Pulsed vertical jet in cross flow at mean blowing ratios 0.35 and 0.45

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PULSED VERTICAL JET IN CROSS FLOW AT MEAN BLOWING RATIOS 0.35 AND 0.45

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering in

The Department of Mechanical Engineering

by

Pierre-Emmanuel Bouladoux
Ecole Nationale Supérieure d’Ingénieurs de Constructions Aéronautiques, Toulouse, France
December 2006
To my family.

To my grandmother Marraine and my grandfather Caï

who passed away while I was in Louisiana.

To the dream of flight.
Acknowledgements

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# Table of Contents

Dedication ................................................................................................................................. ii

Acknowledgements ..................................................................................................................... iii

List of Tables ................................................................................................................................. vii

List of Figures ................................................................................................................................. viii

List of Equations ............................................................................................................................ xiii

Abstract ........................................................................................................................................... xiv

Chapter 1: Introduction .................................................................................................................. 1
  1.1. Background .......................................................................................................................... 1
  1.2. Motivation .......................................................................................................................... 4
  1.3. Literature Survey ............................................................................................................... 4
  1.4. Objectives .......................................................................................................................... 7

Chapter 2: Definitions and Notations .......................................................................................... 8
  2.1. Notations .......................................................................................................................... 8
  2.2. Units and Conversion ....................................................................................................... 8
  2.3. Definitions ....................................................................................................................... 8
    2.3.1. Blowing Ratios: BR ....................................................................................................... 9
    2.3.2. Duty Cycle: DC ........................................................................................................... 10
    2.3.3. Forcing Frequency: \( f_i \) ............................................................................................ 10

Chapter 3: Experimental Apparatus and Procedures ................................................................. 11
  3.1. Wind Tunnel ..................................................................................................................... 11
  3.2. Jet .................................................................................................................................... 14
    3.2.1. Generalities ............................................................................................................... 14
    3.2.2. Air Supply ................................................................................................................ 14
    3.2.3. Jet Control Valve System ......................................................................................... 17
    3.2.4. Jet Pipe .................................................................................................................... 18
    3.2.5. Pulsing System .......................................................................................................... 19
  3.3. Traverse System ................................................................................................................. 19
  3.4. Constant Temperature Anemometry ............................................................................... 24
    3.4.1. Principles .................................................................................................................. 24
    3.4.2. Probes ....................................................................................................................... 25
    3.4.3. Calibrations .............................................................................................................. 27
      3.4.3.1. Single Wire Probe ............................................................................................... 27
      3.4.3.2. X-Wire Probe .................................................................................................... 30
    3.4.4. Experiments ............................................................................................................. 32
  3.5. Visualizations and Particle Image Velocimetry ................................................................. 34
    3.5.1. Introduction .............................................................................................................. 34
    3.5.2. LASER ..................................................................................................................... 34
    3.5.3. Camera ..................................................................................................................... 37
    3.5.4. Lenses ....................................................................................................................... 37
    3.5.5. Synchroniser ............................................................................................................. 39
    3.5.6.1. TiCl\(_4\) ................................................................................................................ 39
    3.5.6.2. TiCl\(_4\) Seeding System Description ....................................................................... 41
  3.6. Experimental Procedures and Settings for Visualizations and PIV ............................... 46
Chapter 6: Conclusion
References
Appendix: Data Processing Matlab Codes
Vita
List of Tables

Table 3-1: Table of DC to set to get a certain duty cycle at a certain frequency. .......................................................... 19
Table 3-2: Available probes ......................................................................................................................................... 26
Table 5-1: Free stream spectrum frequencies ............................................................................................................. 62
Table 5-2: Boundary layer exploration results (U_{∞} = 1.6m/s, x/DJ = 0, y/DJ = 0) ..................................................... 63
Table 5-3: Boundary layer test results at a fan frequency of 3Hz .............................................................................. 65
Table 5-4: Comparison of nominal and actual W_{max}/U_{∞} .......................................................................................... 71
Table 5-5: Unforced JICF visualizations conditions .................................................................................................... 74
Table 5-6: Unforced JICF CTA tests conditions ........................................................................................................... 75
Table 5-7: Significant frequencies of the flow at BR = 0.150 and BR = 0.188 .......................................................... 81
Table 5-8: Significant frequencies of the flow at BR = 0.250 ................................................................................ 84
Table 5-9: Significant frequencies of the flow at BR = 0.300 ................................................................................ 87
Table 5-10: Significant frequencies at BR = 0.365 and BR = 0.465 ......................................................................... 91
Table 5-11: Significant frequencies of the flow at BR = 0.600 ................................................................................. 93
Table 5-12: Flow conditions of the visualizations at BR_m = 0.35 ............................................................................. 95
Table 5-13: Flow conditions of the visualizations at BR_m = 0.45 ............................................................................. 97
Table 5-14: Mean and standard deviation of BR_m .................................................................................................. 97
Table 5-15: Harmonic frequencies [Hz] of perfect forced signals at the various forcing conditions ......................... 98
Table 5-16: Case definition for forced JICF .............................................................................................................. 99
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>(a) River flowing into another (<a href="http://www.lyon.fr">www.lyon.fr</a>); (b) chimneys; (c) Boeing 747 fire fighter aircraft (<a href="http://www.evergreenaviation.com">www.evergreenaviation.com</a>)</td>
<td>1</td>
</tr>
<tr>
<td>1-2</td>
<td>AV-8B Harrier</td>
<td>2</td>
</tr>
<tr>
<td>1-3</td>
<td>(a) Jet engine (<a href="http://www.bartleby.net">www.bartleby.net</a>) and (b) gas turbine (<a href="http://www.middle-watch.co.uk">www.middle-watch.co.uk</a>) schematics</td>
<td>2</td>
</tr>
<tr>
<td>1-4</td>
<td>Turbine blade (<a href="http://www.pr.afrl.af.mil">www.pr.afrl.af.mil</a>)</td>
<td>3</td>
</tr>
<tr>
<td>1-5</td>
<td>Vortex structures in the JICF (Fric and Roshko, 1994).</td>
<td>5</td>
</tr>
<tr>
<td>3-1</td>
<td>Wind tunnel test section and transverse jet schematic (prepared by J. Oertling)</td>
<td>11</td>
</tr>
<tr>
<td>3-2</td>
<td>Wind tunnel remote control (a) and main breaker (b)</td>
<td>12</td>
</tr>
<tr>
<td>3-3</td>
<td>Wind tunnel access window: (a) closed; (b) open</td>
<td>13</td>
</tr>
<tr>
<td>3-4</td>
<td>Wooden roof of the wind tunnel</td>
<td>13</td>
</tr>
<tr>
<td>3-5</td>
<td>Acrylic roof of the wind tunnel</td>
<td>14</td>
</tr>
<tr>
<td>3-6</td>
<td>Jet orifice</td>
<td>14</td>
</tr>
<tr>
<td>3-7</td>
<td>Compressed air tank</td>
<td>15</td>
</tr>
<tr>
<td>3-8</td>
<td>Air dryer</td>
<td>16</td>
</tr>
<tr>
<td>3-9</td>
<td>Jet control system: (a) front; (b) side.</td>
<td>17</td>
</tr>
<tr>
<td>3-10</td>
<td>Traverse</td>
<td>20</td>
</tr>
<tr>
<td>3-11</td>
<td>Traverse control: (a) zeta drives; (b) indexer</td>
<td>20</td>
</tr>
<tr>
<td>3-12</td>
<td>Motors: (a) y axis; (b) z axis.</td>
<td>21</td>
</tr>
<tr>
<td>3-13</td>
<td>Motion Control and Home VI</td>
<td>21</td>
</tr>
<tr>
<td>3-14</td>
<td>Motion Control and Acquisition 6 Channels VI</td>
<td>22</td>
</tr>
<tr>
<td>3-15</td>
<td>LASER in position for a horizontal sheet</td>
<td>23</td>
</tr>
<tr>
<td>3-16</td>
<td>TSI IFA 300</td>
<td>25</td>
</tr>
<tr>
<td>3-17</td>
<td>TSI hot wire probes used for CTA: (a) 1210 straight probe; (b) 1212 bent probe; (c) 1218 boundary layer probe; (d) 1241 X-wire straight probe</td>
<td>26</td>
</tr>
<tr>
<td>3-18</td>
<td>Calibration wiring: Single sensor probe (continuous lines), and X probe (continuous and doted) (prepared by G. Bidan)</td>
<td>28</td>
</tr>
<tr>
<td>3-19</td>
<td>LASER external firing wiring diagram (prepared by G. Bidan)</td>
<td>36</td>
</tr>
</tbody>
</table>
Figure 3-20: Kodak Megaplus Model ES 1.0 Camera

Figure 3-21: (a) 50mm lens; (b) 105mm lens.

Figure 3-22: (a) 12.5-75mm video zoom lens; (b) 70-210mm zoom lens.

Figure 3-23: C-mounts.

Figure 3-24: Synchronizer: (a) front; (b) back.

Figure 3-25: TiCl$_4$ storage.

Figure 3-26: Protection equipment: (a) Respiratory mask; (b) Goggles; (c) Rubber gloves.

Figure 3-27: Cleaning kit.

Figure 3-28: Image (a) with and (b) without moisture seeding.

Figure 3-29: Visualization Settings.

Figure 3-30: Camera control settings for visualizations.

Figure 3-31: Forcing DAQ board.

Figure 3-32: NI PCI 6220 card.

Figure 3-33: Data Acquisition board.

Figure 3-34: TSI 40241 flow meter.

Figure 3-35: TSI 4140 flow meter.

Figure 3-36: (from right to left) rotameter, pressure transducer and power supply of the pressure transducer.

Figure 3-37: Flow meter TSISetup program.

Figure 3-38: Flow meter reading 2.0 (a) and 3.1 (b) VIs.

Figure 3-39: Oscilloscope (a) and Multimeter (b).

Figure 4-1: Image processing: (a) raw image; (b) processed image.

Figure 5-1: Wind tunnel velocity calibration.

Figure 5-2: Free stream power spectrum at $U_\infty = 1.6\text{m/s}$.

Figure 5-3: Boundary Layer Power Spectrum.

Figure 5-4: Boundary layer profiles at $x/D_j = 0.00$.

Figure 5-5: Boundary layer profiles at $y/D_j = 0.00$.

Figure 5-6: Power Spectrum of the jet without cross flow.

Figure 5-7: Power spectrum with and without cross flow/flow meter.
Figure 5-8: Mean velocity and RMS velocity profiles at $W_{\text{max}}/U_\infty \approx 0.5$ (a, b); $W_{\text{max}}/U_\infty \approx 1.0$ (c,d); $W_{\text{max}}/U_\infty \approx 1.5$ (e,f) without cross flow scaled with $W_{\text{max}}$. .......................................................... 69

Figure 5-9: Mean velocity and RMS velocity profiles at $W_{\text{max}}/U_\infty \approx 0.5$ (a, b); $W_{\text{max}}/U_\infty \approx 1.0$ (c,d); $W_{\text{max}}/U_\infty \approx 1.5$ (e,f) without cross flow scaled with $W_{\text{mean}}$. ................................................................................................................. 70

Figure 5-10: Profiles of U and W for the steady state JICF. .......................................................................................................................... 71

Figure 5-11: RMS velocities (a), Skewness (b) and Kurtosis (b) of the unforced JICF. .............................................................. 72

Figure 5-12: Target with positions of the CTA surveys. .......................................................................................................................... 74

Figure 5-13: Example of disturbance due to the air conditioning system at BR = 0.150, position F (3.50, 0.75): (a) time record, (b) power spectrum, (c) corrected power spectrum. .............................................................. 76

Figure 5-14: Example of disturbance due to the air conditioning system at BR = 0.175, position B (0.00, 0.25): (a) time record, (b) power spectrum.................................................................................................................................. 76

Figure 5-15: Examples of rectified records at D (1.00, 0.25): (a) BR = 0.250, (b) BR = 0.300, (c) BR = 0.365 and (d) BR = 0.465.......................................................................................................................... 77

Figure 5-16: Unforced vertical jet in cross flow at BR$_m$=0.150; Visualizations (f$_r$=30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e). ..... 78

Figure 5-17: Unforced vertical jet in cross flow at BR$_m$=0.188; Visualizations (f$_r$=30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e)...... 79

Figure 5-18: CTA survey positions for (a) BR = 0.150; (b) BR = 0.188................................................................................................. 80

Figure 5-19: Unforced vertical jet in cross flow at BR$_m$=0.250; Visualizations (f$_r$=30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e)........... 82

Figure 5-20: CTA survey positions at BR = 0.250 ................................................................................................................................. 83

Figure 5-21: Unforced vertical jet in cross flow at BR$_m$=0.300; Visualizations (f$_r$=30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e)...... 85

Figure 5-22: CTA survey positions at BR = 0.300 .............................................................................................................................................. 86

Figure 5-23: CTA time records at BR=0.300 at (a) A, (b) C, (c) G........................................................................................................... 87

Figure 5-24: Unforced vertical jet in cross flow at BR$_m$=0.365; Visualizations (f$_r$=30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).... 88

Figure 5-25: Unforced vertical jet in cross flow at BR$_m$=0.465; Visualizations (f$_r$=30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e)..... 89

Figure 5-26: CTA survey positions at (a) BR = 0.365; (b) BR = 0.465................................................................................................. 90

Figure 5-27: Unforced vertical jet in cross flow at BR$_m$=0.600; Visualizations (f$_r$=30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e)...... 92

Figure 5-28: CTA survey positions at BR = 0.600................................................................................................................................. 93

Figure 5-29: Presence of forcing harmonics in the raw spectra of the flow (BR$_m$ = 0.35) .............................................................. 98
Figure 5-30: High (a) and low (b) flow characteristics (BR$_l$ = 0.1875, DC = 0.25, $f_l$ = 0.5Hz) .................................................100

Figure 5-31: Jet shut off..............................................................................................................................................................100

Figure 5-32: Phase averaged cycle (BR$_l$ = 0.1875, DC = 0.25, $f_l$ = 5.0Hz).................................................................101

Figure 5-33: Puff build up (a) and low flow (b) (BR$_l$ = 0.1875, DC = 0.25, $f_l$ = 10.0Hz). ..................................................102

Figure 5-34: Similarity of (BR$_l$ = 0.1875, DC = 0.50) (top) and (BR$_{pp}$ = 0.25, DC = 0.50) (bottom) at $f_l$ = 1.0Hz
(phase averaged pictures) .............................................................................................................................................102

Figure 5-35: Similarity of (BR$_l$ = 0.1875, DC = 0.70) (top) and (BR$_{pp}$ = 0.25, DC = 0.70) (bottom) at $f_l$ = 5.0Hz
(phase averaged pictures) .............................................................................................................................................103

Figure 5-36: Forced vertical jet in cross flow at BR$_{m}$=0.35, BR$_{pp}$=0.25, DC=0.70, $f_b$=0.5Hz; Visualizations at jet
mid-plane, x-z (1-42); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity
signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations:
raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................................................105

Figure 5-37: Forced vertical jet in cross flow at BR$_{m}$=0.35, BR$_{pp}$=0.25, DC=0.50, $f_b$=1.0Hz; Visualizations at jet
mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity
signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations:
raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................................................106

Figure 5-38: Forced vertical jet in cross flow at BR$_{m}$=0.35, BR$_{pp}$=0.25, DC=0.70, $f_b$=5.0Hz; Visualizations at jet
mid-plane, x-z (2-46); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity
signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations:
raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................................................107

Figure 5-39: Forced vertical jet in cross flow at BR$_{m}$=0.35, BR$_{pp}$=0.25, DC=0.1875, $f_b$=10.0Hz; Visualizations at jet
mid-plane, x-z (1-47); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity
signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations:
raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................................................108

Figure 5-40: Phase averaged cycle evolution with DC (left to right DC = 0.25, 0.50, 0.70) and $f_b$ (top to bottom $f_b$ =
0.5, 1.0, 5.0, 10.0Hz) for BR$_{pp}$ = 0.15...............................................................................................................................110

Figure 5-41: Forced vertical jet in cross flow at BR$_{m}$=0.35, BR$_{pp}$=0.25, DC=0.25, $f_b$=0.5Hz; Visualizations at jet
mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity
signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations:
raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................................................112

Figure 5-42: Forced vertical jet in cross flow at BR$_{m}$=0.35, BR$_{pp}$=0.15, DC=0.50, $f_b$=1.0Hz; Visualizations at jet
mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity
signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations:
raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................................................113

Figure 5-43: Forced vertical jet in cross flow at BR$_{m}$=0.35, BR$_{pp}$=0.25, DC=0.25, $f_b$=5.0Hz; Visualizations at jet
mid-plane, x-z (1-46); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity
signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations:
raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................................................114

