists of large-scale structures, small-scale structures and a cascade of structures in between. Large-scale structures are defined as flow structures with a streamwise wavelength, \( \lambda_x \) larger than the integral length scale, \( \delta \), whereas small-scale structures are those structures that are
smaller than the integral length scale, $\delta$. The integral length scale for a turbulent boundary layer is the boundary layer thickness, $\delta$. The large-scale structures are predominantly found away from the wall, while the small-scale structures are found everywhere in the flow but are responsible for the production of the bulk of the turbulence close to the wall. The large-scale structures within the turbulent boundary layer interact with the smaller scales in the flow in a non-linear manner through a process of amplitude and frequency modulation [7] which will be elaborated upon later in the thesis.

The primary long-term research objective of this work is to target and control the large-scale structures within the turbulent boundary layer in order to change the wall shear stress by exploiting this non-linear interaction (i.e. amplitude and frequency modulation) between the turbulence scales. Towards this end, the focus of this thesis is to begin to establish ways to manipulate the large-scale structures in the chosen model flow field and to characterize the physical effect of this manipulation.
This thesis is organized as follows. Chapter 2 describes the current chosen model flow field, the reasons for choosing it, as well as prior work on a plane wall jet. Chapter 3 describes the experimental test facility and instrumentation devices used in carrying out the present work. Chapter 4 describes the results of the experimental investigation into the effects of manipulating the large-scale structures in the wall jet. Chapter 5 gives some conclusions from the experiment and offers suggestions for future work.
2. BACKGROUND

A turbulent boundary layer is typically observed at high Reynolds numbers and consists of large-scale and small-scale flow structures and a range of scales in between. The large-scale structures within turbulent boundary layers interact with the smaller scales in the flow in a non-linear manner through a process of amplitude and frequency modulation [7]. This thesis is a first step in exploiting this interaction in order to control the turbulent boundary layers. This chapter describes the chosen model flow field, the reasons for choosing it and prior work describing the dynamics of a plane wall jet.

2.1. Interaction Between Large-scales and Small-scales

The process of turbulence production in the near-wall cycle has been studied and described by several researchers such as Kline et al. [4]. The term “near-wall” is a region where there is a highly energetic (turbulent kinetic energy) peak near the wall. The near wall peak was found to be around the wall normal location \( z^+ = 15 \) and the term “cycle” here refers to the cycle of quasi-streamwise vortices and streaks [27]. The superscript + refers to viscous scaling of lengths i.e. \( z^+ = z * u_\tau / \nu \), where \( u_\tau \) is the friction velocity and \( \nu \) is the kinematic viscosity.

Mathis et al. [7] showed that large-scale motions within turbulent boundary layers interact with the smaller scales in the flow in a non-linear manner, through a process of amplitude and frequency modulation. Brown and Thomas [8] initially observed this modulation effect of the large-scale on the smaller scales. This non-linear amplitude and frequency modulation effect is illustrated in Fig.2. The velocity measured from a hot-wire
anemometer in the near wall region at $z^+ \approx 6$ is decomposed into the large-scale $U_L$ and the small-scale $U_s$ components. Highlighted in the green box is a low speed large-scale ($\lambda_x > \delta$) event, where the large-scale structures reduce both the amplitude and frequency of the small-scale structures. Highlighted in the black box is a high speed large-scale ($\lambda_x > \delta$) event where the large-scale structures increase both the amplitude and frequency of the small-scale structures.

![Figure 2: Amplitude and frequency modulation effect as seen at a wall normal location $z^+ = 6$ [26].](image)

Past efforts on controlling wall turbulence using passive flow control methods, e.g. riblets [6],[32],[33] have focused on directly controlling the near-wall turbulent cycle. Passive flow control strategies require no external energy or no additional mass to be injected into the system [29]. The most effective passive flow control strategy for reducing drag is by using riblets. Riblets are micro-grooves on the surface and are aligned with the freestream direction as illustrated in Fig.3. The grooves in a riblet surface help reduce turbulent skin-friction drag by diminishing mixing and momentum losses of the low-speed region of the fluid near the wall [32]. Starling and Choi [34] demonstrated that riblets can also delay the transition to turbulence of an excited laminar boundary. Riblets
of different geometries have been tested in wind tunnels, demonstrating drag reductions of the order of 10 per cent over flat plates [6]. For example Debisschop & Nieuwstadt [10] demonstrated that the maximum drag reduction of triangular riblets was roughly between 7 to 13 percent. Riblets have also been used successfully to reduce the overall drag of aerofoils [11]. Riblets used during flight testing of Airbus 320 reduced drag overall by 2 percent based on the fuel savings obtained. The riblets used covered over 70 percent of its surface [25]. Riblets have proved to be effective in reducing drag, however, using riblets in transportation aircrafts has certain disadvantages i.e. the cost of riblet films, time and cost of installation and removal of riblet films, lack of durability due to aging and other operational aspects [2].

Figure 3: Riblet film viewed under a scanning electron microscope: a) 44-lm riblet film, and b) 62-lm riblet film [12].
Active Flow Control refers to the use of electronically controllable disturbances that are introduced into the flow field by actuators such as blowing, suction, etc. Examples for which active flow control has proved to be promising are control of flow separation and mixing. [28]. Because most active flow control methods used in controlling wall turbulence need to operate at high Reynolds number, directly targeting the near-wall cycle has some disadvantages. This is because as the Reynolds numbers increase, the large scales become larger while the small scales become smaller. This leads to smaller sensors and actuators being required for control, which in turn increases the complexity of practical control strategies that target the flow in the near-wall cycle.