Figure 5-44: Forced vertical jet in cross flow at BR$_{m}$=0.35, BR$_{pp}$=0.15, DC=0.50, $f_b$=10.0Hz; Visualizations at jet
mid-plane, x-z (2-48); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity
signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................115

Figure 5-45: Forced vertical jet in cross flow at $BR_m=0.45$, $BR_p=0.1875$, DC=0.50, $f=0.5\text{Hz}$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................118

Figure 5-46: Forced vertical jet in cross flow at $BR_m=0.45$, BR$=0.1875$, DC=0.70, $f=1.0\text{Hz}$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................119

Figure 5-47: Forced vertical jet in cross flow at $BR_m=0.45$, $BR_p=0.1875$, DC=0.70, $f=5.0\text{Hz}$; Visualizations at jet mid-plane, x-z (1-49); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................120

Figure 5-48: Forced vertical jet in cross flow at $BR_m=0.45$, $BR_p=0.25$, DC=0.50, $f=10.0\text{Hz}$; Visualizations at jet mid-plane, x-z (1-44); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................121

Figure 5-49: Forced vertical jet in cross flow at $BR_m=0.45$, $BR_p=0.25$, DC=0.50, $f=0.5\text{Hz}$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................124

Figure 5-50: Forced vertical jet in cross flow at $BR_m=0.45$, $BR_p=0.25$, DC=0.25, $f=1.0\text{Hz}$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................125

Figure 5-51: Forced vertical jet in cross flow at $BR_m=0.45$, $BR_p=0.25$, DC=0.50, $f=5.0\text{Hz}$; Visualizations at jet mid-plane, x-z (1-42); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................126

Figure 5-52: Forced vertical jet in cross flow at $BR_m=0.45$, $BR_p=0.25$, DC=0.25, $f=10.0\text{Hz}$; Visualizations at jet mid-plane, x-z (2-49); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j) .................................................................127
List of Equations

Equation 2-1: Equation linking the different parameters. .......................................................................................................................... 9

Equation 3-1: Reaction of TiCl₄ and H₂O. ........................................................................................................................................... 40

Equation 3-2: Reaction between HCl and H₂O. ................................................................................................................................... 40

Equation 3-3: Formation of TiOCl₂. ......................................................................................................................................................... 41

Equation 5-1: Definitions of δ, δ⁺, θ and H............................................................................................................................................... 64
Abstract

This thesis deals with a pulsed vertical jet transverse to a cross flow ($U_{\infty}=1.6m/s$) at mean blowing ratios 0.35 and 0.45. First the reasons of this study are explained and the previous work in the field is described. Then the experimental setup, the experimental procedures and the data processing are detailed. The system (wind tunnel and jet) is characterised before studying the Jet in Cross Flow (JICF). The JICF is explored under unforced and forced conditions through LASER sheet visualizations and constant temperature anemometry (CTA) measurements using hot-wire sensors. Blowing ratios ranging from 0.150 to 0.600 are studied for the unforced JICF to cover the range of blowing ratios present in the forced cases. Mean blowing ratios of 0.35 and 0.45 were studied at various low and peak-to-peak blowing ratio conditions, duty cycles of 0.25, 0.50 and 0.70, and forcing frequencies of 0.5Hz, 1.0Hz, 5.0Hz and 10.0Hz. Associated physical phenomena and the influence of the various parameters are discussed.
Chapter 1: Introduction

1.1. Background

Jets in cross flow, alias JCIF, have been extensively studied for over half a century. However it is still a field of research heavily worked on since the applications are numerous and on the edge of technology, and since the phenomena linked to JCIF are not fully understood yet. Therefore, experimental studies and numerical simulations are often performed.

JCIF are the concern of different fields of engineering. They can be encountered as simply as looking at a river flowing into another one, as looking at the smoke getting out of a chimney or when a fire fighter aircraft drops water or retardant on a fire. In the same order of ideas, one can also think of the blood flow in our body, volcano fumes, pollutant dispersion, and thermal plumes into cross winds at high altitude.

![Image](image1.jpg) ![Image](image2.jpg) ![Image](image3.jpg)

Figure 1-1: (a) River flowing into another (www.lyon.fr); (b) chimneys; (c) Boeing 747 fire fighter aircraft (www.evergreenaviation.com).

For example environmental engineering is interested in JCIF. A better understanding of JCIF can lead to improve the dispersion of fumes into the atmosphere. It can also lead to a prevision of the behaviour of pollutants dispersed in a river or even in the ocean if we consider the water streams running at sea. JCIF could help to improve our respect for environment.

JCIF have also been studied concerning the vertical/short take off and landing (V/STOL) aircrafts such as the AV-8B Harrier, the V22 Osprey, or the United States Marines Corps version of the Joint Strike Fighter (JSF). These programs require study of JCIF to understand their behaviour in a vertical or transitional phase of flight. These studies can be integrated into the onboard computers to give the pilot a better handling of his aircraft in those
sensitive phases of flight. To stay on the aeronautics side, planes using vectorised propulsion like the Lockheed
Martin F-22 Raptor or the Sukhoi 37 Super Flanker also require the help of JICF studies.

![Figure 1-2: AV-8B Harrier.](image)

Jets can also be blown on wings to enhance the lift or enlarge the flight domain of airplanes and avoid
stalling. This is used on modern civil aircraft airfoils. The Boeing 747 for example has airbrakes with holes so that
some flow can go through and that even at extreme attitudes the flow on the airfoil stays attached and the airfoil
gives lift to the plane.

JICF are also studied for the improvement of mixing. Whether it is mixing chemicals (chemistry
experiments, chemical industry), or mixing fuel with air in a combustor, JCIF are involved. The goals being to get
better efficiency with less starting material, studies have helped improve the mixing of oxygen and fuel.

This is particularly true for jet engines used on modern aircrafts and gas turbines used in power plants. In
those two cases, JCIF are present also in the turbine stage (see Figure 1-3). Jet engines and gas turbines have three
main stages: the compressor, the combustion chamber and the turbine, which provides power back to the
compressor. In those gas turbines, the higher the temperature at the turbine entrance, the more efficiency and power.
For power plants it means more power produced for less raw material. For aircrafts, it means more thrust with lower
fuel consumption. This is how the F-22 Raptor can reach super cruise without afterburners.

![Figure 1-3: (a) Jet engine (www.bartleby.net) and (b) gas turbine (www.middle-watch.co.uk) schematics.](image)
The main goal of research in turbomachinery has been to find ways to get the turbine inlet temperature higher. But turbines are fragile and expensive pieces of equipment. Therefore care must be taken not to go beyond the point where taking the temperature higher will damage the turbine, and particularly the turbine blades. Then the idea, while getting the temperature higher, is to push that point back, or bypass the rules…

At first material science was put to work to find new material with better structural and thermal properties. When the limit of these materials was reached, thermal science was called upon the problem. The idea was to cool the blades so that they could work at temperature way above their structural and melting limits.

As limits are pushed further and further, the cooling of turbine blades has taken a more and more important part in the study of turbomachinery. Different types of cooling have been studied and used so far. First to be implemented was the cooling via internal channels inside the blades. A coolant fluid is run inside the blade to cool it down. These internal channels are still extensively studied.

As limits were still pushed further, it became necessary to protect the blades from the outside. There came the idea of film cooling. Cool air is taken from the high pressure compressor stage, run into the blades and bled from holes on the blade to create a thin protective envelop of cold air surrounding the turbine blade. The word cold is used in a relative way here, meaning colder than the high-pressure combustor outlet/turbine inlet temperature.

This solution seems perfect but it knows its limits. This flow must protect the blades without disturbing too much the primary flow circulating in the turbine. Otherwise it would diminish the performance of the turbine, which is the opposite of what we want to do. Moreover, creating channels and holes in a turbine blade is a difficult and expensive process. Today, most gas turbines used in power generation or jet engines use film cooling, and turbine blades look like Swiss cheese or a shower head (see Figure 1-4).

Figure 1-4: Turbine blade (www.pr.afrl.af.mil).
However, film cooling can be improved. Indeed the coolant flow disturbs the flow along the turbine blades. Therefore ways to reduce the amount of coolant flow are researched. In a design concern, ways to reduce the number of holes are looked into as well. In order to do that, ways must be found to protect a greater surface with a less number of holes on a blade or with lower coolant flows. Lower coolant flow requirements lead to higher flow rates through the turbine, which in turn lead to higher thrust/power production.

This is where pulsed film-cooling may be promising. It is believed that by forcing (pulsing) the coolant flow, the quantities of coolant used may be reduced while achieving a better or equal coverage of the blades.

1.2. Motivation

Pulsed film cooling could be a way to push even further the limits of the function of gas turbines. That is the reason why experiments and simulations are conducted on the topic. However before trying to see if pulsed film cooling improves the efficiency and performance of gas turbines, the first step in that direction is a better understanding of the JICF under pulsed conditions.

Fluid dynamics and heat transfer are intimately connected. But before testing the thermal capabilities of pulsed film cooling, a better understanding of the pulsed jets in cross flow and therefore also simply the JCIF must be undertaken.

As a consequence prior to a heat transfer study, it is important to understand the mechanisms of the fluid happening in the jet in cross flow while it is pulsed at different frequencies, duty cycles, blowing ratios. Our study is just a first step toward a better understanding and therefore a better system. When we understand the fluidic phenomena at the jet and downstream, then will we be able to do an extensive fluid study and then a thermal study and then try to find the best way to improve the film cooling and therefore the performances of the gas turbines.

1.3. Literature Survey

JICF have been studied extensively over the past 60 years. In his article Margason (1993) described thoroughly various experimental and numerical studies, which have marked the first 50 years of research in the field. A few interesting articles are presented here.

In the 70’s, most studies were interested by JICF for their application to V/STOL aircrafts and environmental purposes. Then it extended to the improvement of combustors (i.e. mixing enhancement) or film cooling for gas turbines (i.e. limit the mixing). Either way studies can be useful, since applications look sometimes for opposite characteristics.
Most studies have been concentrating so far on the dynamics of the jets and the phenomena linked to the JICF. A lot of studies concern the structure of the jets, forced or not. Most studies agree the JCIF is characterized by 4 main vortical structures: the horseshoe vortex upstream of the jet, the counter-rotating vortex pair (CVP) far downstream of the jet, the ring like vortex at the jet exit and the wake vortices downstream of the jet.

Two articles by Fric and Roshko (1994) and Kelso et al are often quoted for their explanation of the structure of the jet in cross flow. As can be seen on Figure 1-5, four structures are determined. First are the horseshoe vortices, which form around the exit of the jet. Then the ring like vortices, also named jet shear layer vortices. These ring vortices are the source of the third kind of vortices and most well-know in the JICF field, the counter rotating vortex pair, which has a kidney shape and are present in the far field of the jet. This vortices are very important for the mixing of the jet with the cross flow, which makes them undesirable for film cooling since our goal is the reduction of the mixing of the jet flow with the cross flow. Finally, when the jet detaches downstream of the exit, wake vortices, like the one behind a cylinder form. Indeed, at the exit, the jet is similar to a cylinder in the flow.

![Figure 1-5: Vortex structures in the JICF (Fric and Roshko, 1994).](image)

Various configurations have been studied in heat transfer or fluid dynamics, experimentally or numerically, with gas or liquid. Consequently, there is a lot of material to cover. Most studies deals with steady state JICF. A few
deal with the pulsed JCIF. Most of the ones dealing with pulsed jets look for a way to control the jet better and do not deal with duty cycles.

Various configurations have been studied: square jets, compound angles jets, inclined jets. Those studies have been made by simulations or experiments, or both, like a recent study (2005) by Jia et al (2005) LASER Doppler anemometry was used to study jets with 30, 60 and 90 degree inclinaison angles, and simulations run at these angles as well as 15 to 40 degrees when the simulation revealed good. The blowing ratios were ranging from 2 to 9. For jets inclined more than 40° they noticed a recirculation bubble in the field downstream of the jet, which size depended on the blowing ratio. For jet inclined with angles smaller than 30° this bubble vanishes. Another comparable study was made numerically by Y.T. Yang and Y.X. Wang on a 3D fluidic and thermal simulation of a 45° inclined jet for blowing ratios ranging from 3 to 7.

However most studies deal with blowing ratios above 1, and the few studying at lower blowing ratio do not modulate it. When the flow is modulated, no attention was given to the duty cycle, except for the following heat transfer study.

A recent study by Ekkad et al (2004) is the first one trying to show how the pulsed jet in cross flow can improve the film cooling in gas turbine. The study concentrated on the film effectiveness and the heat transfer associated with a pulsed jet situated on a leading edge model. The study was realised for pulsing frequency of 5, 10 and 20Hz, duty cycles of 10, 25, 50, 75 and 100% (steady state, fully open), and six blowing ratios ranging from 0.25 to 2.0. It studied the steady state and pulsed flow for each blowing ratio. The conclusions corroborate various studies on the steady state jet. At low blowing ratio, the flow is attached, which mean a high effectiveness of the film cooling. When the blowing ratio is higher, the jet penetrates and spreads more but lifts off the surface. The highest film effectiveness was observed between blowing ratios of 0.5 and 1.0. As for the pulsed test results, they showed that for the range of frequency used the variation of the frequency was not a factor affecting heat transfer of film effectiveness as long as the jet was pulsed. Same could be said for duty cycles higher than 50%. In a nutshell, the pulsing enhances the film effectiveness and slightly lowers the heat transfer coefficient. However, there is a duty cycle limit beyond which the jet flow is dramatically altered and basically almost disappears.

The only down side of this study was that the jet was pulsed in a fully open/fully closed fashion with the blowing ratio being the open part flow blowing ratio. Consequently, the actual average blowing ratio was lower than the nominal one, i.e. the steady state blowing ratio it was compared too. This is the main difference between our
study and this study. In our study, there is always some flow coming out of the jet, and the average blowing ratio is the nominal blowing ratio.

A follow up study by Ou and Rivir (2006) observed the additional effect of hole shape geometry on the heat transfer coefficient and film cooling efficiency over a leading edge model with an afterbody. Cylindrical and a diffusion-shaped hole were studied at blowing ratios ranging from 0.75 to 2.00, duty cycles of 50%, 70% and 100% (steady state) and forcing frequencies of 5Hz and 10Hz. Both the shaped hole geometry and the forcing gave improved performances compared to the cylindrical geometry and the steady flow.

Coulthard et al (2006) presented a comparable study on the influence of pulsing on the film cooling effectiveness and the heat transfer. The setup consisted in a flat plate with a single row of cylindrical holes with a 35° inclination. Blowing ratios from 0.25 to 1.5 and various duty cycles and frequencies were explored using an infrared camera, thermocouples, hot and cold wire anemometry. The general conclusion of this study was that forcing decreases the film cooling effectiveness and increases the heat transfer coefficients. These conclusions go against the previously mentioned studies by Ekkad and Rivir.

At the same time Nikitopoulos et al (2006) presented an assessment of the potential improvements an active control of film cooling (implying pulsing) could bring to gas turbines. This study was the starting point of our research.

1.4. Objectives

While motivated by the improvement of gas turbine blades film cooling, our study was a fluid dynamics experimental study of an isolated jet in cross flow under unforced and forced conditions. The main goal was to understand the pulsed JICF.

More accurately our objectives were: 1) the design and the implementation of an experimental setup of a pulsed JICF permitting the study via constant temperature anemometry (CTA), visualizations and particle image velocimetry (PIV); 2) characterisation of the system (wind tunnel + jet); 3) study of the steady sate JICF; 4) study of the pulsed JICF under various forcing conditions.

This thesis presents the experimental setup, the processing procedures used as well as the results concerning the unforced JICF and the forced JICF at mean blowing ratios of 0.35 and 0.45.
Chapter 2: Definitions and Notations

Before going into more details about our experimental setup and procedures, the variables used in this thesis must be introduced as well as the definitions of the main parameters of our experiments.