At low friction Reynolds numbers i.e. $Re_\tau < 1000$, the small scales in the flow predominantly contribute to the turbulence production in the near-wall region or the near-wall cycle. This is because at low Reynolds number, much of the kinetic energy production happens within the viscous buffer layer as illustrated in Fig.4 [5]. Here, the friction Reynolds number is the Reynolds number based on the boundary layer thickness and friction velocity, $u_\tau$, which is defined as

$$Re_\tau = \delta \frac{u_\tau}{\nu}$$

where $\delta$ is the integral length scale, $u_\tau$ is the friction velocity and $\nu$ is the kinematic viscosity. The friction velocity, $u_\tau$, is defined as

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

where $\tau_w$ is the wall shear stress and $\rho$ is the density of the fluid.
However, as the Reynolds number increases, the near-wall cycle is no longer responsible for the production of the bulk of the turbulence. Instead, the large-scale motions become dynamically important and predominantly contribute to the turbulent kinetic energy as illustrated in Fig.5 [5].

Flow control is much more attractive from an engineering perspective if instead of the small-scale structures, the large-scale structures within the boundary layer are targeted. The advantages of this are,

I. The required frequency response of sensors required for flow control are fairly low.
II. The size of sensors and actuators required are more feasible from an engineering perspective i.e. of order of millimeters.

III. One can potentially impact larger regions with control because the large-scale structures are the dominant energy carrying eddies at high Reynolds numbers and also persist for long distances.

By systematically manipulating the large-scale structures, the non-linear relationship between the energy of the large-scales in the flow and its interaction with the small-scales can be established and the associated modulation effect characterized. Exploiting the non-linear amplitude and frequency modulation effect of the large-scales on the smaller scale offers a pathway to controlling the small-scales (i.e., of the near-wall cycle) through modifications of the larger-scales. This approach offers a means through which wall shear stress, $\tau_w$, can be selectively reduced or increased. To systematically study these interactions, the plane wall jet was chosen as the model flow field. This flow field offers the opportunity to independently control the large-scale structures of the flow.

2.2. Literature review of Wall Jet

The term “wall jet” was first used by Glauert [13] in 1956. Launder & Rodi [15] defined a wall jet as “a shear flow directed along a wall where, by virtue of the initially supplied momentum, at any station, the streamwise velocity over some region within the shear flow exceeds that of the free-stream”. The free-stream can be either stagnant or co-flowing with a velocity lower than the streamwise velocity [21]. Glauert [13] and Launder & Rodi [15] classified wall jets into three types: plane, radial, and three-
dimensional. The current study uses a plane wall jet as the model flow field. A plane wall jet, as described, is formed when a high-momentum fluid is injected from a rectangular nozzle along the wall [16]. Launder & Rodi [15] suggest that the nozzle should be wide enough so that the changes of the flow characteristics in the spanwise direction are negligible.

The plane wall jet considered in the current work exited into stagnant air. The flow goes through a contraction and then a rectangular nozzle, and exhausts over a plane wall into an undisturbed environment. The nozzle is wide enough to ensure two-dimensionality in the cross-stream direction [21]. Figure 6 illustrates a typical fully developed mean streamwise velocity profile with an external stream velocity of zero. Here, $u_m$ is the maximum velocity and $z_m$ is the wall normal position where $u = u_m$. The point, above $z_m$ (in the free jet portion), where the velocity is decreased to half of the maximum velocity ($u_m/2$) is called $z_m/2$ or half width of a wall jet. This is also the integral length scale of the wall jet.

The plane wall jet develops a boundary layer on the wall and a shear layer between the high momentum fluid exiting the nozzle and the stagnant air in the tunnel. The stagnant air in the tunnel is entrained by the wall jet as it convects in the streamwise direction thereby creating a shear layer. Both the shear layer and the boundary layer grow and approach one another as the flow moves in the streamwise direction, eventually merging as the fluid moves downstream. The two layers meet at some point to form a fully developed turbulent flow [22]. Using experimental data from Hall and Ewing [23], Smith [22] concludes that the flow becomes fully developed in the streamwise direction at a distance between 20 and 25 times the nozzle exit height, $b$. 
Wall jets are of both fundamental and practical engineering interests because of the formation and interaction of the two layers, i.e., a boundary layer and a free-shear layer. The two layers correspond to two sources of turbulence, i.e., the free-jet transitions through a Kelvin–Helmholtz instability (inviscid) while the boundary layer transitions through viscous instabilities. The Kelvin–Helmholtz instability in the free-jet portion naturally leads to large scale structures. Thus the plane wall jet was used as the model flow field because of the following reasons:

1. It is possible to perturb/excite the large-scales at the onset of turbulence independent of the near-wall layer.
2. It contains very energetic large scales as a result of the outer shear layer.
3. It is a model flow field to study mixing and reactions.

Wall jet type flows are encountered in turbine blade cooling and high-lift aerodynamics. In turbine blade cooling (Fig.6), a wall jet is used to prevent the cooling
liquid from mixing with the ambient flow in order to maintain a protective layer as far
downstream as possible. In high lift airfoils, it is desirable for a wall jet to stimulate
mixing of the wall jet with the ambient flow as illustrated in Fig.7. Circulation control
airfoils operate based off a phenomenon known as the “Coanda effect”, where a low
pressure sheet of air remains attached to the curved trailing edge of the airfoil primarily
due to the balance between centrifugal forces in the jet and the reduced pressure at the
wall due to the jet velocity [37]. Circulation control airfoils have various characteristics
that have been considered for application to helicopter rotors where the cyclic lift
variations around the blade azimuth can now be achieved by cyclic blowing on blades of
fixed pitch [35],[36]. Circulation control airfoils have also been used to replace lift
devices on the leading and trailing edges of a wing by use of Coanda surfaces and slot
blowing. Englar & Taylor [37] concluded that the application of tangential blowing over
the bluff trailing edge of elliptic airfoil profiles offers very high lift generation at
relatively low blowing rates. This approach may reduce the mechanical complexity
associated with obtaining cyclic variation in the blade pitch [37].
Figure 7: Modern high-pressure turbine blade [17].