2.1. Notations

Here are a few notations we will use through this document. This is not an exhaustive list.

\begin{itemize}
  \item \(A_J\) Jet Exit Area [m\(^2\)]
  \item \(BR\) Blowing Ratio; \(BR = (\rho_J U_J)/(\rho_\infty U_\infty)\)
  \item \(BR_h\) High Blowing Ratio; \(BR_h = (\rho_J U_{Jh})/(\rho_\infty U_\infty)\)
  \item \(BR_l\) Low Blowing Ratio; \(BR_l = (\rho_J U_{Jl})/(\rho_\infty U_\infty)\)
  \item \(BR_m\) Mean Blowing Ratio; \(BR_m = (\rho_J U_{Jm})/(\rho_\infty U_\infty)\)
  \item \(DC\) Duty Cycle; \(DC_{act} = T_h/(T_h + T_l) = T_h/T_f\)
  \item \(DC_{act}\) Actual Duty Cycle Measure
  \item \(DC_{set}\) Computer Set Duty Cycle
  \item \(DC_{th}\) Theoretical Duty Cycle from Relation with the Blowing Ratios
  \item \(f_a\) Actuation Frequency [Hz]
  \item \(f_s\) Sampling Frequency [Hz]
  \item \(f_\mu\) Frame Rate of Image Acquisition [Hz]
  \item \(Q_1\) Jet Volumetric Flow Rate [m\(^3\)/s]; \(Q_1 = Q_M + Q_S\)
  \item \(Q_M\) Air Supply Volumetric Flow Rate [m\(^3\)/s]
  \item \(Q_S\) Seeding Supply Volumetric Flow Rate [m\(^3\)/s]
  \item \(T_f\) Actuation Period [s]
  \item \(T_h\) High Flow Rate Time [s]
  \item \(T_l\) Low Flow Rate Time [s]
  \item \(TI\) Turbulence Intensity
  \item \(u(x,y,z,t)\) Streamwise Component of Velocity [m/s]
  \item \(U_\infty\) Free stream or Cross flow Velocity [m/s]
  \item \(U_J\) Jet Velocity [m/s]; \(U_J = Q_j/A_J\)
  \item \(v(x,y,z,t)\) Spanwise Component of Velocity [m/s]
  \item \(w(x,y,z,t)\) Vertical Component of Velocity [m/s]
  \item \(\rho_\infty\) Free stream or Cross flow Air Density [kg/m\(^3\)]
  \item \(\rho_J\) Jet Air Density [kg/m\(^3\)]
\end{itemize}

2.2. Units and Conversion

\begin{itemize}
  \item \(^\circ\text{C}\) Celsius Degree
  \item \(^\circ\text{F}\) Fahrenheit Degree
  \item \(\text{ft}\) Foot (feet)
  \item \(\text{m}\) Meter
  \item \(\text{m/s}\) Meter per Second
  \item \(\text{PSI}\) Pound per Square Inch
  \item \(\text{PSIG}\) Pound per Square Inch
  \item \(\text{SCFM}\) Standard Cubic Feet per Minute
  \item \(\text{StdL/M}\) Standard Liter per minute
\end{itemize}
2.3. Definitions

Here we present a few definitions of the main parameters of our experiments. Our experiments have six parameters, four of which are independent.

2.3.1. Blowing Ratios: BR

The blowing ratio is defined as the ratio between the jet mass flow rate and the cross flow mass flow rate. Several blowing ratios can however be defined.

The mean blowing ratio, or \( BR_m \), is the average of the ratio of the mass flow rate per unit area of the jet flow over the mass flow rate per unit area of the cross flow. Our wind tunnel velocity, after exploratory tests, was set at 1.6 m/s, or 3Hz on the wind tunnel fan command remote. Therefore our blowing ratio was only dependent on the jet velocity. At first this was computed using hotwire measurements and relying on the repeatability of tests and the precision of the valve system. However this method proved to be unreliable. So we installed a flow meter to get our actual flow rates and mass averaged velocities. We also added a second flow meter on the seeding system because we saw on some experiments the influence of the seeding was important on our flow exiting the jet. As the time went and the experiments were done, the studied blowing ratios evolved. Three mean blowing ratios were our target at the beginning: 0.5, 1.0, 1.5. By studying experimental results we changed and decided to study four of them: 0.25, 0.5, 0.75 and 1.0. Further study brought these to three mean blowing ratios: 0.25, 0.35 and 0.45. This thesis emphasizes on the two higher of those three mean blowing ratios. The mean blowing ratio is a goal to reach and is controlled by setting the two following blowing ratios: the low blowing ratio and the high blowing ratio of the cycle. The low blowing ratio or \( BR_l \) is the time average of the blowing ratio during the low flow rate part of the forcing cycle. The high blowing ratio or \( BR_h \) is the time average of the blowing ratio during the high flow rate part of the cycle. We also define the peak-to-peak blowing ratio, \( BR_{pp} \), as the difference between \( BR_h \) and \( BR_l \).

\( BR_m, BR_h, BR_l, DC \) and \( BR_{pp} \) are linked through simple formulas.

\[
\begin{align*}
BR_m &= BR_h \times DC + BR_l \times (1 - DC) \\
BR_m &= BR_l + BR_{pp} \times DC \\
BR_m &= BR_h - BR_{pp} \times (1 - DC) \\
BR_{pp} &= BR_h - BR_l \\
DC &= \frac{T_h}{T_f}
\end{align*}
\]

Equation 2-1: Equation linking the different parameters.
Henceforth, the setting of two of the four blowing ratios gives the two others. Evidently we fixed the mean blowing ratio, which left one arbitrary parameter to chose. We did some experiments at a fixed low blowing ratio and some at fixed peak-to-peak blowing ratios.

2.3.2. Duty Cycle: DC

The duty cycle DC is the ratio between the amount of time at which the solenoid valve is open, which means we have a higher flow rate coming through the jet, over the period of the cycle. The inverse of the forcing frequency $f_r$ is also referred to as, $T_r$, the forcing period. The duty cycle is set on the same Virtual Instrument Labview program as the forcing frequency. The signal sent to the valve is therefore really precise too. However, the actual duty cycle, i.e. what really happens at the jet exit is different from the one we set for the pulsing hardware. Therefore, after working with nominal values for the duty cycle, i.e. the value we set for the hardware, we decided to do the experiment with the actual duty cycle. Using the signal from flow meters with adequate frequency response, we can set a nominal duty cycle, which enables us to get the actual duty cycle we want. This problem mainly arises at higher forcing frequencies, when the flow has trouble following the system. It has to be noticed that this characteristic would also vary with the flow rate of the jet. However our range of flow rates being fairly small, we did not have to take care of that problem. For our study, except again for exploratory tests where we explored the span of duty cycles, we used three duty cycles, which were 0.25, 0.50, 0.75 or 0.70. At the two low frequencies, the nominal and actual blowing ratios are almost coincident. But at higher frequencies, the nominal blowing ratio needs to be adjusted to get the actual blowing ratios targeted and therefore be able to compare our different tests.

2.3.3. Forcing Frequency: $f_f$

The forcing frequency $f_f$ is the frequency at which the flow is pulsed. This frequency is set on a Virtual Instrument Labview program and transferred to the solenoid valve via a DAQ board through a module using an independent power source of 17 volts. As this signal cannot be recorded by our modules, the same program also creates a second signal identical to the valve signal at the same frequency to either get a copy of the valve signal when we do hotwire tests or just flow meter reading for comparison purposes, or to trigger the visualization system. For our experiments, except some exploratory tests where we explored the range of frequency of the valve, we mainly used four forcing frequencies: 0.5Hz, 1.0Hz, 5.0Hz, and 10.0Hz.
Chapter 3: Experimental Apparatus and Procedures

This chapter presents the experimental setup we designed and used, as well as the procedures to use it properly.

3.1. Wind Tunnel

Our study took place in the aerodynamic wind tunnel of the LSU Hurricane Center. This wind tunnel is an open loop wind tunnel. Its contoured contraction is 10ft by 12ft at the beginning, and 2ft by 3ft at the end. This contraction is 9ft long and is preceded by a number of conditioning screens. The wind tunnel has a 16ft long test section of cross section 2ft by 3ft at the beginning and 2ft by $3^{1/2}$ft at the end. This expansion is meant to keep a constant pressure gradient inside the test section and consequently a constant velocity all along the potential core of the test section flow. Downstream of the test section is an upward elbow, which leads to another duct section of the wind tunnel which ends at the fan. This fan can run at frequencies ranging from 0Hz to 60Hz for a linearly corresponding velocity range of 0m/s to 30m/s. The results section presents a calibration of the wind tunnel velocity range using constant temperature anemometry, which confirms those nominal data. It is controlled by a remote control. The fan composes of a rotor and a stator. The rotor has 12 blades, and the stator has 9 blades. The last section of the wind tunnel downstream of the elbow is common between the aerodynamic wind tunnel and the
boundary layer wind tunnel of the LSU Hurricane Center. The elbow can be exchanged with an S part to connect that last section to the boundary layer wind tunnel.

![Remote control and main breaker](image)

(a) Remote control (b) Main breaker

Figure 3-2: Wind tunnel remote control (a) and main breaker (b).

Procedure to turn on the wind tunnel

1) Push the main breaker/switch (Figure 3-2(b)) situated on the western wall of the wind tunnel room on the on position.

2) Turn the Set Speed black knob until hearing a click.

3) Press the red Start button

4) Set the desired frequency using the Set Speed knob and the liquid crystal screen.

In all our experiments, except when we explored the wind tunnel velocity range, we set this frequency at 3Hz, which corresponds to the desired speed inside the wind tunnel: 1.6m/s.

During experiments, we made sure the wind tunnel room back doors stayed closed and that nobody was working or passing in front of the wind tunnel entrance so that the ambient air was as little disturbed as possible when it got into the wind tunnel.

Procedure to turn off the wind tunnel

1) Turn the Set Speed black knob to 0 until hearing a click.

2) Push the main breaker/switch situated on the western wall of the wind tunnel room on the off position.

For the purpose of our experiments (Jet in Cross Flow), modifications had to be made to the wind tunnel test section. As a consequence, we took it apart and rebuilt it with new parts and keeping a few old ones. We completely changed the floor of the wind tunnel, in order to make space for the jet setup. It has to be noted that the
opening and flange for the current jet will fit the new inclined jet that will be implemented later on. We also changed some of the walls. We kept the wall with the access window of 20\text{1/2} \text{ in. by 14in/1ftx2ft} which is very practical to access the inside of the test section when the roof is on. This opening enables different operations in the wind tunnel, like the placement of the hotwire probes or of the calibration target for visualizations/PIV into the wind tunnel, the cleaning of the wind tunnel or of the jet pipe, or other various maintenance operations of the wind tunnel.

![Figure 3-3: Wind tunnel access window: (a) closed; (b) open.](image)

We replaced the opposite wall by an acrylic sheet of 8ft by 2ft which settled into a small grove made in the new floor to put the wall in place at the right angle. This acrylic wall was designed to enable the realizations of visualization/PIV experiments.

![Figure 3-4: Wooden roof of the wind tunnel.](image)

We also designed two new roofs. The first one is designed for hotwire experiments. Built in wood, it has three long channels along the longitudinal direction. These channels are designed to let the probe holder pass through the roof and enables longitudinal and vertical sweeps at three positions on the y-axis. It can also enable lateral and vertical sweeps at three positions on the x-axis if it is flipped by 90°. One of these channels is filled with brushes to prevent leakage. The other two are taped when they are not in use for the same reason. The alternative roof is an acrylic roof designed for visualizations/PIV experiments. Since the roofs are not fixed, we have seals on all the top surface of the walls to make sure no leakage occurs.
Additionally the wooden wall and floor of the wind tunnel have been polished and painted in mate black on the inside to improve the quality of the visualizations/PIV images. After each experiment series with use of seeding, the floor is washed, as well as the acrylic roof and wall to ensure that the quality of the images is good.

3.2. Jet

3.2.1. Generalities

With the wind tunnel, the jet is the core of our system. Its jet has a 1” diameter and is placed on the centreline of the wind tunnel test section 30” downstream of the contraction.

3.2.2. Air Supply

The main flow of the jet is provided with a constant supply pressure. At first we explored three supply pressures: 20, 40 and 60PSIG and observed the jet velocity range at these pressures. Since we needed low speed to
explore low blowing ratios, we chose to provide the jet with a constant 20PSIG for our experiments. This air supply comes from a high-pressure tank charged by a compressor in line with an air dryer. The compressor is a 1997 Atlas Copco GR110 with a maximum nominal working pressure of 20.0bar (290PSI), a nominal inlet power of 119kW and a nominal rotational shaft speed of 1790 rpm.

![Figure 3-7: Compressed air tank.](image)

**Procedure to turn on the compressor**

1) Check that the valve bypassing the air dryer is open or that the air dryer is on.

2) Set the desired settings using the menu on the liquid crystal control screen of the compressor.

3) Press the green button to start the compressor.

**Procedure to turn off the compressor**

Press the red button to stop the compressor. (not the emergency stop button).

The air getting out of the compressor must be dried before getting into the tank. This is for two reasons. First if it is not dried, some water can condense in the tank and moisture can get in the pipes, which could decrease the life of the system. Secondly, as it will be explained later, we need to use dry air for our visualization experiments with the use of TiCl$_4$ which reacts with the moisture in the air.

The air dryer is a Pneumatic Inc. PHS-500 Heatless Regenerative Air Dryer. It has a nominal capacity of 500 SCFM, a nominal purge pressure of 42 PSIG, and a nominal maximal pressure of 350 PSIG. Its inlet temperature must be inside the span of 70°F to 120°F.

**Procedure to turn on the air dryer**

1) Open the valve upstream of the air dryer.

2) Open the valve downstream of the air dryer.
3) Close the valve bypassing the air dryer.
4) Turn the air dryer switch to the on position.

![Figure 3-8: Air dryer.](image)

**Procedure to turn off the air dryer**

1) Turn the dryer switch to the off position (or at the end).
2) Open the valve bypassing the air dryer.
3) Close the valve upstream of the air dryer.
4) Close the valve downstream of the air dryer.
5) Turn the dryer switch to the off position (if not done first).

**Procedure to turn on the jet**

1) Turn on the compressor.
2) Turn on the air dryer.
3) Open the yellow gate valve on the wall opposite to the compressor.
4) Open the gate valve upstream of the pressure regulator on the jet supply air-line.
5) Verify that the needle valve downstream of the pressure regulator and upstream of the red pipe leading to the jet control system is fully open.
6) Set the desired supply pressure (here 20PSIG) at the pressure regulator.

This pressure may need to be adjusted depending on the valve settings controlling the BR_h and BR_l.

**Procedure to turn the jet off**

1) Close the gate valve upstream of the pressure regulator on the jet supply air-line.
2) Close the yellow gate valve on the wall opposite to the compressor.
3) Turn off the air dryer.
4) Turn off the compressor.
5) Re-open the gate valve upstream of the pressure regulator on the jet supply air-line in order to bleed the air trapped between this valve and the yellow gate valve.
6) Re-close this valve.

3.2.3. Jet Control Valve System

The jet control valve system is formed by three valves, two needle valves and one solenoid valve controlling respectively the blowing ratio and the forcing. The needle valves are Swagelok B-1RM4 Brass Integral Bonnet Needle Valves with 1/4 in. MNPT connexions. It can withstand a pressure of 3000PSI at 100°F. The solenoid valve used was manufactured by Precision Dynamics. It requires a 12VDC power supply and has a 10W power. In our experiments it was powered by a 17VDC power supply. It has an orifice of 5/32 in.

Figure 3-9: Jet control system: (a) front; (b) side.

The flow coming from the compressor-dryer-tank supply system is divided in two branches: a straight branch with a needle valve and a bypass branch with the solenoid valve and the second needle valve. The straight branch sets the low blowing ratio. The bypass branch determines the high blowing ratio but actually sets the peek-to-peek blowing ratio. Indeed, when the solenoid valve is closed, air only flows through the straight branch, and when the solenoid valve is open, the flow goes into both branches. Therefore the bypass branch brings an additional quantity of flow to the jet.

At first a calibration of the valve system was realized to determine the velocity range of the jet and link the jet velocity to the valve settings, and the valves were set by hand following this calibration. But several facts made
this method unreliable for precise experiments. First the valve positioning cannot be really accurate since it is done by hand and since the calibration was made with quarter of turns on the valves. Secondly, as the valve gets worn, we could not be really sure that the positions of the calibrations were still the same after a while. Consequently, we could not be sure of our valve settings. Thirdly the calibration was made via constant temperature anemometry at the center of the jet exit, without cross flow. Therefore we measured the velocity at the center of the jet and not the average velocity of the jet flow, which we need to compute an accurate blowing ratio. Finally our experimental range of velocity for the jet is really low, so that the needle valves are only slightly open and a quarter of turn calibration, if the only possible for enough accuracy was not enough.

So a flow meter was acquired, which was placed downstream of the jet control valve system. This was for two reasons. The flow meter has a low operating pressure limit. The goal was to measure the flow at the jet exit. With this system, the jet flow rate and consequently the blowing ratio can be known precisely, which enable us to set the valves accurately.

**Procedure to set the low and high blowing ratios:**

1) Verify the air supply pressure is at 20PSI on the jet line.
2) Close the solenoid valve using the National Instrument test panels on the pulsing computer.
3) Turn the virtual instrument (VI) for the flow meter reading on.
4) If using the electronic seeding flow meter, set the right seeding flow. If not, the VI has a set value for the seeding corresponding to the seeding that will be set on the rotameter.
5) Set the straight valve to the right setting.
6) Open the solenoid valve using the National Instrument test panels
7) Set the needle valve downstream of the solenoid valve till reaching the desired high flow.
8) Check the high and low flow again and check it while pulsing at 0.5Hz.
9) Do the appropriate modifications if needed.
10) Close the National Instrument test panels.