Figure 8: Schematic of a Coanda jet over a semi-circular trailing region of a circulation control airfoil with external flow [18].
2.3. Excited Plane Wall Jet

Katz et al. [19] experimentally and theoretically investigated the effects of external two-dimensional excitation on a plane turbulent wall jet. They used two methods of forcing, i.e., one global and the other local. Figure 8 shows a schematic of the wall-jet apparatus used by Katz et al. in order to show where and how the wall jet was excited. A loudspeaker mounted on the wall of the plenum chamber acted as the global method of forcing, providing oscillations across the entire jet. A thin metal strip acting as a local method of forcing was attached to the upper lip of the nozzle using scotch-tape as a pivot and attached to a taut piano wire downstream moved up and down depending on the movement of two shakers mounted outside the facility. Therefore, in the global case, pressure fluctuations in the settling chamber were imposed on the entire jet using a speaker mounted on the wall of the plenum chamber, whereas in the local case, a small flap attached to the outer nozzle lip was used to excite modes in the shear layer.

Excitation of the plenum chamber using a speaker resulted in a fairly even distribution of oscillations across the entire jet in the plane of the nozzle, while the oscillations produced by the flap resulted in amplitudes which were concentrated near the outer lip of the nozzle and near the solid surface. Katz et al. [19] found that (1) regardless of the method of forcing used, the mean velocity distribution was almost identical and (2) the external excitation had no effect on the rate of spread of the jet nor on the decay of its maximum velocity. However, there was an effect to the flow near the surface, which was found to be profoundly different from the unforced flow, indicating a reduction in wall stress, exceeding at times 30%. The external excitation targeted the large-scale structures. These effects were observed in the fully developed region of the wall jet (i.e., at $x/b >$
and were found to be insensitive to the method of forcing, but they were sensitive to the frequency and the amplitude of the excitation [19].

Figure 9: A schematic of the wall jet apparatus used by Katz et al [19].

Schober and Fernholz [20] used the experimental facility shown in Fig.9 to study turbulence control in wall jets. The shear layer originating from the nozzle is manipulated by a thin steel wire stretched parallel to the wall jet exit. The wire frequency was measured using strain gauges mounted on the support prongs. Two cases that were studied were 1. a still wire and, 2. an oscillating wire. In the case of the still wire, the tension in the wire was adjusted as high as possible to obtain high eigen frequencies and avoid the self-excited oscillations; the adjustments were limited only by the wire strength. In the case of the oscillating wire, the tension in the wire was significantly lowered to obtain eigen frequencies of approximately 175 Hz. They concluded that;
- Case 1: Still wire. The structure of the turbulence in the wall jet could be significantly modified by perturbing the initial shear layer near the nozzle. This approach prevented the shear-layer roll-up and pairing processes. The wire reduced the size of the turbulent structures, the spreading of the wall jet, and the mixing with the ambient fluid. The skin friction increased, but the two-dimensionality of the wall jet was not affected.

- Case 2: Oscillating wire. An oscillating wire introduced flow structures into the initial shear layer, which depended on the wire frequency instead of depending upon the shear-layer properties. When low frequencies were used, large vortices were formed which increased in size over several stages of vortex pairing. The skin friction significantly reduced but the two-dimensionality of the flow was lost because of the nature of the oscillations.

For the manipulation and suppression of the shear layer, Schober and Fernholz [20] recommend that: (1) the trip wire should be positioned very accurately in the middle of the shear layer and, (2) the trip wire should be positioned upstream of the natural shear-layer roll-up.
Controlling the large-scale structures offers a pathway through which the wall shear stress, $\tau_w$, can be selectively reduced, as demonstrated by the prior work discussed previously. To this end, the focus of the present research is to establish ways to manipulate the large-scale structures in the plane wall jet and characterize this effect. A plane wall jet facility was built to carry out this study.
3. EXPERIMENTAL SETUP

A plane wall jet was chosen as the model flow field for this study. This chapter describes the experimental test facility and instrumentation devices used.

3.1. Experimental Facility

The air flow for the jet was supplied by a blower. The blower was connected to a settling chamber that contained a honeycomb. The honeycomb was used to straighten the flow before it passed through a set of two screens. The screens were used to reduce the turbulence in the flow before it exited through the nozzle. Flow proceeds over the contraction and exits into the tunnel parallel to the floor. There is a screen above the nozzle exit and one at the end of the tunnel.

The tunnel test section, a schematic of which is shown in Fig.11 has physical dimensions of 3.65m length x 0.641m width x 0.743m height. The slot width, b, of the wall jet measures normally 0.25 inches. Acrylic sheets were used to seal the sides and top of the tunnel. The coordinate system used throughout the study is also shown in Fig.11 as well. The streamwise, spanwise and wall-normal directions are represented by x, y and z respectively with u, v and z describing the respective velocity components.

Hot-wire anemometry (HWA) was used to carry out measurements of the velocity field. The hot-wire sensor was mounted on to a streamlined strut which was connected to a traverse system that was located on top of the tunnel. The traverse system was manufactured by Velmex. The streamlined strut was chosen over an aluminum rod to reduce vibrations in the hot-wire when carrying out measurements very close to the wall.
of the tunnel. Previous use of an aluminum rod resulted in hot-wire damage due to vibrations in the rod.

The flow temperature for each test case run was measured with a thermocouple to monitor flow temperature variations during each test case run. The velocity at the nozzle exit was calculated by measuring the pressure difference in the settling chamber and the ambient pressure using a low-pressure transducer (OMEGA DP25B-S). A data acquisition (DAQ) system was used to acquire measurements carried out by the hot-wire.