This procedure could be slightly modified in order to set the low and the peek-to-peek blowing ratios.

**3.2.4. Jet Pipe**

The downstream end of the jet control/pulsing system connects to the filter of the flow meter and then the flow meter itself. Then the flow meter connects to the jet pipe. This is an 18in.long stainless still pipe of diameter
1in. It is designed so that the flow can be seeded with TiCl₄ and so that the seeded flow can settle, in order not too have any undesirable effects at the exit. It includes 8 holes of 1/8in diameter to let the TiCl₄ charged Nitrogen into the jet flow. These holes are placed 4in. downstream of the connection of the tube to the flow meter. 12 in downstream of this connection is a collar to fix the pipe to an acrylic laminated plate which goes into the floor of the wind tunnel.

### 3.2.5. Pulsing System

The pulsing system consists of the solenoid valve, its power supply, the National Instrument SC-2345 DAQ chassis and associated modules, and the computer which controls it.

A virtual instrument Labview program controls the DAQ board, which sends a signal to the solenoid valve to open or close. This program enables to set the frequency and duty cycle of the pulsing. It can also be used to send a trigger signal to the visualization system, or to send a fake valve signal to the data acquisition computer to simulate the valve signal, which cannot be recorded by our DAQ board because it exceeds its limits.

As we said when we defined the duty cycle, there can be a difference between the duty cycle set in the program and the duty cycle obtained depending on the frequency. Consequently we did a small calibration to know what to set to get what we wanted. The Table 3-1 shows what duty cycle is obtained when a duty cycle is set at the various forcing frequency we used.

**Table 3-1: Table of DC to set to get a certain duty cycle at a certain frequency.**

<table>
<thead>
<tr>
<th>DC to get [%]</th>
<th>ff = 0.5Hz</th>
<th>ff = 1.0Hz</th>
<th>ff = 5.0Hz</th>
<th>ff = 10.0Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>25</td>
<td>25</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>70</td>
<td>70</td>
<td>70</td>
<td>60</td>
<td>55</td>
</tr>
</tbody>
</table>

### 3.3. Traverse System

The traverse system was developed by an LSU senior project team. More information about the design of this major tool of our project can be found in their final report (see References). Jeremiah Oertling designed most of
the softwares to operate it. This system allows a precise positioning of the hotwire probes for CTA but also of the LASER or of the camera for visualization/PIV experiments depending on the plane of view of the experiment.

Figure 3-10: Traverse.

This is a three-axis movement system. The x-axis stage is formed of two beams while the y-axis stage stands on the x-axis and the z-axis stage stands on the y-axis. The latter are composed of a single beam each. Each axis is actuated by an independent motor, which is controlled by an independent encoder. The fact that the x-axis is composed of two beams but only one of them is motorised was a source of trouble. Indeed, when the x-axis is moving, the unmotorised beam lags. Moreover, at a static position the unmotorised beam has a liberty of movement. As a consequence there is a loss in the positioning precision if operated in automatic mode. This problem was not solved, but we minimized it by moving only in one direction when doing experiments along the x-axis, and by always going back to the same starting position.

Figure 3-11: Traverse control: (a) zeta drives; (b) indexer.

Each axis is also equipped with three switches. Two of these switches are limit switches to restrain the movements of the traverse. The last one is a home switch used to determine a coordinate system for the traverse and
know the traverse position. On the x-axis, the switches are set on the motorised beam. The zeta drives and the switches are all connected to an indexer. This indexer is connected to the data acquisition computer, which also controls the traverse, and to a remote control box. The traverse can be controlled manually via the remote or the computer using a Virtual Instrument Labview program called Motion Control and Home.vi.

![Figure 3-12: Motors: (a) y axis; (b) z axis.](image1)

![Figure 3-13: Motion Control and Home VI.](image2)

**Procedure to use the Motion Control and Home.vi**

1) Start the VI.

2) Press the Home button to make the traverse go home. Otherwise, all positions set will be relative to the position of the traverse when the program is started, i.e. the (0, 0, 0) position will not be the home position of the traverse.

3) Press again the Home button to turn it off. Otherwise, after going to the required position, the traverse will go back home.
4) Set the coordinate of the desired point in the red boxes.

5) Press the Go button.

6) To go home, press the Home button. Press it again to disable the previously advised feature.

The traverse can also be associated with the data acquisition during Constant Temperature Anemometry experiments via another Virtual Instrument Labview program called Motion Control and Acquisition.vi or its derivatives like Motion Control and Acquisition Alternate.vi or Motion Control and Acquisition-6ch.vi, which was designed for combined flow measurements with X-wire probes and flow meters. With these programs, the traverse is fully automated and integrated in the measurement system. Indeed the system links the CTA measurement system and the traverse to ensure coordination.

![Motion Control and Acquisition VI](image)

**Figure 3-14: Motion Control and Acquisition 6 Channels VI.**

To run this program, a grid first needs to be created as a text file. This grid must contain the coordinates of the different points where measurements will be taken. It can also contain the number of samples and the sampling rate at each point. If these parameters are not specified in the grid, they need to be set in the program prior to running it. Once the grid is loaded, and the program started, first the traverse will go to the home position. In each grid file the last point is set at \((x, y, z) = (1, 1, 1)\), so that when the program starts it always goes home from the same starting position for the reasons we explained earlier. Once the traverse is home, it will go to the first point of measure, take the required number of samples at the specified sample rate. Then it will move to the next position and so on to the last point. To reduce the influence of possible vibrations on the probe holder, a stiffening rod was installed on the z-axis of the traverse, and time delays between the arrival instant at a point of measurement, the
actual measurement instant, and the departure instant from one position to the next position have been set. Most experiments are run along a single axis (x, y, or z), or at static positions. In those cases, the unused axises are disabled to ensure safety of the traverse and better precision on the position.

The traverse is also used during visualizations. Two configurations have been implemented so far. The first configuration is used to take x-y plane of view visualizations. The camera is placed on the z-axis of the traverse and can move up or down to get a wider or narrower field of view. It can also move along the x and y axis to take images at various locations in the flow. The LASER is placed on the side of the wind tunnel, facing the acrylic window we talked about previously to deliver a horizontal LASER sheet. It is strapped on a stainless steel plate fixed to a vertical beam placed on another beam parallel to the wind tunnel axis (or the x-axis of the traverse). It can be moved manually in both the x and z directions in order to position the LASER sheet at the correct position.

![LASER in position for a horizontal sheet.](image)

The second configuration is used to take x-y plane of view visualizations. The original z-axis of the traverse is removed and placed on the longitudinal beam alongside the traverse so that the camera can be moved up and down easily, as well as along the x-axis manually. The vertical beam, which was previously holding the LASER is set on the y-axis in place of the usual z-axis. The LASER is strapped on its stainless steel plate in a vertical position this time, head down. It can move along the x and y axis to position the sheet correctly. However it is still along the z-axis, since the plane of view is vertical. In this configuration, care must be taken while using the Motion Control AND Home VI since the x and y axis control the position of the LASER and the z position controls the position of the camera.

**Procedure to set the home and limit switches**

For automated constant temperature anemometry experiments, the precision of the traverse is needed, and an origin must be given to the system. For the x and y axis, this origin is chosen at the center of the jet exit: this is
the point (0, 0). For the z axis, the origin is chosen to be 10 diameters above the jet. When the traverse is at (0, 0, -10) the sensor must be at the center of the jet exit.

The switches must be set accordingly. On the x and y axis, the limit switches can be set arbitrarily as long as the traverse has enough space to move for the corresponding experiment. On the z axis the positive limit switch can be set arbitrarily as long as the traverse does not have enough way to move in a harmful way for the probe. The negative limit switch must be set according to the position of the probe at the jet exit center.

To set the switches precisely, the traverse must always come to the switch from the same direction. The switch has a zone of influence. Coming always from the same direction is the only way to keep the desired precision.

Setting the home switch and the negative z axis limit switch is a repetitive procedure. Small adjustments must be done until reaching the correct position.

**Procedure**

1) Set the switches.

2) Send the traverse to a positive position relative to the switch settings.

3) Send the traverse home.

4) Send the traverse to (0, 0, -10).

5) Check the position.

6) Adjust the switches if necessary.

7) Repeat 2) to 6) as many times as necessary.

**3.4. Constant Temperature Anemometry**

**3.4.1. Principles**

The constant temperature anemometry uses heat transfer principles to indirectly measure the velocity of a flow. A thin wire is placed in the flow and submitted to an electrical current. This current maintains the wire at a constant temperature. The flow in which the hotwire is immersed has a tendency to cool this by convection. The velocities are determined from the current needed to keep the temperature constant through a calibration equation.

One wire can only measure one component of a velocity, the one perpendicular to the wire. The measurement is biased by any component non-perpendicular to it. Consequently, to measure a flow with only one component in the velocity single wire probes can be used. For flow with two major components in the velocity field
a 2 wire probe can be used with proper calibration. For flow with velocity field with components in 3 directions, a 3 wire probe can be used. However there are limitations to the use of such probes. It can also be noticed that a flow field with 3 components can be deduced using a cross wire probe through proper multi orientation measurements.

The CTA system is composed of the TSI IFA300 bridge chassis, the computer on which the IFA300 software is installed, the probe holder, the probe and a thermocouple.

The TSI IFA300 bridge chassis only reads the voltages it is getting from the probe and the thermocouple and transfer them to the computer with the IFA 300 software.

The TSI IFA 300 software has features to calibrate probes, and acquire measurements. However, we only used it to control the IFA bridge electronics. From the bridge unit we get the voltages that we process to do our calibrations and experiments.

![Figure 3-16: TSI IFA 300.](image)

### 3.4.2. Probes

Different types of probes were used during our experiments (see Figure 3-17). First we used single wire probes, which are probes with only one sensor and designed to measure only one component of a flow. There are different kinds of single wire probes: straight, boundary layer, bent. Then there are cross wire probes with two sensors, which are designed to measure two components of the flow, and can also be used to measure three if a proper post treatment is used. Available probes and their status are detailed in Table 3-2.

To support the probes and connect them to the IFA300, we had two probe holders: one is for single wire probes, and the second one is for cross wire probes. The two probe holders are 3ft long.

Those probe holders are inserted into the wind tunnel to the cross flow as well as the jet flow. The probe holders are protected by a probe holder. However, in order to avoid any vibration to perturb the measurements, we decided to reinforce the probe holder by a stiffening rod.
Figure 3-17: TSI hot wire probes used for CTA: (a) 1210 straight probe; (b) 1212 bent probe; (c) 1218 boundary layer probe; (d) 1241 X-wire straight probe.

<table>
<thead>
<tr>
<th>Probe Model #</th>
<th>Probe Type</th>
<th>Probe Serial #</th>
<th>TSI Reference #</th>
<th>Probe Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1210-TI.5</td>
<td>straight single wire</td>
<td>965044</td>
<td>800024578</td>
<td>calibrated</td>
</tr>
<tr>
<td>1210-TI.5</td>
<td>straight single wire</td>
<td>973122</td>
<td>800024578</td>
<td>calibrated</td>
</tr>
<tr>
<td>1211-20</td>
<td>vertical single wire</td>
<td>994014</td>
<td>278378</td>
<td>calibrated</td>
</tr>
<tr>
<td>1212-TI.5</td>
<td>bent single wire</td>
<td>976013</td>
<td>800026734</td>
<td>calibrated</td>
</tr>
<tr>
<td>1212-TI.5</td>
<td>bent single wire</td>
<td>976014</td>
<td>230573</td>
<td>broken</td>
</tr>
<tr>
<td>1218-TI.5</td>
<td>boundary layer probe</td>
<td>5087</td>
<td>800026734</td>
<td>not calibrated</td>
</tr>
<tr>
<td>1218-TI.5</td>
<td>boundary layer probe</td>
<td>70550029</td>
<td>N/A</td>
<td>not calibrated</td>
</tr>
<tr>
<td>1241-20</td>
<td>straight X-wire</td>
<td>14066</td>
<td>300004641</td>
<td>calibrated</td>
</tr>
</tbody>
</table>
3.4.3. Calibrations

Before using a probe it needs to be calibrated. The calibration basically links known velocities to known voltages. A polynomial curve can then be formed that links voltages to velocity. Some corrections need to be applied after that too. In our cases we only use the IFA300 to get the voltages and then do our own calibrations determining velocity and yaw coefficients.

3.4.3.1. Single Wire Probe

Single wire probes are used to take measurement in a flow with one major component. The wire must be placed perpendicular to this component.

To calibrate a single wire probe, the following material is requested:

✓ Single wire probe: straight, bent, vertical or boundary layer type,
✓ Shorting probe,
✓ Probe holder,
✓ TSI IFA 300,
✓ Computer with the IFA 300 software,
✓ Data Acquisition computer,
✓ National Instrument DAQ board with the appropriate modules described in 3.7,
✓ BNC Cables,
✓ TSI Calibrator with internal/external nozzles sets (2/10mm), (3/14mm),
✓ Probe Covering device.

The programs used are:

  o IFA 300 software
  o Data Acquisition-6ch.vi Virtual Instrument Labview program

Procedures to calibrate a single wire probe:

1) Connect the wires for a single wire probe calibration (see Figure 3-18)
2) Turn Compressor on
3) Open 2” ball valve in the Flow Control lab slightly
4) Check blue tank pressure and adjust valve in combination with the red valve on the wall opposite to the 2” ball valve just opened.
5) Open small valve downstream of the 2” ball valve.
6) Open slowly the valve leading to the calibrator. Make sure the pressure is 30 PSI.
7) Turn on the power supplies of the IFA system and of the data acquisition system.
8) Turn on the IFA computer and the data acquisition computer.
9) Turn the IFA bridge unit on and check if you hear a blowing noise from the calibrator.
10) Make sure the internal nozzle #2, and the 10mm exit nozzle.
11) Run the IFA 300 software.
12) Go to Calibration => Probe Data
13) Enter the operating resistance of the probe, which is available on the box of the probe being calibrated.
14) Read the resistance of the cable by following the on-screen instructions and using the shortening probe.

      Save the value.

The probe resistance is typically of the order of 6Ω at room temperature. If the order of magnitude is different, something is wrong either system.
15) Set the gain and offset by following the next steps:
   a) Select the gain and offset on the software window
   b) Go to dP and Vel and set a 0m/s velocity
   c) Go back to the gain and offset window and take the low flow measurement.
   d) Go to dP and Vel and set a 50m/s velocity
   e) Go back to the gain and offset window and take the high flow measurement.
   f) Compute and apply.

16) Chose a calibration table by clicking on Autocal Table and selecting one.

   The calibration table is the same for all single wire probes. However, we usually copy one to the current calibration folder and rename it by using the model Probe Serial Number_Probe Holder Length.

17) Save as Probe#_ProbeHolderLength.

18) Click on calibrate.

19) Click again on calibrate on the new screen.

20) Following the instructions, install the internal nozzle #3, and 14mm exit nozzle on the calibrator and cover the probe.

21) On the data acquisition computer, open the Virtual Instrument Labview program DataAcquisition3Channels.vi and set the following parameters.

22) Create a folder in which to save the data of the calibration, generally with the date of the calibration and the probe serial number and the probe holder length.

23) Start the VI, select the right folder where to save the data and create the file name in the following way: point number, starting at 0 to 33 + V.txt.

24) Press Calibrate on the IFA computer.

25) When the light goes red, the required velocity is reached, press simultaneously save on the data acquisition computer and stop calibration on the IFA computer.

26) Restart the VI and name the next file.

27) Uncover the probe after the first point, and press no in the pop-up window asking if you really want to end the calibration on the IFA computer and repeat the operation.

28) At point 17, follow the instruction: change back to internal nozzle #2, 10mm exit nozzle, cover the probe.
29) Take off the cover when asked and keep repeating operation till the calibration is finished.

30) At the end of a calibration, check the calibration curve, it needs to look like a parabolic curve. If not, it means there is a problem and the calibration must be redone.

31) Transfer the data of the calibration as well as the .CL file of the calibration to the data processing computer. Then the calibration data must be processed. This part is treated in the data processing part.

3.4.3.2. X-Wire Probe

For an x-wire probe the calibration procedure is similar but there are a few differences since there are two wires/sensors. The beginning of the process is identical to the single wire probe calibration. However, some more measurements need to be done to correct the yaw coefficient. The principle is the same and one only needs to follow the instructions given by the software.

X-wire probes are used to take measurement in flows with two major components. The placement of the probe depends on the velocity field.

To calibrate an x-wire probe, the following material is requested:

✓ X-wire probe,
✓ Shortening probe for two wire probe holder,
✓ Probe holder for two wire probes,
✓ TSI IFA 300,
✓ Computer with the IFA 300 software,
✓ Data Acquisition computer,
✓ National Instrument DAQ board with the appropriate modules described in 3.7,
✓ BNC Cables,
✓ TSI Calibrator with internal/external nozzles sets (2/10mm), (3/14mm),
✓ Probe covering device.