Figure 11: Schematic of the experimental setup showing salient features.
3.2. Hot-wire Anemometry and Calibration

A hot-wire was used to conduct measurements of the fluctuating velocities, from which mean flow velocities and turbulence quantities were calculated. The velocity spectra was also calculated to study the distribution of turbulence energy with eddy wavelength. The hot-wire used in the experiment was made up of a thin Wollaston wire of ≈ 2.5 microns in diameter placed between two prongs. The wire was mounted to the traversing system located on top of the tunnel. The prongs were aligned parallel to the tunnel wall.

The total length of time in seconds of the velocity sampled at each position was 240 seconds, and the sample rate was 50 kHz. The hot-wire system used in the experiment employed a constant temperature anemometer technique. The constant temperature anemometer (CTA) technique keeps the sensor, which is connected to a bridge circuit much like a Wheatstone bridge circuit, at a constant temperature. For the sensor to stay at a constant temperature, the CTA must supply more current, and hence more voltage, to the sensor. This voltage which varies with the velocity of the flow across the sensor and is recorded by the data acquisition system used [22].

The hot-wire was calibrated using a jet before and after every experiment (pre-calibration and post-calibration). The hot-wire was placed at the jet exit and the jet exit velocity varied from 0 to approximately 19 ms\(^{-1}\) and calibrated. A total of 15 calibration points are used during each pre-calibration and post-calibration. Figure 12 shows a typical set of calibration curve.
3.3. Perturbation Configurations

An unforced flow case was studied as the baseline as illustrated in the schematic of Fig. 13. Three different flow cases were studied corresponding to three different perturbation configurations, i.e., a rod, sand paper and sand paper plus a still wire. These devices were used to perturb the large-scale structures in order to study their effects in the flow. In the rod configuration, a rod measuring 1.8 mm in diameter was placed on the floor of the tunnel in the vicinity of the wall jet exit (approximately 0.25 inches), as shown in the schematic of Fig. 14. Glue was used to hold the rod in place during the course of the experimental run. The ratio of the rod to the height of the exit was 0.28. The rod was chosen as one of the perturbation configurations because it reduces the
development length required to obtain a fully developed turbulent layer. In the sandpaper configuration, a 60 grit sandpaper measuring 4 inches wide was placed on the floor of the tunnel in the vicinity of the wall jet exit (approximately 0.25 inches), as shown in the schematic of Fig.15. Glue was use to stick the sandpaper to the bottom of the tunnel. The sandpaper was used as one of the perturbation configurations because it also reduces the development length required to obtain a fully developed turbulent layer. In the sandpaper and wire configuration, both the wire and sandpaper were placed in the vicinity of the wall jet exit as shown in the schematic of Fig.16. The wire was placed above the wall jet exit to manipulate the outer layer while the sandpaper was placed on the tunnel floor to ensure that any changes made to the outer layer does not affect the turbulence transition in the inner layer.

Figure 13: Unforced wall jet.
1.8 mm Diameter Rod

Figure 14: Rod configuration.

Sandpaper 60 grit

Figure 15: Sandpaper configuration.
3.4. Data Collection and Reduction Flow Chart

Shown in Fig. 17 are the steps carried out from the time of data collection to post processing of the data to obtain relevant results. Flow velocity measurements were made in the tunnel using hot-wire anemometry and the results acquired using a DAQ system. The DAQ system has four channels through which different quantities are measured, i.e., velocity fluctuations are acquired through channel one, pressure fluctuations are acquired through channel two, the atmospheric pressure was measured using channel three and ambient temperature was measured using channel four. The hot-wire was calibrated using a jet. A matlab code was written to control the DAQ system, and also used to calculate the mean velocity profile, turbulence intensity profile, and spectrogram.
Figure 17: Experiment flow chart.

- **Time History**
  - Velocity [m/s]
  - Time [s]
  - Tsample = 240 s
  - Fsample = 50 kHz

- **Hot-Wire Anemometry**

- **DAQ System**

- **Computer**

- **Hotwire Calibration**
  - Pre-Calibration
  - Post-Calibration

- **Mean Velocity Profile**

- **Turbulence Intensity Profile**
4. RESULTS AND DISCUSSION

This chapter discusses the measurements made and the associated results. Different perturbation configurations of the wall jet were used to manipulate the large-scale structures in the wall jet. The different perturbation configurations were such that they altered the wall jet downstream of the exit, yet the actual perturbation location is in the vicinity of the wall jet exit. Investigations were conducted at three different streamwise locations along the tunnel, i.e., $x/b = 100$, 200 and 300. Hot-wire anemometry was used to measure the fluctuating velocities. The spectrogram was calculated to reveal the distribution of turbulence energy as a function of scale wavelength.

4.1. Unforced Wall Jet: Baseline

A baseline was first established using an unforced wall jet. The mean velocity profiles at streamwise location $x/b = 100$, 200 and 300 are shown in Fig.18. The velocity development as the flow proceeds along the tunnel center line is clearly seen. The maximum velocity ($u_m$) decreases as the flow develops down the tunnel i.e. at $x/b = 100$, $u_m \approx 8.05$ ms$^{-1}$, at $x/b = 200$, $u_m \approx 5.2$ ms$^{-1}$, and at $x/b = 300$, $u_m \approx 4.01$ ms$^{-1}$. The boundary layer thickness, $\delta$, is the $z$ location in the outer layer where the maximum velocity ($u_m$) has decreased to half of the maximum velocity ($u_m/2$). As the maximum velocity decreases, the boundary layer thickness increases as flow moves down the tunnel, i.e., at $x/b = 100$, $\delta \approx 55.1$ mm, at $x/b = 200$, $\delta \approx 105.4$ mm, and at $x/b = 3$, $\delta \approx 145.9$ mm.
Figure 18: Velocity profile in the unforced wall jet.