The programs used are:

- IFA 300 software
- Data Acquisition-3Ch

Procedure

1) Connect the wires for an X-wire probe calibration (see Figure 3-18)
2) Turn Compressor on.

3) Open 2” ball valve in the Flow Control lab slightly.

4) Check blue tank pressure and adjust valve consequently with the red valve on the wall opposite to the 2” ball valve just opened.

5) Open small valve downstream of the 2” ball valve.

6) Open slowly the valve leading to the calibrator. Make sure the pressure is 30 PSI.

7) Turn on the power supplies of the IFA system and of the data acquisition system.

8) Turn on the IFA computer and the data acquisition computer.

9) Turn the IFA bridge unit on and check if you hear a blowing noise from the calibrator.

10) Set internal nozzle #2, and the 10mm exit nozzle.

11) Open the IFA 300 software.

12) Go to Calibration => Probe Data

13) Enter the operating resistance of each probe, which is available on the box of the probe being calibrated.

14) Read the resistance of the cable by following the computer instructions and using the shortening probe. Save the value.

15) Set the gain and offset by following the next steps for the two probes:
   
   a) Select the gain and offset
   
   b) Go to dP and Vel and set a 0m/s velocity
   
   c) Go back to the gain and offset window and take the low flow measurement.
   
   d) Go to dP and Vel and set a 50m/s velocity
   
   e) Go back to the gain and offset window and take the high flow measurement.
   
   f) Compute and apply.

16) Chose a calibration table by clicking on Autocal Table and selecting one.

   The calibration table is the same for all cross wire probes. However, we usually copy one to the current calibration folder and rename it using the model Probe Serial Number_Probe Holder Length.

17) Save as Probe#_ProbeHolderLength.

18) Click on calibrate.

19) Click again on calibrate on the new screen.
20) Following the instructions, install the internal nozzle #3, and the 14mm exit nozzle and cover the probe.

21) On the data acquisition computer, open the Virtual Instrument Labview program DataAcquisition3Channels.vi and set the following parameters.

22) Create a folder in which to save the data of the calibration, generally with the date of the calibration and the probe serial number and the probe holder length.

23) Start the VI, select the right folder where to save the data and create the file name in the following way: point number, starting at 0 to 33 + V.txt.

24) Press Calibrate on the IFA computer.

25) When the light goes red, the required velocity is reached, press simultaneously save on the data acquisition computer and stop calibration on the IFA computer.

26) Restart the VI and name next file.

27) Uncover the probe after the first point, and in the pop-up window asking if you really want to end the calibration on the IFA computer and repeat the operation.

28) At point 17, follow the instruction and change back to the internal nozzle #2, and the 10mm exit nozzle and cover the probe.

29) Take off the cover when asked and keep repeating operation till the straight part of the calibration is finished.

30) Keep following the software instructions to do the calibrations of the yaw coefficient. We do not use this part of the cross wire calibration.

31) When the calibration by the IFA 300 is finished, go to experiments and settle for an X probe experiment.

32) Set velocities on the calibrator between 0 and 10m/s by increments of 0.5 using the dP and velocity set window.

33) For each velocity, take measurements at the 11 different angles available on the calibrator.

34) Transfer the data of the calibration as well as the .CL file of the calibration to the data processing computer.

Then the calibration data must be processed. This part is treated in the data processing part.

3.4.4. Experiments

As we mentioned earlier, the IFA is only used during the experiments to get the voltages from the probe and the thermocouple to the data acquisition computer via the NI DAQ board.
Procedure to start a CTA experiment

1) Setup the flow conditions.

2) Install the probe holder and the probe by following the next procedure.

3) Insert the probe holder in its holder fixed on the z-axis platform. Let the knob loose as it will need to be moved to put the probe in position.

4) While one person maintains the probe holder slightly raised, another person inserts the probe in the probe holder receptacle designed to this effect.

5) Then let the probe holder go down gently and rotate it till the contacts of the probe get in the probe holder.

For a cross wire probe, this setup is a little bit more challenging since the probe and probe holder must be in the same configuration as they were during the calibration used to process the data. On the probe holder and the probe we are using, a mark has been made so that the probe and the probe holder must be connected with those marks coinciding.

6) Install the thermocouple by slipping it into the wind tunnel between the top of the wall and the roof. When the roof is put back, the foam seal will compress. Then the thermocouple is in the cross flow and the integrity of the wind tunnel is maintained.

7) Connect the wires properly according to the experiment.

8) Turn on the power supply of the IFA300 system.

9) Turn on the IFA300 computer and the IFA300 bridge unit.

10) Start the IFA300 software.

11) Got to Acquisition => Probe Table

12) Select the proper probe calibration file using the add probe and clear probe buttons.

13) Read the probe resistance to check the probe is ok.

14) Press the next screen green button.

15) On the next screen, set the desired sampling rate and the low pass filter frequency according to the Nyquist criteria.

16) Press the Acquire green button.

17) On the next screen, press the trigger green button.

18) Check the temperature in °C to see if the system is working properly.
The IFA300 is now ready and voltages are transferred to the DAQ board.

19) Start the desired data acquisition VI on the acquisition computer and run it.

Procedure to stop a CTA experiment

1) Press the close red button on all screens till the IFA300 program is shut down.
2) Shut down the IFA300 computer and the IFA300 bridge unit.
3) Take off the probe from the wind tunnel by having somebody carefully and slowly lifting up the probe holder while somebody else take the probe off the probe holder.
4) Put the probe back in its box.

If the probe is not put back in the box, one must make sure that signs are set to warn everybody not to touch it and check that there is no risk of something hitting the probe.

Hot wire probes must be treated carefully as they are very fragile and somewhat expensive.

3.5. Visualizations and Particle Image Velocimetry

3.5.1. Introduction

The best way to observe how the flow exiting of the jet interact with the cross flow of the wind tunnel is to actually visualize it. In order to do that, the flow or the flows must be seeded and there must be enough light to take an image. Since the flow events are fairly fast, we need a strong pulse of light for a short time, hence the use of the LASER (Light Amplification by Stimulated Emission of Radiation), which delivers a large amount of energy for a very short time. PIV (Particle Image Velocimetry) is a flow measurement process, which combines the advantages of the visualizations and the accuracy of flow measurement system. The principle is simple. The LASER is fired twice with a very short time delay and the camera takes an image at each of these instants (or one image double exposed). The post-processing software then correlates the relative change in the positions of particles to compute velocity vectors. The final image looks like a visualization image with the velocity vectors on it. The visualization/PIV system consists of a LASER, a camera, a synchroniser and a visualization computer. It is linked to the pulsing system for trigger purposes. Additionally the visualization system would be useless without the seeding system of the jet.

3.5.2. LASER

For our experiments we used a Gemini 30 PIV Nd:YAG LASER system. It is a compact dual LASER head system which provides a green pulse (wavelength 532nm). There are two LASER heads in this system but only one
orifice. Each LASER can be pulsed at 30Hz. Each LASER head has its own power supply with incorporated internal cooling system and its own remote control.

The remote control of LASER 1 has a slight difference with the remote control of LASER 2 in the fact that it has the attenuator knob, which is used to set the intensity level of the LASER.

The LASER system can either be used manually in an independent way, by using the remote controls, or in an automated way in connection with a synchroniser and a camera. Depending on the desired function, the switches on the back of the power supplies will be set accordingly on internal or external.

Procedure to turn on the LASER

1) Make sure the interlock on the LASER right in front of the lens is closed.
2) Check that the wires and switches on the back of the LASER power supply are connected and in the right position for the desired use of the system.
3) Check the water level on the front of the LASER power supply. If it is low, it is recommended to refill the cooling system with de-ionized water.
4) Turn on the switch on the back of the power supplies.
5) Check the light on the top front of the power supply, the top one must be orange, the others must be off.
6) Turn the keys on the top front of the power supply to the 1 position.
7) Check the lights on the top front of the power supply; they must all be lit but the second one from the top.
8) On the remote of the LASERs, check that the flashlamp intensity is down to the minimum and that the attenuator is down to the minimum too.
9) Press the Standby button down and hold for a few seconds to start the LASER. It may require to be pushed several times to start the water pump.
10) Once the light stops blinking on the standby button, the LASERs are ready to use.

Procedure to fire the LASER manually

Firing the LASER manually may be useful while setting it up, to check if it works first, and to check if the LASER heads are aligned, focused, and to check if the LASER sheet is properly positioned.

1) Set the switches on the back of the LASER power supplies to the internal trigger position.
2) Turn the LASER on.
3) Set the flashlamp intensity to the maximum on both LASERs.
4) Use the attenuator to set the intensity of the LASER.

5) Set the firing conditions (1 shot, 30Hz, frequency between 0 and 30Hz) with the appropriate knob on the remote control of each LASER.

6) Press the fire button on each LASER to fire.

Each LASER can be fired independently of the other. However, LASER 2 needs LASER 1 on for the attenuator control.

**Procedure to fire the LASER externally**

1) Wire the system according to Figure 3-19

![Figure 3-19: LASER external firing wiring diagram (prepared by G. Bidan).](image)

2) The external firing mode is used during our visualizations and PIV experiments.

3) Set the switches on the back of the LASER to the external position.

4) Turn the knob on the remote control to the external position

5) Turn the LASER on.
6) Turn the flashlamp knobs all the way up.

7) Set the attenuator to get the desired LASER intensity.

The LASER is then ready to be fired externally.

Procedure to turn off the LASER

1) Put both LASERs on standby.

2) Turn the flashlamp intensity down on both LASERs as well as the attenuator.

3) Press the stop button on both remotes.

4) Turn the keys on top of the power supplies to the 0 position.

5) Push the switches on the back of the power supplies to the 0 position.

More information on the Gemini 30 LASER system and associated procedures can be found in the manual of the system.

3.5.3. Camera

![Figure 3-20: Kodak Megaplus Model ES 1.0 Camera.](image)

The camera we used was a Kodak Megaplus Model ES 1.0 (Figure 3-20). It has a 1MP CMOS sensor. It provides black and white .tif images of 1008 by 1016 pixels. It can take images at a maximum frame rate of 30Hz. The lens connexion is a C-mount. The synchroniser and the Insight NT computer control it.

3.5.4. Lenses

Various lenses are available for use with the Megaplus Camera.

Nikon Nikkor 50mm f/1.2; aperture range: 16 to 1.2; minimum focus: 1.7ft/0.5m, shown in Figure 3-21.

Nikon Micro Nikkor 105 mm f/2.8D AF; aperture range: 32 to 2.8; minimum focus: 1ft/0.314m, shown in Figure 3-21

Panasonic Video Lens TV 200M Lens J6x12; aperture range: closed to 1.8; zoom range: 12.5 to 75mm, shown in Figure 3-22.

Quantaray Zoom for Nikon; aperture range: 22 to 3.0; zoom range: 28 to 200mm.
Figure 3-21: (a) 50mm lens; (b) 105mm lens.

Figure 3-22: (a) 12.5-75mm video zoom lens; (b) 70-210mm zoom lens.

Promaster Spectrum 7 Multi Coated Compact Automatic Tele Zoom Lens for Pentax; aperture range: 32 to 4.5; zoom range: 70 to 210mm, shown in Figure 3-22. This lens requires a C-mount adapter for Pentax lenses.

Figure 3-23: C-mounts.
The Camera has a C mount. Therefore for the Nikon lenses, we used two available C mount adapters for Nikon lenses. The Panasonic video lens had a C mount so no adapter was needed.

We tried each lens and finally we used the Panasonic for our visualizations. Indeed, even if it gave a little fisheye effect, which was not dramatic for visualizations, it enabled us to get the wider and more focused images.

3.5.5. Synchroniser

![Synchronizer: (a) front; (b) back.](image)

To control the LASER and the camera in a coordinated way, we used a LASERPULSE Synchroniser Model 610034 from TSI (Figure 3-24). The synchroniser is controlled by the Insight NT software. It can be triggered by the software or by an external trigger.

3.5.6. Seeding System

The most important part of the visualization process is the seeding. Indeed, without seeding particles in the flow, we cannot see it. Several seeding processes can be used in a flow: oil, smoke, dye, particles resulting from a chemical reaction. In our case, we used TiCl$_4$, i.e. titanium tetrachloride to seed our flow.

3.5.6.1. TiCl$_4$

The Titanium Tetrachloride, TiCl$_4$ is a chemical known for its smoking reaction when exposed to moisture. It is a colorless (or slightly yellow) liquid. It reacts with an exothermal reaction with water to form the highly
corrosive and toxic Hydrogen Chloride HCl and Titanium Dioxide TiO$_2$ in the form of microscopic white particles (~0.5µm).

$$TiCl_4 + H_2O \rightarrow TiO_2 + 4HCl$$

**Equation 3-1: Reaction of TiCl$_4$ and H$_2$O.**

These are the reason why TiCl$_4$ is so attractive for PIV and visualizations, as well as why it is so hard to operate with. Indeed when exposed to the ambient atmosphere, the TiCl$_4$ reacts with the water vapour/moisture in the air. This is the reason why it was used to create smoke screen in the Navy and why it was used to create smoke by aircraft performing at air shows. However, this dense smoke is really corrosive and toxic since it also contains HCl, which also reacts with water to form Hydrochloric acid. That is why its use was stopped.

$$HCl + H_2O \rightarrow H_3O^+ + Cl^-$$

**Equation 3-2: Reaction between HCl and H$_2$O.**

This is why precautions must be taken while handling TiCl$_4$. It must be stored in a special container with special markings (Figure 3-25). This container must be able to withstand shock and will also absorb the liquid if there is any leak in the bottle.

![Figure 3-25: TiCl$_4$ storage.](image)

When handling the TiCl$_4$, one must wear a respirator mask, gloves rated for HCl and goggles (Figure 3-26). Indeed, TiCl$_4$ smoke/vapour can damage eyes, skin, mucous membranes, as well as the lungs. Most of these hazards can be attributed to HCl. But TiCl$_4$ is also a very aggressive acid, exothermically reacting with bases and violently, even explosively with water, while releasing HCl.

Another problem is that TiCl$_4$ also reacts with water to form Titanium Oxychloride TiOCl$_4$ which has a tendency like TiO$_2$ to clog holes and pipes, which is a problem we also experienced.
$TiCl_4 + H_2O \rightarrow TiOCl_2 + 2HCl$

Equation 3-3: Formation of TiOCl₂.

Figure 3-26: Protection equipment: (a) Respiratory mask; (b) Goggles; (c) Rubber gloves.

In spite of these drawbacks, we decided to use TiCl₄ because of the very small size of TiO₂ particles, which are excellent for PIV and visualizations, since they disperse light really well and because of their small size have appropriately low response times and can follow the flow with fidelity. Moreover we only use small amounts of TiCl₄ with the appropriate protection measures.

3.5.6.2. TiCl₄ Seeding System Description

The TiCl₄ seeding system was the first to be designed. The system is designed to be portable so that it can be refilled in a small fume hood, and also to enforce an easy disconnection process so that any leak in the global system does not create a TiCl₄ leak.

The system is made out of stainless steel to give a better resistance to corrosion, since TiCl₄ is a very corrosive chemical. It is built around a stainless steel L structure with a window. Two needle valves are fixed on the structure to ensure the carrying flow of Nitrogen. The Nitrogen flows from a bottle into Teflon or PTFE tubing, which connects to the actual system through a compression fitting. It separates into two branches: a bypass section, controlled by a needle valve, and an actual seeding section. The tubing from this section connects to the first needle valve, which actually controls the seeding flow. The Nitrogen flows into a glass container purchased from MDC Vacuum, which contains TiCl₄. It either bubbles through or blows over the TiCl₄ depending on the quantity available in the glass container and then the flow charged with TiCl₄ vapour goes through another tube, which is never immersed in TiCl₄ in order not to get liquid TiCl₄ in the system downstream of the container and directly in
the jet. This seeding flow passes through a second needle valve, which is fully opened while the seeding is on in order not to put too much pressure on the glass container, which was designed for vacuum. The seed flow goes out of the portable system through another Taigon/Teflon/PTFE tube and gets into the chamber around the stainless steel jet pipe in which eight small holes have been drilled so that the TiCl₄ vapours slowly get into the jet in an equally partitioned manner.

![Figure 3-27: Cleaning kit.](image)

This system needs extra attention and cleaning needs to be done at the end of each experiment for the chamber and the holes as well as the jet pipe, in order to keep the same flow conditions and seeding conditions. Indeed the TiCl₄ has a high reactivity with the humidity in the air and the reaction products tend to clog the holes as well as the small-size piping. The Nitrogen used is dry. However since the system is disconnected when not in use, it is in contact with the atmosphere. The cleaning can be done with paper towels and water too, being careful of not getting chemical burns. A thorough drying process must be implemented at the end of the cleaning to remove residual moisture in the TiCl₄ lines.

**Procedure to fill up the TiCl₄ glass container**

**Material required:**

- TiCl₄ seeding system
- Fume Hood
- Rubber gloves, respirator masks and protection goggles
- TiCl₄
- Beaker
- Two 7/16’ wrenches
Procedure

1) Bring the TiCl₄ seeding system under a fume hood.
2) Put on gloves, respiratory masks and protection goggles.
3) Remove the Plexiglas front of the system by unscrewing the four bolts on the front of it.
4) Loosen the eight bolts of the container top.
5) Get the bottle of TiCl₄ out of the plastic bag out of the metallic box out of the cardboard box and get it ready in the fume hood with the beaker.
6) Unscrew the bolts of the top of the container and keep the bolts, washers and spring washers ready to screw it back.
7) Keep the container closed manually.
8) In the meantime, open the TiCl₄ bottle and pour the desired quantity in the beaker.
9) Close the TiCl₄ bottle quickly.
10) Pour the beaker content into the glass container and put the container back in place.
11) Put the bolts back in place.
12) Close the TiCl₄ bottle completely and put it back in its bag/metallic box/cardboard box.
13) Clean the beaker by blowing air first and then with water. Then dry it thoroughly.
14) Put the Plexiglas front back in place.

All the tools used must be dry since TiCl₄ reacts vigorously with water. If the glass container or the whole system needs to be cleaned, it must be really dry before refilling, including the pipes, so that no clogging can happen.

At first we decided to seed the jet only with TiCl₄, using the moisture in the air provided by the compressor tank. Even with the air dryer on, there is still some moisture in the jet air, and there is also moisture in the wind tunnel. Because the moisture in the jet stream is very low we mostly observed the contours of the jet flow (zones of interaction with the cross flow) and not the jet flow in its entirety. The dry Nitrogen with TiCl₄ injected in the dry air stream of the jet only reacts when the jet mixes with the cross flow, which is moist air coming from the room. Therefore we could only see the mixing of the jet, which was not exactly what we wanted to observe. We want to observe the coverage of the wall by the jet flow. Consequently it is better if we see the actual jet flow, which is the reason why the moisture seeding was introduced.
Henceforth we decided to insert some moisture in our system to get more smoke inside the jet itself. Various versions of this system have been tried until a good enough for the purposes of the experiments was arrived at. The current seeding system is approximately the same as the TiCl4 system. Some water is placed in a steel container, which is bolted to a small stainless steel table. It consists in two gate valves: one for the seeding, one for the bypass and two needle valves to control the seeding flow. The Nitrogen flows in through Teflon/Taigon/PTFE tubing. The system breaks into three branches: two for the seeding, each one controlled by a needle valve, and one for the bypass flow, controlled by a gate valve. The two seeding branches get in the container and bubbles Nitrogen through the water or blows on water depending on the quantity in the container. The flow then comes out via a third branch controlled by the second gate valve.

Figure 3-28: Image (a) with and (b) without moisture seeding.
Then the question of where to introduce the seeding was addressed. First we tried to insert moisture upstream of the jet control valve system. It was placed as a short-cut to the gate valve upstream of the pressure regulator which gives our 20 psi supply pressure for the jet. This turned out to be a bad idea since we had accumulation of moisture/water in the pipes, which is detrimental to the components of the system. Our solution was to set a stainless steel T right downstream of the flow meter and upstream of the jet pipe to insert moist Nitrogen in the jet. This system worked fine. However we thought that it would be good to have complete independence between the two seeding systems: water and TiCl$_4$, for safety reasons and practicality of the setting.

**Procedure to seed the jet flow**

This procedure varies depending on the will to have moisture seeding or not in the jet and on the seeding flow measurement system in place (rotameter or flow meter). This procedure is described extensively below.

In every case we set our total seeding flow at a blowing ratio BR$_{\text{Seeding}}$ = 0.07 (around 15mm at 10 PSI on the rotameter). This was kept constant during our experiments involving the seeding system. We wait until the jet and cross flows are established, make sure that the Nitrogen bottle is fully open and that the appropriate flow meter reading program (fmreading2.0.vi for the electronic flow meter, 3.1 for the rotameter) is running.

**If using the flow meter the procedure is as follows:**

1) Open the needle valve bypassing the TiCl$_4$ container and set the pressure at the pressure regulator on the Nitrogen bottle to 10PSI while having a flow rate around the proper BR$_{\text{Seeding}}$.

2) Close this valve.

3) Verify that all the valves of the seeding systems are closed.

   First we set the moisture seeding (if needed) which usually is set to approximately a third of the total seeding, i.e. BR$_{\text{Seeding}}$ = 0.0233.

4) Open the needle valve leading to the moisture seeding system.

5) Open the gate valve downstream of the water container.

6) Crack one of the needle valves upstream of the water container open till reaching the proper BR$_{\text{Seeding}}$.

   It is better if the Nitrogen supply pressure stays at 10PSI. However, this is not necessary since the flow meter used to measure the seeding flow has an included pressure correction.

   Then we set the TiCl$_4$ seeding flow.

7) Open fully the needle valve downstream of the TiCl$_4$ container.
8) Crack the needle valve upstream of the TiCl$_4$ container open until reaching the appropriate $BR_{\text{Seeding}}$. 

**If using the rotameter (and pressure transducer)**

1) Open the needle valve bypassing the TiCl$_4$ container and set the pressure on the screen to 10PSI with a flow rate corresponding approximately to the required $BR_{\text{Seeding}}$.

2) Close this valve.

3) Verify that all the valves of the seeding systems are closed.

4) Open the needle valve leading to the moisture seeding system.

5) Open the gate valve downstream of the water container.

6) Crack one of the needle valves upstream of the water container open till reaching the proper $BR_{\text{Seeding}}$ (i.e. around 5mm at 10PSI).

7) Open fully the needle valve downstream of the TiCl$_4$ container.

8) Crack the needle valve upstream of the TiCl$_4$ container open until reaching the appropriate $BR_{\text{Seeding}}$ while compensating for pressure variations if any.

This part is the really hard part, because the pressure regulator on the Nitrogen bottle is not really precise, and both the valves and the pressure regulator must be manipulated at the same time to set the proper blowing ratio and the proper pressure. While using this setup, one has to be careful not to exceed the pressure transducer limit (30PSI max).

**Procedure to stop the seeding systems**

1) Close the valves upstream of the water and TiCl$_4$ containers.

2) Close the valves downstream of the water and TiCl$_4$ containers.

3) Open the bypass valves on both systems.

**3.6. Experimental Procedures and Settings for Visualizations and PIV**

**Procedure to setup for visualizations and PIV**

1) Turn on the pulsing computer, the visualization computer, the data acquisition computer.

2) Turn on the LASERs.

3) Turn on the flow meter(s) and pressure transducer if necessary.

4) Turn on the wind tunnel and set velocity to 1.6m/s

5) Turn on the jet and set the proper set of parameters
Procedure to take images

1) Set the proper settings in the LaserPulse window in the Insight NT software.
2) Load the settings and press the run button.
3) Open the Camera control window and set the proper settings.
4) Press the start button in the camera control window.

Save the images by pressing the save button after reviewing them.

Figure 3-29: Visualization Settings.
Figure 3-29 shows the settings for the Laserpulse windows for the visualizations. During visualizations, the synchroniser is triggered externally, and images are taken in phase with the period of the cycle.

On the camera control window, the different parameters need to be set as shown in Figure 3-30. The family name, the directory and the number of images in a sequence can be changed depending on the experiments.

![Camera Control Window](image)

Figure 3-30: Camera control settings for visualizations.

For the PIV experiments, some changes need to be made in the Laserpulse window. First in the operating mode, instead of double pulse, frame straddling needs to be set for the computer controlled camera mode. Moreover, both LASERs need to be set on high.

Procedure to turn the system down after visualizations and PIV experiments

1) Close all valves on both seeding systems
2) Close the needle valve leading to the water seeding system downstream of the water system
3) Open the bypass gate valve on the water system
4) Close the bypass gate valve on the water system
5) Open the gate valve downstream of the water container
6) Close the gate valve downstream of the water container

This procedure depressurizes the water seeding system. It is then at atmospheric pressure.

7) Disconnect the water seeding system by disconnecting the upstream and downstream compression fittings.
8) Close the Nitrogen bottle valve.
9) Open the bypass needle valve on the TiCl₄ seeding system till the Nitrogen left in the pipes has bled out.
10) Check the pressure regulator on the Nitrogen bottle to see that the Nitrogen system is depressurized.
11) Close the bypass needle valve on the TiCl$_4$ seeding system.

At this point only the TiCl$_4$ glass container of the TiCl$_4$ seeding system is still pressurized.

12) Disconnect the TiCl$_4$ seeding system by disconnecting the upstream and downstream compression fittings

This procedure isolates the seeding systems so that no water or TiCl$_4$ can get into the lines while the system is at rest.

13) Close the yellow valve situated on the opposite wall of the compressor.

14) Shut down the compressor and the air dryer.

15) Turn off the seeding flow flow meter if it is in line of the system.

16) Disconnect the flow meter(s) from the system and put their ending protections back on and store the main flow flow meter.

This is in an effort to prevent anything from happening to the flow meters, which are really sensitive.

17) Clean the inside of the jet pipe with a brush, clean the orifice with a wet paper towel.

When cleaning the jet pipe, one must be careful not to accidentally put anything in the filter of the main flow meter. The best way is to put a paper towel on the exit of the filter to prevent anything from getting in it.

18) Check the holes on the TiCl$_4$ seeding system, and clean them using a pipe cleaner.

19) Close the gate valve upstream of the pressure transducer on the main line in order to isolate the jet system.

20) Turn the computers, the LASERs, the synchroniser and the oscilloscope off.

21) Turn off the power supplies of all the equipment.

When using the LASER, one should always wear LASER goggles in order to protect the eyes from the intense light. When doing PIV or Visualizations, one should place signs on the doors of the lab to warn people about the LASER and the TiCl$_4$.

3.7. NI SC2345 Boards and Command Modules

The data acquisition system and the pulsing system both work using a National Instruments SC 2345 DAQ chassis. Each chassis has different modules in it which are designed to receive or send digital or analog signals.

The pulsing system chassis is a SC 2345. For our experiments it connects to the computer via a NI PCI 6220 card. It is set up with two modules. The first module is a SCC RLY01. It is a relay module, which receives a 17V input from the solenoid valve power supply and gives a 12V output to the solenoid valve when it receives a logic signal. The second module is a SCC DO01. It is a digital output module, which is used to send a copy of the
valve trigger signal to the second DAQ board or to produce another trigger signal for the synchroniser while taking visualizations.

![Forcing DAQ board.](image1)

**Figure 3-31: Forcing DAQ board.**

![NI PCI 6220 card.](image2)

**Figure 3-32: NI PCI 6220 card.**

The second DAQ chassis we are using is the data acquisition board. It is also a SC 2345. Its connexion to the data acquisition computer is made via a NI PCI MIO-16E-4 board. On this chassis we used three identical modules.

![Data Acquisition board.](image3)

**Figure 3-33: Data Acquisition board.**
These modules are all SCC AI03. They are analog input modules, which are used to acquire the signals coming from our different system of measure (hotwire sensors, thermocouple, flow meters) but also the copy of the trigger signal coming from the other DAQ board. These modules can receive signals ranging from -10V to +10V. This is the reason why we couldn’t acquire the 12V signal going to the solenoid valve, which is why we had to create a copy of this signal.

3.8. Flow Meters

As we explained we based our experiments on valve positioning and supply pressure at the beginning, and realized it was not accurate or reliable enough for our experiments. As a consequence we had to look for flow measurement equipment. At first we were measuring the velocity out of the jet via the hotwire and deduced the blowing ratio from this measurement. Although not completely erroneous this method was not precise.

To ensure quality measurement and better understanding of our experiment, as well as better reproducibility we purchased two flow meters with adequate frequency response from TSI to measure our flow.

One of them measures the flow coming from the compressor and the tank, after the pulsing system. The other one measures the nitrogen seeding flow. The sum of the two flows gives us the total flow out of the jet.

3.8.1. Jet Flow Meter TSI 40241 and Filter

At first we were only looking for a measure of our jet flow. After looking at different ideas and supplier, we opted for a TSI flow meter. Estimating the range of flow rate of our jet by using the jet velocity survey we talked about earlier, we could make a wise choice for our flow meter. The model TSI 40241, which is a mass flow meter, was chosen for its fast response time and flow rate range. Its body is in plastic, which we had to consider when connecting it to the system. The flow meter based its measurement on two-wire sensors inside it.

This flow meter was delivered with a particle filter that needs to be put right upstream of the flow meter. Also in the box was a mini DIN cable. However, we had to provide a power supply to this flow meter and set the connexions to our computer to control it, and to the DAQ board to acquire the data out of it. More information is available in the manual.

This flow meter measures the main flow, i.e. the jet flow. It is placed downstream of the pulsing system to be able to observe the behaviour of the flow in the jet under pulsing. It should be noted that our first experiments were done without these flow meters, which change somewhat the acoustic behaviour of the system because of their cross section, length and the associated volume. The exit of the pulsing system is connected to an air filter provided
with the flow meter via a 1/2inNPTx3/8inNPT reducer. This filter leads to the flow meter to which it is connected by a system of pipe fittings in order not put any pressure on the TSI flow meter plastic nipple. The exit of the flow meter is connected by the same way to the stainless steal pipe of the jet. This flow meter did not have its own power supply. Consequently we had to create it, while respecting the specified by the manufacturer specifications.

![Figure 3-34: TSI 40241 flow meter.](image)

### 3.8.2. Seeding Flow Meter TSI 4140

For our first visualizations experiments we operated our seeding system only with TiCl$_4$ and only by setting a constant supply pressure of 10PSI. Then we did constant temperature anemometry measurements with the bypass flow open at the same pressure we used for the seeding. First we noticed a difference in our flow, which lead us to acquire the jet flow meter.

Moreover we did not know the exact amount of seeding we were introducing in the jet. As a consequence, we decided to get a way to measure our seeding Nitrogen flow. This way we would know exactly our total flow rate and we could repeat experiment far more precisely by setting the same seeding flow rate and the same jet flow rate.

After approximating our Nitrogen seeding flow rate, we opted for another TSI flow meter, a 4140 model. This model has a flow rate range of 0.01 to 20 StdL/min, a response time of less than 4ms (we managed to use it with a response time of 1ms), and can work with air, oxygen and nitrogen (we used the last one). It has a liquid
crystal display if it is to be used just as a setting system. It was delivered with its own power supply and two mini DIN cables. Then again we had to do the connection to our computer and the DAQ board.

This flow meter is used to measure the seeding flow coming from the nitrogen supply. We want this flow to be as constant as possible in order not to influence too much our experiments. The characteristics of the flow meter are given in the appendix. This flow meter is positioned right after the pressure regulator placed at the exit of the Nitrogen bottle. The flow runs from left to right when looking at the front panel of the flow meter. The exit of the flow meter connects to the TiCl$_4$ bubbling system.

### 3.8.3. Rotameter and Pressure Transducer

![Figure 3-36: (from right to left) rotameter, pressure transducer and power supply of the pressure transducer.](image)

When the seeding flow flow meter was broken, we replaced it by a rotameter associated with a pressure transducer for time delay reasons. The rotameter was purchased from Omega as well as the pressure transducer. The pressure transducer is needed to ensure a right reading of the rotameter. Indeed this reading is dependent on the pressure running in the line. In order to protect those two components, we created a Plexiglas. We installed the rotameter and the pressure transducer on it, as well as the seeding flow meter when we got it back from repair. The pressure transducer was powered by an Omega power supply PSS-10 of 10V at 400mA showed hereunder. The rotameter was operated fully open. Only the pressure and the valve positions on the seeding systems were modified.

### 3.8.4. Flow Meters Control and Data Acquisition

TSI supplies a software which allows to set the parameters of their flow meters (see Figure 3-37). To set the blowing ratios, a real time reading of both flow meters was needed. A VI reading the flow meters signals from the DAQ board, modifying it in flow rate and blowing ratio was created. This program also adds the seeding flow
blowing ratio and the jet flow blowing ratio to get the real blowing ratio out of the jet, which is the one that needs to be set.

When we had to change the seeding flow meter to the rotameter, we adapted the program to add to the jet flow meter a constant blowing ratio of 0.069, this way we were still setting the total blowing ratio. Moreover this modified program also presented the data from the pressure transducer so that we could monitor this one at the same time in real time.

As for the measurement, TSI supplies a dummy Virtual Instrument program, which can be modified to receive the data from the flow meter. However, since we wanted to associate the flow meters measurement with the hotwire, we modified our own program to acquire the signal from the flow meters, via the DAQ board.

![Figure 3-37: Flow meter TSISetup program.](image)

![Figure 3-38: Flow meter reading 2.0 (a) and 3.1 (b) VIs.](image)
3.9. Others

3.9.1. Computers

Our research work required an extensive use of computers. Five computers were used for this project.