Figure 19 shows the turbulence intensity of the streamwise velocity as it develops downstream of the nozzle exit. The turbulence becomes more energetic downstream at all wall normal locations. However, the turbulence intensity profile shown in Fig.21 is an integrated quantity and does not show the energy distribution of the wavelength, $\lambda_x$ components, i.e., the turbulence intensity does not reveal how the eddies of various sizes contribute to the kinetic turbulent energy, and particularly if the large-scale structures or the small-scale structures are more energetic.

The turbulence intensity can be decomposed into its wavelength components by calculating the spectra. The spectral variation in the wall normal direction is shown as a contour plot in Fig.20 and is referred to here on as the spectrogram. The turbulent
intensity is related to the spectral density of the streamwise velocity fluctuations, $\phi_{xx}$ through the expansion;

$$\frac{\overline{u'^2}}{u_m^2} = \frac{1}{u_m^2} \int_0^\infty \phi_{xx} k_x dk_x = \frac{1}{u_m^2} \int_0^\infty \phi_{xx} k_x d \log k_x$$

where $k_x$ is the streamwise wavenumber.

The spectra shown in Fig.20 includes energetic contributions from a range of motions. However, the prominent features that will be highlighted here are large-scale structures and small-scale structures. The large-scale structures in the flow are above the horizontal line in Fig.20 while the small-scale structures in the flow are below. The streamwise length-scale $\lambda_x (\lambda_x = 2\pi/k_x)$, which is the $y$-coordinate, is non-dimensionalized by the boundary layer thickness, $\delta$. The height $z$, in the $x$-coordinate is also non-dimensionalized by boundary layer thickness, $\delta$. As the spectrogram in Fig.20 is shown in log coordinates, the pre-multiplied energy spectra, $k_x \phi_{xx}$ is used to indicate that equal area under the curve represent equal contribution to turbulent kinetic energy. Each point on the turbulence intensity profile of Fig.21 is found by integrating vertically along the spectrogram. Considering the large-scale structures shown in Fig. 20, it is clear that the large-scale structures are more dominant in energy content than the small-scale structures. The color contours represent the energy magnitude in the spectrogram.
Figure 19: Turbulence Intensity development in the unforced wall jet
Figure 21: Turbulence Intensity Development in an unforced wall-jet at $x/b = 300$.

Figure 20: Spectrogram of an unforced wall-jet at $x/b = 300$

$\lambda_x$: Streamwise length-scale

$\delta$: Boundary layer thickness

$k_x$: Streamwise wavenumber

$\Phi_{xx}$: Spectral density of the streamwise velocity fluctuations

$u_m$: Maximum velocity
The wall shear stress, $\tau_w$, was measured by calculating the velocity gradient close to the wall as illustrated in Fig.22. The last 10 points of the velocity graph were used, and deemed close enough to the wall.

$$\tau_w = \mu \frac{\partial u}{\partial z}, \text{where } z = 0$$

![Graph showing wall shear stress](image)

*Figure 22: Calculating the Wall shear stress.*

Fig.23 through Fig.25 show the spectrogram at different streamwise locations in the tunnel showing the large-scale structures becoming more energetic and reaching further and further towards the wall as the flow develops downstream.
Figure 23: Spectrogram of the unforced wall jet at $x/b = 100$.

\[ \tau_w = 0.029915 \text{ Pa} \]
\[ u_r = 0.15743 \text{ m s}^{-1} \]

Figure 24: Spectrogram of the unforced wall jet at $x/b = 200$.

\[ \tau_w = 0.024598 \text{ Pa} \]
\[ u_r = 0.14299 \text{ m s}^{-1} \]
4.2. Effects of a Rod Trip on the Wall Jet Development

A 1.8 mm diameter rod was placed on the floor of the tunnel in the vicinity of the exit (approximately 0.25 inches) from the wall jet to manipulate the development of the wall jet downstream of the nozzle. The ratio of the rod to the height of the nozzle exit was 0.28. The rod reduces the development length required to obtain a fully developed turbulent layer.

The mean velocity profiles at streamwise location $x/b = 100, 200$ and $300$ are shown in Fig.26 and the velocity development as flow proceeds along the tunnel center line is clearly seen. The maximum velocity ($u_m$) decreases as the flow develops down the
tunnel i.e. at $x/b = 100$, $u_m \approx 7.79 \text{ ms}^{-1}$, at $x/b = 200$, $u_m \approx 5.06 \text{ ms}^{-1}$, and at $x/b = 300$, $u_m \approx 3.77 \text{ ms}^{-1}$. The maximum velocity ($u_m$) values at all streamwise locations when the rod is placed in the flow are less than the maximum velocity ($u_m$) values when the wall jet is unforced as summarized in Table 1.

Table 1: Table showing the difference between velocity measurements in the unforced wall jet and wall jet with a rod.

<table>
<thead>
<tr>
<th></th>
<th>The Unforced Wall jet</th>
<th>Rod</th>
<th>Percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x/b = 100$</td>
<td>8.05 ms$^{-1}$</td>
<td>7.79 ms$^{-1}$</td>
<td>3.283 %</td>
</tr>
<tr>
<td>$x/b = 200$</td>
<td>5.2 ms$^{-1}$</td>
<td>5.06 ms$^{-1}$</td>
<td>2.729 %</td>
</tr>
<tr>
<td>$x/b = 300$</td>
<td>4.01 ms$^{-1}$</td>
<td>3.77 ms$^{-1}$</td>
<td>6.170 %</td>
</tr>
</tbody>
</table>

As the maximum velocity ($u_m$) decreases, the boundary layer thickness, $\delta$, increases as flow moves down the tunnel i.e. at $x/b = 100$, $\delta \approx 0.0537 \text{ m}$, at $x/b = 200$, $\delta \approx 0.1051 \text{ m}$, and at $x/b = 300$, $\delta \approx 0.1449 \text{ m}$. The boundary layer thickness, $\delta$, decreases when the rod is placed in the flow when compared to the boundary layer thickness, $\delta$, in the unforced wall jet at similar streamwise locations as summarized in Table 2.

Table 2: Table showing the difference between boundary layer thickness, $\delta$, in the unforced wall jet and wall jet with a rod.

<table>
<thead>
<tr>
<th></th>
<th>The Unforced wall jet</th>
<th>Rod</th>
<th>Percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x/b = 100$</td>
<td>0.0551 m</td>
<td>0.0537 m</td>
<td>2.574 %</td>
</tr>
<tr>
<td>$x/b = 200$</td>
<td>0.1054 m</td>
<td>0.1051 m</td>
<td>0.285 %</td>
</tr>
<tr>
<td>$x/b = 300$</td>
<td>0.1459 m</td>
<td>0.1449 m</td>
<td>0.688 %</td>
</tr>
</tbody>
</table>
Figure 27 shows the turbulence intensity development of the streamwise velocity at the three streamwise locations along the tunnel when the rod was placed on the floor of the tunnel in the vicinity of the jet exit. It is apparent that the turbulence becomes more energetic downstream at all wall normal locations as in an unforced wall jet. However, there is a significant difference between the turbulence development when the rod is compared to the unforced wall jet. The turbulence is significantly more energetic at $x/b = 300$ when the rod is used to trip the boundary layer than for the unforced wall jet i.e. the peak energy values of turbulence are approximately 7.6 % higher. The spectrograms in Figs.28 through 31 at different streamwise locations show the large scale structures becoming more energetic, and reaching further and further towards the wall as flow develops downstream as was found with the unforced wall jet.
Figure 27: Turbulence Intensity Development in wall jet with a rod.

Figure 28: Spectrogram of a wall jet with a rod at $x/b = 100$.

$x/b = 100$

$\tau_w = 0.041899 \, Pa$

$u_r = 0.18632\, m/s^{-1}$

Figure 28: Spectrogram of a wall jet with a rod at $x/b = 100$. 
Figure 29: Spectrogram of a wall jet with a rod at $x/b = 200$.

$x/b = 200$

$\tau_w = 0.033307 \text{ Pa}$

$u_\tau = 0.16616 \text{ m s}^{-1}$

*Figure 29: Spectrogram of a wall jet with a rod at $x/b = 200$. 
Figure 31: Spectrogram of a wall-jet with a rod at $x/b = 300$.

$\tau_w = 0.026048 \text{ Pa}$

$u_\tau = 0.14695 \text{ m s}^{-1}$

Figure 30: Spectrogram of an unforced wall-jet at $x/b = 300$.

$\tau_w = 0.013352 \text{ Pa}$

$u_\tau = 0.10529 \text{ m s}^{-1}$
Comparing the spectra graphs (Fig.30 and Fig.31) at $x/b = 300$ for the unforced wall jet to the wall jet with a rod, the large scale structures are clearly more energetic and reach closer to the wall when the rod is placed in the flow than for the unforced wall jet at the same location i.e. the large-scale structures when the rod is placed in the flow is approximately 15.4 % more energetic at $\frac{\zeta}{\delta} = 0.015$ than the large-scale structures in the baseline.

4.3. Effects of Sandpaper Trip on the Wall Jet Development

Sandpaper was placed on the floor of the tunnel in the vicinity of the exit (approximately 0.25 inches) from the wall jet to manipulate the wall jet in the downstream region. The sandpaper reduces the development length required to obtain a fully developed turbulent layer.

The mean velocity profiles at streamwise location $x/b = 100$, $200$ and $300$ are shown in Fig.32. The velocity development as flow proceeds along the tunnel center line is clearly seen. The maximum velocity ($u_m$) decreases as the flow develops down the tunnel, i.e., at $x/b = 100$, $u_m \approx 7.36 \text{ ms}^{-1}$, at $x/b = 200$, $u_m \approx 4.99 \text{ ms}^{-1}$, and at $x/b = 300$, $u_m \approx 3.84 \text{ ms}^{-1}$. The maximum velocity ($u_m$) values at all streamwise locations are less than the maximum velocity for the baseline as summarized in Table 3.
Table 3: Table showing the difference between velocity measurements in the unforced wall jet (baseline) and wall jet with a sandpaper trip.

<table>
<thead>
<tr>
<th>x/b = 100</th>
<th>The Unforced Wall jet</th>
<th>Sandpaper</th>
<th>Percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.05 ms(^{-1})</td>
<td>7.36 ms(^{-1})</td>
<td>8.955 %</td>
<td></td>
</tr>
<tr>
<td>x/b = 200</td>
<td>5.2 ms(^{-1})</td>
<td>4.99 ms(^{-1})</td>
<td>4.122 %</td>
</tr>
<tr>
<td>x/b = 300</td>
<td>4.01 ms(^{-1})</td>
<td>3.84 ms(^{-1})</td>
<td>4.331 %</td>
</tr>
</tbody>
</table>

As the maximum velocity (\(u_{\text{m}}\)) decreases, the boundary layer thickness increases as flow moves down the tunnel, i.e., at \(x/b = 100\), \(\delta \approx 0.0574\) m, at \(x/b = 200\), \(\delta \approx 0.1131\) m, and at \(x/b = 300\), \(\delta \approx 0.1496\) m. Table 4 summarizes the differences in boundary layer thickness, \(\delta\), at similar streamwise locations when the sandpaper trip was placed in the flow and the unforced wall jet.