3.9.1.1. IFA 300 Computer

Type       PC
OS         Microsoft Windows 98 Second Edition
Characteristics  Genuine Intel Pentium Pro Processor
Hard Drives Partitions  Micron (C:) 1.99GB FAT (System)
                     Hotwire 1 (D:) 38.1GB FAT32 (Data)
                     Micron (E:) 2GB (Not used)

Notice: to transfer data from this computer, i.e. the .CL files, use the floppy drive.

3.9.1.2. Data Acquisition Computer

Type       PC
OS         Microsoft Windows 2000 SP3
Characteristics  x86 Family 6 Model 7 Stepping 3
                     AT/AT Compatible
                     392,740KB RAM
Network     Full Computer Name: trvrsbeast.engrad
                     Workgroup: FLOW CONTROL
Hard Drives Partitions  Local Disk (C:) 7.85GB NTFS (System)
                     Local Disk (D:) 9.04GB FAT32 (Data)

Notice: to transfer data from this computer use a USB drive or the ftp server (network connection).

3.9.1.3. Visualization and PIV Computer

Type       PC
OS         Microsoft Windows NT
Characteristics  x86 Family 6 Model 7 Stepping 3
                     AT/AT Compatible
                     130,480KB RAM
Hard Drives Partitions
   (C:) 1.99GB (System)
   (D:) 10.6GB
   Data_1 (U:) 9.76GB (Data)
   Data_2 (V:) 9.76GB (Data)
   Data_3 (W:) 9.76GB (Data)
   Data_4 (X:) 7.97 GB (Data)

Notice: to transfer data from this computer, connect to the network and upload the data to the computer.

Notice: (D:) is inaccessible

Notice: USB and CD burner out of order.

3.9.1.4. Pulsing Computer

Type: PC
OS: Microsoft Windows 2000 SP4
Characteristics: Intel Pentium 4 CPU 1.5GHz
AT/AT Compatible
196,08KB RAM

Network
   Full Computer Name: daqbeast.engrad
   Domain: engrad

Hard Drives Partitions
   Local Disk (C:) 37.2GB (System and Data)

Notice: to transfer data from this computer, use a USB drive, or the network.

3.9.1.5. Data Processing Computer

Type: PC
OS: Microsoft Windows XP Professional Version 2002 Service Pack 2
Characteristics: Intel Pentium 4 CPU 3.00GHz
3GHz, 3GB of RAM

3.9.2. Oscilloscope and Multimeter

A Tektronix TDS 224 Four Channel Digital real-time oscilloscope and a Radioshack Auto Range High speed sampling Bargraph digital multimeter were also used in our experiments to check various voltages and signals we operated with and help us troubleshoot problems we could have with them.
Figure 3-39: Oscilloscope (a) and Multimeter (b).
Chapter 4: Data Reduction

Our experiments generated a high quantity of raw data, from voltage files recorded in text files to images from visualization. This raw data needed to be processed. That is what this part of this document is dealing with, the post treatment of the data. For most of our data reduction we used Matlab, but we also used programs such as Tecplot.

4.1. Constant Temperature Anemometry Data Reduction

4.1.1. Processing with Matlab

Matlab was used for most of the data processing in this project. Constant Temperature Anemometry experiments gave us text files, in which voltages from the hotwire(s), the thermocouple and the flow meters were recorded. This part of this thesis gives a few details about what each program we used was designed do.

4.1.1.1. Calibration Programs

4.1.1.1.1. Single Wire Probe

The calibration of a single sensor probe as we do it gives us 34 text files with velocity and temperature voltages. The goal of the calibration is to get the coefficients of the polynomial curve fitting the calibration profile of the probe.

The program we used for these calibrations, which is listed in the appendix, was developed by a previous student and we modified it for our purpose.

To run this program, first an excel file with the characteristics of the calibration contained in the calibration (.CL) file obtained on the IFA computer during the calibration must be created. The main changes are the gain and offset applied to the voltages depending on the probe, as well as the actual calibration velocities reached during the calibration. Basically, the program takes this data and makes a polynomial fit on the curve of the velocity as a function of the voltage. Then it plots this curve and writes the coefficients in a text file. Then those coefficients will be inserted in an excel file which will be used by the experiment data reduction programs.

4.1.1.1.2. Cross Wire Probe

The calibration of a cross wire probe is slightly different because in addition to the velocity coefficients, we need to compute yaw coefficients. As we explained in the calibration procedures earlier, straight velocity files are taken as well as 11 angle velocity files for 21 velocities between 0 and 10m/s which is far beyond our range of
operation in our experiments. From there, the program computes the velocity and yaw coefficients that will be applied to process experimental data. The program can be found in the appendix.

4.1.1.2. Experiment Post-Processing Programs

Reducing experimental hotwire data varies with the experiments. It first starts by the transformation of the voltages in velocity, then we apply a number of post-processing steps as needed including phase averaging, spectrum analyses or just time record generation. Programs written for such post-processing are included in the appendix.

4.1.2. Flow Meter Measurements

While taking flow meter measurements, as with the hotwire measurements, raw voltages are acquired on the DAQ board and are then processed. The post-processing involved phase averaging and then extraction of averages of the flow blowing ratio mean, high and low values as well as the actual duty cycle. The post processing was also done using Matlab.

4.2. Visualizations

4.2.1. Processing with Matlab

After the visualizations, Matlab was used in order to combine, resize, average and modify images. Matlab read images of various formats and transformed them into matrices, which can be modified and retransformed into images. Figure 4-1 is an example of post-processing done with Matlab in order to correlate each image with the time instant during the pulsing cycle at which it was taken.

Figure 4-1: Image processing: (a) raw image; (b) processed image.
Chapter 5: Results and Discussion

5.1. System Characterization

Before studying the JICF, the characteristics of the system had to be determined. To realise comparable experiments and get conclusions out of them we need to know what the response of each system is before having them work together.

5.1.1. Wind Tunnel

First we studied the aerodynamic wind tunnel we used to generate the cross flow. All along this part of the study the jet exit was covered.

5.1.1.1. Wind Tunnel Velocity Calibration

After redesigning the test section of the wind tunnel, we wanted to confirm that our design was correct. After a high frequency study in order to determine the integral timescale, the wind tunnel velocity response to the fan frequency was explored using CTA. A single wire bent probe (SN 976014) was placed at the centreline of the

![Wind tunnel velocity calibration graph](image)

**Figure 5-1: Wind tunnel velocity calibration.**
wind tunnel above the jet position (x = 0). The test was run several times to ensure the results were consistent. Those tests were made at a sampling rate of 200Hz, using a filter of 100Hz over a 4s period (i.e. 800 points). Figure V 1 shows the results of one of these experiments. The relationship of the wind tunnel velocity to the fan frequency is linear. As the frequency ranges from 0 to 60Hz, the velocity ranges from 0 to 30m/s. Setting the desired velocity is therefore easy: the frequency must be close to double the velocity desired. It can also be noticed that this calibration corroborates the original Pitot tube calibration of the wind tunnel to which it was compared.

Following this calibration, we studied the power spectrum of the free stream and boundary layer at various low speeds. The results presented are for a fan frequency of 3Hz, which corresponds to a velocity of 1.6m/s in the free stream. It was chosen so that the boundary layer would be laminar.

5.1.1.2. Free Stream Power Spectrum

The wind tunnel fan is run at a frequency of 3Hz. The stator has 9 blades and the rotor 12. The expected frequencies in the free stream of the wind tunnel are 3Hz, 9Hz, 12Hz their harmonics and combinations (27Hz, 36Hz, 324Hz).

The experiment is run with a single sensor hot wire bent probe at three positions along the x axis at the center line of the wind tunnel: 1) x/D_J = -4.75 upstream of the jet center, 2) x/D_J = 0.00 above the center of the jet, 3) x/D_J = 4.75 downstream of the jet center. This is done to ensure the uniformity of the free stream along the test section. At each position, 16 samples of 32,768 points are taken at 20 kHz with a 10 kHz filter according to the Nyquist criteria. For each of these tests, the power spectrum is computed and properly smoothed as well as the mean velocity and the turbulence intensity of the flow. The free stream speed is close to 1.6m/s and the free stream turbulence intensity is less than 0.25%.

Figure 5-2 shows the raw and smoothed power spectrum of the free stream at the position right above the jet. The expected frequencies and some of their harmonics can be found as well as the electrical frequency (60Hz) and its harmonics. Table 5-1 details these frequencies. It is noted that the 324Hz combination frequency does not appear. The important observation to be noted is that all these frequencies have very low energy level (more than 8 orders of magnitude compared to the most energetic part of the spectrum). Most of the energy of the flow is situated in frequencies lower than 1 Hz. The flow velocity is very low (U∞ = 1.6m/s) and as mentioned before there is very little turbulence in the free stream. So, while it is useful to note these frequencies it is also evident that the probability of them interfering with our flow is low.
Figure 5-2: Free stream power spectrum at $U_\infty = 1.6\text{m/s}$.

Table 5-1: Free stream spectrum frequencies.

<table>
<thead>
<tr>
<th>Flow expected frequencies [Hz]</th>
<th>Flow frequencies found [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, 9, 12, 27, 36, 324 and harmonics</td>
<td>3, 9, 13, 19, 23, 28, 38, 53, 74, 160</td>
</tr>
<tr>
<td><strong>Electrical frequency and harmonics found [Hz]</strong></td>
<td><strong>60, 120, 180, 240, 300, 360, 420, 480, 540…</strong></td>
</tr>
</tbody>
</table>

### 5.1.1.3. Boundary Layer

The free stream characterises the cross flow. However, the JICF is interacting first and foremost with the boundary layer of the wind tunnel. As the free stream, the boundary layer was first explored through higher sampling frequency tests to get the power spectrum and the integral timescale. After choosing the final free stream velocity more accurate characterizations were made to determine the boundary layer profile.

#### 5.1.1.3.1. Exploration and Power Spectrum

First we realised high frequency tests at various wind tunnel fan frequencies at the position of the jet exit $(x/D_J, y/D_J) = (0, 0)$ to determine the spectrum at several points of the boundary layer as well as the settings for the profile tests. The sampling rate was 5 kHz, with a low pass filter at 2 kHz accordingly with the Nyquist criteria. Each test lasted around 210s, with a total number of samples of 1,048,576 points.

Table 5-2 shows results of these exploratory tests. The integral time scale was computed using autocorrelation method. $N_{95\%}$ and $N_{99\%}$ are respectively the minimum number of points to take to get a value with a
95% and 99% uncertainty respectively on the mean. These values were computed using the normal or student-t distribution as appropriate. For each of these 9 locations the power spectrum was computed and properly smoothed. Different block averages were applied (1, 3, 7, 15, 31 blocks).

Table 5-2: Boundary layer exploration results ($U_\infty = 1.6\text{m/s, } x/D_J = 0, y/D_J = 0$).

<table>
<thead>
<tr>
<th>$z/D_J$</th>
<th>$U$ [m/s]</th>
<th>$T_I$ [%]</th>
<th>$u_{rms}$ [m/s]</th>
<th>$N_{95%}$</th>
<th>$N_{99%}$</th>
<th>Integral Time Scale [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.067</td>
<td>0.332</td>
<td>4.741</td>
<td>0.016</td>
<td>87</td>
<td>149</td>
<td>4.891</td>
</tr>
<tr>
<td>0.267</td>
<td>1.196</td>
<td>3.471</td>
<td>0.042</td>
<td>47</td>
<td>80</td>
<td>7.651</td>
</tr>
<tr>
<td>0.467</td>
<td>1.534</td>
<td>1.404</td>
<td>0.022</td>
<td>8</td>
<td>14</td>
<td>4.334</td>
</tr>
<tr>
<td>0.667</td>
<td>1.599</td>
<td>0.495</td>
<td>0.008</td>
<td>1</td>
<td>2</td>
<td>4.936</td>
</tr>
<tr>
<td>0.867</td>
<td>1.603</td>
<td>0.430</td>
<td>0.007</td>
<td>1</td>
<td>2</td>
<td>1.756</td>
</tr>
<tr>
<td>1.067</td>
<td>1.611</td>
<td>0.388</td>
<td>0.006</td>
<td>1</td>
<td>1.0</td>
<td>2.650</td>
</tr>
<tr>
<td>1.267</td>
<td>1.605</td>
<td>0.390</td>
<td>0.006</td>
<td>1</td>
<td>1.0</td>
<td>3.811</td>
</tr>
<tr>
<td>1.467</td>
<td>1.602</td>
<td>0.457</td>
<td>0.007</td>
<td>1</td>
<td>2</td>
<td>5.440</td>
</tr>
<tr>
<td>11.067</td>
<td>1.598</td>
<td>0.393</td>
<td>0.006</td>
<td>1</td>
<td>1.0</td>
<td>3.419</td>
</tr>
</tbody>
</table>

Figure 5-3: Boundary Layer Power Spectrum.

Figure 5-3 shows the 3 block averaged power spectrum at 4 different vertical locations above the jet position. The spectrum inside the boundary layer is very similar to the spectrum of the free stream. The bulge around 9Hz is present on all spectrums. Around 24-27Hz (harmonic of 12Hz- combination of fan frequency and number of blades on stator) each spectrum presents a local peak. The spectrum at the position closest to the wall ($z/D_J = 0.067$)
shows some differences compared to the other three. It shows a bulge between 1.1 and 2.5Hz, as well as around 3Hz and 70Hz (harmonic of 36Hz, combination of fan frequency and number of blades on rotor maybe), which are not so marked at the other positions. The boundary layer seems more sensitive to the frequencies linked to the fan than the cross flow. These spectrums also confirm the affirmation made earlier that the energy of the flow is concentrated at very low frequency, well under 1Hz, which is the low limit of our forcing frequencies. As also mentioned regarding the free stream, while it is useful to note these frequencies it is also evident that the probability of them interfering with our flow is low.

5.1.1.3.2. Profile

Boundary layer profiles were taken at several locations around the jet at the selected cross flow velocity of 1.6m/s. The boundary layer thickness $\delta$, the displacement thickness $\delta^*$, the momentum thickness $\theta$ and the shape factor $H$ were computed at each of these points.

$$U(z = \delta) = 0.99 \times U_\infty$$

$$\delta^* = \int_0^\infty \left(1 - \frac{U}{U_\infty}\right) dz$$

$$\theta = -\int_0^\infty \frac{U}{U_\infty} \left(1 - \frac{U}{U_\infty}\right) dz$$

$$H = \frac{\delta^*}{\theta}$$

Equation 5-1: Definitions of $\delta$, $\delta^*$, $\theta$ and $H$.

These experiments were realised using the automated traverse and acquisition system described in 3.3. A comprehensive grid was built, incorporated each position and the corresponding sampling conditions (frequency, number of samples) deduced from the exploration tests (see Table 5-2). Table 5-3 shows the results of these experiments at the various locations. The shape factor at the location of the jet is 2.46, which is not far from the theoretical value 2.59 of the Blasius solution for a laminar boundary layer on a flat plate. This is confirmed by the Reynolds number relative to the beginning of the test section (the jet is placed 30 diameters downstream of the end of the contraction). It can be noted that the study by Ekkad and Rivir was also made under laminar boundary layer conditions. This was intended for comparison purposes of the studies.

Figure 5-4 shows the boundary layer profiles at the various y positions and Figure 5-5 shows the boundary layer profiles at the various x stream wise positions. The boundary layer is uniform across the wind tunnel to a satisfactory extent.
Table 5-3: Boundary layer test results at a fan frequency of 3Hz.