Table 4: Table showing the difference between boundary layer thickness, \(\delta\), in the unforced wall jet and wall jet with a sandpaper trip.

<table>
<thead>
<tr>
<th>x/b = 100</th>
<th>The Unforced wall jet</th>
<th>Sandpaper</th>
<th>Percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0551 m</td>
<td>0.0574 m</td>
<td>4.088 %</td>
<td></td>
</tr>
<tr>
<td>x/b = 200</td>
<td>0.1054 m</td>
<td>0.1131 m</td>
<td>7.048 %</td>
</tr>
<tr>
<td>x/b = 300</td>
<td>0.1459 m</td>
<td>0.1496 m</td>
<td>2.504 %</td>
</tr>
</tbody>
</table>
Figure 32: Velocity development in wall jet with sandpaper.

Figure 33 shows the turbulence intensity development of the streamwise velocity at the three streamwise locations along the tunnel when sandpaper is placed on the floor of the tunnel in the vicinity of the jet exit. The turbulence becomes more energetic downstream at all wall normal locations as the flow moves down stream as was the case in the unforced wall jet. The turbulence when the sandpaper trip is placed in the flow at $x/b = 300$ was not found to be significantly different to the turbulence in the baseline at a similar location i.e. it was calculated to be approximately 3.4 % less than the turbulence in the baseline. The spectrograms in figures Fig.34, Fig.35 and Fig.37 show the large scale structures being more energetic and reaching further and further towards the wall as flow develops downstream as in the unforced wall jet and wall jet with a rod.
Figure 33: Turbulence Intensity development in the wall jet with sandpaper.

Significantly lower peak value than Rod at $x/b = 300$

Figure 34: Spectrogram of the wall jet with sandpaper at $x/b = 100$.

$x/b = 100$

$\tau_w = 0.052211 \, Pa$

$u_\tau = 0.20817 \, ms^{-1}$
\( x/b = 200 \)

\[ \tau_w = 0.041324 \text{ Pa} \]
\[ u_T = 0.18496 \text{ m s}^{-1} \]

Figure 35: Spectrogram of the wall jet with sandpaper at \( x/b = 200 \).
Figure 37: Spectrogram of the wall-jet with sandpaper at $x/b = 300$.

$\tau_w = 0.027861 \text{ Pa}$
$u_x = 0.15197 \text{ ms}^{-1}$

Figure 36: Spectrogram of the unforced wall-jet at $x/b = 300$.

$\tau_w = 0.013352 \text{ Pa}$
$u_x = 0.10529 \text{ ms}^{-1}$

Sandpaper 60 grit
Comparing the spectra graphs (Fig.36 and Fig.37) at \( x/b = 300 \) for the unforced wall jet to the wall jet with sandpaper, the large scale structures were less energetic when the sandpaper was placed on the floor than in an unforced wall jet at the same location i.e. the large-scale structures when the sandpaper trip is in the flow is approximately 28.8 \% less energetic at \( \frac{z}{\delta} = 0.015 \) than the large-scale structures in the baseline.

### 4.4. Effects of Sandpaper and String Trips on the Wall Jet Development

Sandpaper and string were placed in the vicinity of the wall jet exit to manipulate the wall jet in the downstream region. The string was placed above the wall jet exit (approximately 0.1 inches from the top of the jet exit) to manipulate the outer layer while the sandpaper placed on the tunnel floor ensures that any changes done to the outer layer does not affect the turbulence transition in the inner layer.

The mean velocity profiles at the different streamwise locations are shown in Fig.38. The maximum velocity \( (u_m) \) decreases as the flow develops down the tunnel, i.e., at \( x/b = 100, \, u_m \approx 7.46 \text{ ms}^{-1} \), at \( x/b = 200, \, u_m \approx 5.15 \text{ ms}^{-1} \), and at \( x/b = 300, \, u_m \approx 3.91 \text{ ms}^{-1} \). The maximum velocity \( (u_m) \) at all streamwise locations when sandpaper and string are placed in the flow are less than the maximum velocity when the wall jet is unforced as shown in Table 5.
Table 5: Table showing the difference between velocity measurements in the unforced wall jet (baseline) and wall jet with sandpaper and string trips.

<table>
<thead>
<tr>
<th></th>
<th>The Unforced Wall jet</th>
<th>Sandpaper and string trips</th>
<th>Percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>x/b = 100</td>
<td>8.05 ms(^{-1})</td>
<td>7.46 ms(^{-1})</td>
<td>7.608 %</td>
</tr>
<tr>
<td>x/b = 200</td>
<td>5.2 ms(^{-1})</td>
<td>5.15 ms(^{-1})</td>
<td>0.966 %</td>
</tr>
<tr>
<td>x/b = 300</td>
<td>4.01 ms(^{-1})</td>
<td>3.91 ms(^{-1})</td>
<td>2.525 %</td>
</tr>
</tbody>
</table>

As the maximum velocity (\(u_m\)) decreases, the boundary layer thickness increases as flow moves down the tunnel i.e. at \(x/b = 100\), \(\delta \approx 0.0589\) m, at \(x/b = 200\), \(\delta \approx 0.1090\) m, and at \(x/b = 300\), \(\delta \approx 0.1527\) m. Table 6 summarizes the differences in boundary layer thickness, \(\delta\), at similar streamwise locations when the sandpaper and string trips were placed in the flow and the unforced wall jet.

Table 6: Table showing the difference between boundary layer thickness, \(\delta\), in the unforced wall jet and wall jet with sandpaper and string trips.

<table>
<thead>
<tr>
<th></th>
<th>The Unforced wall jet</th>
<th>Rod</th>
<th>Percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>x/b = 100</td>
<td>0.0551 m</td>
<td>0.0589 m</td>
<td>6.667 %</td>
</tr>
<tr>
<td>x/b = 200</td>
<td>0.1054 m</td>
<td>0.1090 m</td>
<td>3.358 %</td>
</tr>
<tr>
<td>x/b = 300</td>
<td>0.1459 m</td>
<td>0.1527 m</td>
<td>4.555 %</td>
</tr>
</tbody>
</table>
Figure 38: Velocity development in wall jet with Sandpaper and String.

Figure 39 shows the turbulence intensity development of the streamwise velocity at the three streamwise locations along the tunnel when sandpaper and string are both placed in the tunnel in the vicinity of the jet exit. The turbulence becomes more energetic downstream at all wall normal locations as in an unforced wall jet. Similar to the sandpaper trip, the presence of sandpaper and string trips in the flow did not significantly alter the turbulence when compared to the baseline at streamwise location $x/b = 300$ i.e. the difference in turbulence was calculated to be approximately 3.4 % less than the baseline. The spectrograms in figures Fig.40, Fig.41 and Fig.44 at different streamwise locations in the tunnel show the large scale structures being more energetic and reaching further and further towards the wall as flow develops downstream as shown in any of the other cases.
Figure 39: Turbulence Intensity development in wall jet with sandpaper and string.

Figure 40: Spectrogram of a wall jet with Sandpaper and String at $x/b = 100$.

$x/b = 100$

$\tau_w = 0.066067 \ Pa$

$u_r = 0.23416 m/s$
Figure 41: Spectrogram of a wall jet with sandpaper and string at $x/b = 200$.

$x/b = 200$

\[ \tau_w = 0.030907 \text{ Pa} \]
\[ u_\tau = 0.15997 \text{ m/s}^{-1} \]

*Figure 41: Spectrogram of a wall jet with sandpaper and string at $x/b = 200$.\*
Figure 43: Spectrogram of a wall-jet with sandpaper at $x/b = 300$.  

Figure 42: Spectrogram of an unforced wall-jet at $x/b = 300$.  

Figure 44: Spectrogram of a wall-jet with sandpaper and string at $x/b = 300$. 

Sandpaper 60 grit
Comparing the spectra graphs (Fig.42, Fig.43 and Fig.44) at $x/b = 300$ for the unforced wall jet, wall jet with sand paper and wall jet with sand paper + string, the large scale structures are shown to be least energetic in the sandpaper configuration. The sandpaper and string configuration has less energetic large-scale structures than those in an unforced wall jet but more energetic than those in the sandpaper configuration i.e. the large-scale structures when the sandpaper and string trips are in the flow was approximately 18% less energetic at $\frac{z}{\delta} = 0.015$ than the large-scale structures in the baseline but 10.5% more energetic than the large-scale structures seen as a result of the sandpaper trip.

The different perturbation configurations described in this chapter were found to alter the energy of the large scale structures as discussed. The presence of the rod trip in the flow had the most effect on the energy of the large-scale structures while the sandpaper trip had the least effect on the energy of the large-scale structures.
5. CONCLUSIONS AND FUTURE WORK

A series of experiments were conducted using a single hot-wire sensor to better understand the evolution of large-scale flow structures in the streamwise direction of a plane wall jet. A wall jet facility was built and used to study the effects of manipulating large-scale structures in the boundary layer of the wall jet. Different perturbation configurations of the wall jet were used to manipulate the large-scale structures in order to study their effects on the wall jet. The different perturbation configurations used were a rod, sand paper and sand paper and still wire. An unforced wall jet was used as the baseline.

5.1. Conclusions

1) All the different perturbation cases were shown to change the energy of the large structures in the flow.

2) In all three perturbation configurations, the maximum velocity at the different locations decreased as flow moved downstream of the tunnel but were less than the maximum velocity at similar locations in an unforced wall jet.

3) The turbulence was most energetic when the rod was used as the perturbation when compared to an unforced wall jet or the other perturbation configurations. Both the sandpaper configuration and the sandpaper and string configuration had significantly lower levels of turbulence than in an unforced wall jet. However, the large-scale structures became more energetic in all cases as the flow moved downstream.
4) The large-scale structures were shown to be most energetic and reached closest to the wall in the wall jet perturbed using the rod than in all other flow cases at all streamwise positions.

5) The sandpaper and the sandpaper and string configurations showed less energetic large-scale structures at all streamwise locations than in an unforced wall jet. However, the large-scale structures in the sandpaper and string configuration were more energetic than the large scale structures in the sandpaper configuration at all streamwise locations.

5.2. Future Work

Based on the outcome from this work, below are suggestions for future work;

1) A multiple hot-wire sensor system known as “cross-wire probe” should be used to measure the three velocity components instead of using a single hot-wire sensor used in the current work that doesn’t measure the three velocity components. A multiple hot-wire sensor measures three-dimensional changes occurring in the plane wall jet that a single hot-wire sensor doesn’t measure. It maybe that some of the changes caused by the jet are three-dimensional in nature.

2) Imposing impulsive perturbation at the free jet portion of the jet exit to modify large-scale structures in order to actively reduce or increase wall shear stress. Either acoustic excitation or a wire/flap at the free-jet portion of the nozzle exit can be used to perturb the flow. Impulsive perturbation will provide a frequency characterization instead of a static characterization of the perturbation.
3) Using a wall normal pulsed jet to impulsively modify the large-scale structures in the flow. A pulsed jet will be used as the device to provide an impulsive perturbation to the flow in order to modify the large-scale structures or increase wall shear stress. A wall normal jet is a more practical way of causing changes to the large-scale structures.

4) Design a reactive or closed loop control strategy to control wall shear stress which is the ultimate goal of this work.
REFERENCES