<table>
<thead>
<tr>
<th>x/D_j</th>
<th>y/D_j = -4.00</th>
<th>x/D_j = 0.00</th>
<th>x/D_j = +4.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>x/D_j = -4.75</td>
<td>U_∞ = 1.60 m/s</td>
<td>U_∞ = 1.59 m/s</td>
<td>U_∞ = 1.57 m/s</td>
</tr>
<tr>
<td></td>
<td>T_l = 0.65 %</td>
<td>T_l = 0.64 %</td>
<td>T_l = 0.85 %</td>
</tr>
<tr>
<td></td>
<td>δ = 1.8 cm</td>
<td>δ = 1.49 cm</td>
<td>δ = 1.86 cm</td>
</tr>
<tr>
<td></td>
<td>δ* = 0.440 cm</td>
<td>δ* = 0.462 cm</td>
<td>δ* = 0.485 cm</td>
</tr>
<tr>
<td></td>
<td>θ = 0.199 cm</td>
<td>θ = 0.187 cm</td>
<td>θ = 0.216 cm</td>
</tr>
<tr>
<td></td>
<td>H = 2.21</td>
<td>H = 2.46</td>
<td>H = 2.25</td>
</tr>
<tr>
<td>x/D_j = 0.00</td>
<td>U_∞ = 1.58 m/s</td>
<td>U_∞ = 1.59 m/s</td>
<td>U_∞ = 1.57 m/s</td>
</tr>
<tr>
<td></td>
<td>T_l = 0.44 %</td>
<td>T_l = 0.64 %</td>
<td>T_l = 0.85 %</td>
</tr>
<tr>
<td></td>
<td>δ = 1.34 cm</td>
<td>δ = 1.49 cm</td>
<td>δ = 1.86 cm</td>
</tr>
<tr>
<td></td>
<td>δ* = 0.451 cm</td>
<td>δ* = 0.462 cm</td>
<td>δ* = 0.485 cm</td>
</tr>
<tr>
<td></td>
<td>θ = 0.189 cm</td>
<td>θ = 0.187 cm</td>
<td>θ = 0.216 cm</td>
</tr>
<tr>
<td></td>
<td>H = 2.38</td>
<td>H = 2.46</td>
<td>H = 2.25</td>
</tr>
<tr>
<td>x/D_j = 4.75</td>
<td>U_∞ = 1.60 m/s</td>
<td>U_∞ = 1.59 m/s</td>
<td>U_∞ = 1.57 m/s</td>
</tr>
<tr>
<td></td>
<td>T_l = 0.46 %</td>
<td>T_l = 0.64 %</td>
<td>T_l = 0.85 %</td>
</tr>
<tr>
<td></td>
<td>δ = 1.59 cm</td>
<td>δ = 1.59 cm</td>
<td>δ = 1.86 cm</td>
</tr>
<tr>
<td></td>
<td>δ* = 0.471 cm</td>
<td>δ* = 0.471 cm</td>
<td>δ* = 0.485 cm</td>
</tr>
<tr>
<td></td>
<td>θ = 0.207 cm</td>
<td>θ = 0.207 cm</td>
<td>θ = 0.216 cm</td>
</tr>
<tr>
<td></td>
<td>H = 2.27</td>
<td>H = 2.27</td>
<td>H = 2.27</td>
</tr>
</tbody>
</table>

Figure 5-4: Boundary layer profiles at x/D_j = 0.00.

Figure 5-5: Boundary layer profiles at y/D_j = 0.00.
5.1.2. Jet (without Cross Flow)

After the wind tunnel/cross flow characterisation, the other element of the system which must be characterised is the jet. This part of the study was realised without cross flow and the roof of the wind tunnel was off to ease the operations with the traverse.

5.1.2.1. Valve System Calibration

The flow meters were incorporated late in our research work. A calibration of the valve system was realised at the very beginning of the study to know approximately the range of velocity of the jet and its velocity response to the valves positions. This calibration was used later on to set approximately desired velocity. With the various changes in the system this calibration is now obsolete.

A straight single hot wire probe was placed at the exit of the jet. The positions of the valves were changed. The test was repeated at three different supply pressures: 20PSIG, 40PSIG, and 60PSIG. The results of these tests lead us to set our supply pressure at 20PSIG to be able to reach a lower range of velocity. Those tests were realised with the jet outside of the wind tunnel at a sampling rate of 200Hz with the de-aliasing filter at 100Hz and with a total number of samples of 800.

5.1.2.2. Jet-Exit Spectrum

Once the jet was installed in the wind tunnel, it was characterised. As usual a high frequency sweep was made to determine the integral time scales. Then a tighter grid was created and precise sweeps were run. These sweeps included high frequency sampling to obtain the power spectrum of the jet as well as to verify the validity of the integral time scale. The sampling rate was 5 kHz and the sample 524288 points. A 2 kHz low pass filter respecting the Nyquist criterion was applied. Those sweeps were taken at three values of $W_{Jet Exit}/U_{\infty}$ (ratio of the maximal vertical velocity at the jet exit over the cross flow velocity). These values were targeted to be around 0.5, 1.0 and 1.5. The tests were done without cross flow.

The actual values of $W_{Jet Exit}/U_{\infty}$ were 0.522, 0.989 and 1.524 corresponding respectively to jet Reynolds numbers of 1400 (laminar), 2700 (transitional) and 4100 (low turbulent). For the rest of our study, the blowing ratios (actual, not based on the maximum jet exit velocity) were kept under 1. The jet was consequently in a laminar or transitional state.

Figure 5-6 shows the power spectrums in those three cases at the jet exit. The drop in power is smooth. This means that there is no prevalent low frequency induced by the air supply system (pipes, needle valves, solenoid
valve) at these jet velocities. As for the high frequencies peaks can be seen, common to each test it seems (370Hz, 700Hz, 900Hz). However, they are of low energy compared to the low frequencies, and are far away (>100Hz) from the pulsing system frequencies used during the forced tests (0.5, 1.0, 5.0 and 10.0Hz). This means there is a slighter chance of interaction and amplification of these frequencies by the forcing system.

Figure 5-6: Power Spectrum of the jet without cross flow.

Figure 5-7: Power spectrum with and without cross flow/flow meter.
The previous tests were made without cross flow and without the flow meter. Figure 5-7 shows a comparison of two spectrums. The first one was taken without cross flow and without the flow meter, the second one with both. It shows clearly that the high frequencies of the air supply system are still there and the same, which means that the influence of the addition of the flow meter and its filter on the system has had a limited effect on the natural frequencies of the system.

5.1.2.3. Jet-Exit Profiles

As velocity profiles of the wind tunnel boundary were taken in addition of the spectrum, the velocity profile at the jet exit was studied too. The velocity profiles were taken at \( z/D_J = 0.067 \), right above the jet, and along the \( x \) and the \( y \) axis to ensure symmetry of the jet, since the jet exit is circular.

Figure 5-8 and Figure 5-9 show the velocity profiles at the jet exit at the three nominal ratios \( W_{max}/U_\infty \): 0.5, 1.0, 1.5 (approximately). These figures also present the RMS velocity profile of the jet at the corresponding blowing ratios. Two scalings have been applied, the first one with the maximum jet exit velocity on which we based the local definition of blowing ratio, and a scaling using the average velocity of the jet. The figures show good symmetry of the jet in all the cases studied. The profiles show that the jet is weak: the boundary layers are thick while the center is not broad. The increase of the jet velocity leads to a flattening of the jet: the boundary layers get thinner and the core of the jet becomes more uniform. The RMS velocities also increase.

The jet profile at \( W_{max}/U_\infty = 0.5 \) is slightly asymmetric compared to the other two. This can be attributed to the influence of natural convection in the wind tunnel even if the fan is not on, because of a temperature gradient between the inlet which is at ground level and the discharge which is at ceiling level. The natural convection phenomenon is actually confirmed by the calibration of the wind tunnel, since at a fan frequency of 0Hz, there is a very small flow velocity, which is above the convective threshold of the probe.

The RMS velocity profiles show that the RMS velocity is higher in the shear layer region as expected on the basis that it originates from a pipe flow inside the feed tube. Comparison between the measured cases shows that the turbulence increases as the velocity ratio (i.e. the average jet velocity) increases. The shear layer is a region of strong velocity gradients and consequently more turbulence is produced than at the center of the jet. The higher the velocity ratio gets, the stronger the gradient is, especially since the shear layer region gets thinner. The errorbars on the mean and RMS velocity profiles indicate the statistical uncertainty to 95% confidence interval. The mean and RMS velocity profile shapes are consistent with the corresponding magnitudes of the Reynolds number, which is
laminar for the lowest average velocity and weakly turbulent for the highest. A modest level of velocity fluctuation exists in the jet even at the laminar Reynolds number. This is not unexpected because no attempt at conditioning the flow as it comes from the pulsing system valve manifold, where local velocities are higher and turbulence is generated.

One can also notice that the velocity outside right outside of the jet is not completely zero. This is so because of entrainment along the flat wall all around the jet exit and it includes a low-velocity bias because of probe convective effects and the direction of the velocity, which in that locale is not the one for which the probe has been calibrated.

![Mean velocity and RMS velocity profiles](image)

Figure 5-8: Mean velocity and RMS velocity profiles at $W_{\text{max}}/U_\infty \approx 0.5$ (a, b); $W_{\text{max}}/U_\infty \approx 1.0$ (c, d); $W_{\text{max}}/U_\infty \approx 1.5$ (e, f) without cross flow scaled with $W_{\text{max}}$. 
Figure 5-9: Mean velocity and RMS velocity profiles at $W_{\text{max}}/U_\infty \approx 0.5$ (a, b); $W_{\text{max}}/U_\infty \approx 1.0$ (c,d); $W_{\text{max}}/U_\infty \approx 1.5$ (e,f) without cross flow scaled with $W_{\text{mean}}$.

5.2. Unforced Jet in Cross Flow

Before forcing the jet and in order to be able to compare the forced cases to an unforced reference, the unforced JICF was studied. First a CTA study of the jet profile along the x axis was done using an X-probe. Then an extensive visualization and CTA spectral study was conducted to determine the characteristics of the flow.

5.2.1. Jet-Exit Velocity Profiles

A hot wire X-probe measures two components of a flow as long as the probe is oriented plus or minus 30° from the velocity vector. Using the automated traverse and measurement system, a grid was created to sweep the jet...
profile along the x-axis. These tests were made at a sampling rate of 10,000Hz, with a de-aliasing filter set at 5,000Hz and a sample size of 262144 points. Four cases were explored. The flow meters (main flow and seeding flow) were not yet installed for these tests but the seeding system was implemented. The Nitrogen seeding supply pressure was set at 10PSIG (but no TiCl$_4$ was used in these tests). As for the valves they were set according to previous tests for nominal velocity ratios $W_{\text{max}}/U_\infty \approx 0.5, 1.0$ and 1.5. A test was also done with seeding flow only (both needle valves fully closed).

Figure 5-10 shows the profile of $U$ and $W$ at the jet exit with cross flow at $U_\infty = 1.6$ m/s and $W_{\text{max}}/U_\infty \approx 0.0, 0.5, 1.0$, which corresponds to our range of actual blowing ratio explored during later tests.

![Figure 5-10: Profiles of $U$ and $W$ for the steady state JICF.](image)

<table>
<thead>
<tr>
<th>Nominal $W_{\text{max}}/U_\infty$</th>
<th>Actual $W_{\text{max}}/U_\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.56</td>
</tr>
<tr>
<td>0.50</td>
<td>1.20</td>
</tr>
<tr>
<td>1.00</td>
<td>1.66</td>
</tr>
</tbody>
</table>
A comparison of the nominal settings and actual results is given in Table 5-4. This difference is due mainly to the seeding flow addition but also to the fact that the jet is now in the cross flow. This shows clearly the necessity of the flow meter. The jet profile is clearly bent by the cross flow. The negative values of U show that there is recirculation in front and behind the jet (vortices).

Figure 5-11: RMS velocities (a), Skewness (b) and Kurtosis (b) of the unforced JICF.

Figure 5-11 shows the RMS velocity profile as well as the Skewness and the Kurtosis of the jet at nominal $W_{\text{max}}/U_{\infty} \approx 0.5, 1.0$. The RMS velocities peak where the jet begins: there is more turbulence because it is the shear layer region, where the wind tunnel flow and the jet flow meet. The Skewness is pretty close to 0 (standard value for a symmetric sample) over the jet and diverges from zero around the shear layer region too. Likewise the Kurtosis is close to its standard value of 3 (normal/Gaussian distribution) over the jet but significantly increases in the shear.
regions on the upstream and downstream ends, where re-circulation is expected to exist. This indicates that the measurement in these regions of the jet may be less reliable.

After these tests, which provided basic information regarding the shape of the velocity profiles at the JICF exit, the transient flow meter system was implemented. Forced and unforced tests were run with the visualization setup to take images on the x-z plane and measurements were made with single hot wire probes to determine the spectral signature of the jet.

5.2.2. Visualization and Spectrum Study

5.2.2.1. Presentation

The unforced JICF was explored through x-z plane LASER sheet visualizations and CTA survey at four positions of the x-z plane for each selected case. The system does not allow CTA and visualizations at the same time due to the corrosive nature of the TiCl$_4$ and the sensitivity of the hot wire probes. The two experiments must be done separately. The flow meters allowed us to ensure a good compatibility of those experiments. With their precision and low response time ($\approx$1ms), the seeding flow meter and the main flow meter allow a very precise setting of the blowing ratio in real time. The conditions of the visualizations can consequently be repeated to do the hot wire surveys. Integrated in the data acquisition system, the flow meters signals are recorded during visualizations and CTA tests to be able to compare and make sure the experimental conditions correspond.

The forced visualizations were made first. The unforced test conditions were created to cover (+/- 5%) the range of blowing ratios used during the forced tests. Table 5-5 shows the conditions of the unforced visualizations. The actual blowing ratio during these tests is compared to the nominal one. One can appreciate the precision brought by the flow meters. The standard deviation of the blowing ratio during the test is also given. It shows that the flow is very stable: the standard deviation is under 0.5% for the highest blowing ratio. The unforced JICF visualizations consisted in taking 3 sets of 32 images at a frame rate of 30Hz (limit of the system) for each blowing ratio.

The same blowing ratios were explored for the CTA survey. BR = 0.700, 0.800, 0.900 were also explored with the hot wire. Four positions were surveyed at each blowing ratio: 1) jet exit (A); 2) above the jet exit (B, C); 3) behind the jet (D, E); 4) far field of the jet (F, G, H, I, J). Figure 5-12 shows these positions on an image of a grid target, which shows the scale of an image. An image contains: 1) the jet; 2) half a diameter in front of the jet to be able to visualize the horseshoe vortices upstream of the jet; and 3) 5 diameters behind the jet to observe the evolution of the jet flow. Notice the two white vertical marks showing the position of the jet on the image.
Table 5-5: Unforced JICF visualizations conditions.

<table>
<thead>
<tr>
<th>Nominal BR</th>
<th>Actual BR</th>
<th>Standard Deviation of BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.150</td>
<td>0.1450</td>
<td>0.0010</td>
</tr>
<tr>
<td>0.175</td>
<td>0.1743</td>
<td>0.0010</td>
</tr>
<tr>
<td>0.188</td>
<td>0.1885</td>
<td>0.0010</td>
</tr>
<tr>
<td>0.200</td>
<td>0.1989</td>
<td>0.0010</td>
</tr>
<tr>
<td>0.225</td>
<td>0.2238</td>
<td>0.0010</td>
</tr>
<tr>
<td>0.250</td>
<td>0.2511</td>
<td>0.0014</td>
</tr>
<tr>
<td>0.275</td>
<td>0.2738</td>
<td>0.0027</td>
</tr>
<tr>
<td>0.300</td>
<td>0.3032</td>
<td>0.0032</td>
</tr>
<tr>
<td>0.313</td>
<td>0.3125</td>
<td>0.0033</td>
</tr>
<tr>
<td>0.365</td>
<td>0.3652</td>
<td>0.0031</td>
</tr>
<tr>
<td>0.400</td>
<td>0.4009</td>
<td>0.0032</td>
</tr>
<tr>
<td>0.425</td>
<td>0.4245</td>
<td>0.0034</td>
</tr>
<tr>
<td>0.465</td>
<td>0.4636</td>
<td>0.0035</td>
</tr>
<tr>
<td>0.533</td>
<td>0.5310</td>
<td>0.0037</td>
</tr>
<tr>
<td>0.600</td>
<td>0.5999</td>
<td>0.0041</td>
</tr>
</tbody>
</table>

Figure 5-12: Target with positions of the CTA surveys.

Table 5-6 shows the experimental conditions of the JICF CTA surveys for the blowing ratios corresponding to the cases which will be studied more precisely. It compares the nominal blowing ratio, the actual blowing ratio and the velocity measured by the hotwire at the survey point. At the jet exit position (A) this velocity should correspond to $W_J$, the vertical component of the velocity out of the jet. At that point a straight single wire probe was used. At the other points, a bent single wire probe was used. Therefore if the shape and the spectrum of the velocity are to be usable, the velocity value may not always be relevant. For each of these tests, a time record of the velocity was taken and the power spectrum was computed to corroborate the events we saw with frequencies in the spectra.
The CTA experiments were run at a sampling frequency of 5kHz with a 2kHz low pass de-aliasing filter over 20s (i.e. 100,000 points).

Table 5-6: Unforced JICF CTA tests conditions.

<table>
<thead>
<tr>
<th>(x/D_j, z/D_j)</th>
<th>Nominal BR</th>
<th>Actual BR</th>
<th>Std Dev of BR</th>
<th>U_{wire}/U_∞</th>
<th>RMS</th>
<th>Sk</th>
<th>Ku</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (0.00, 0.00)</td>
<td>0.150</td>
<td>0.1510</td>
<td>0.0013</td>
<td>0.1357</td>
<td>0.0168</td>
<td>0.7602</td>
<td>2.8996</td>
</tr>
<tr>
<td>B (0.00, 0.25)</td>
<td>0.150</td>
<td>0.1498</td>
<td>0.0004</td>
<td>0.2321</td>
<td>0.1139</td>
<td>-0.1158</td>
<td>1.4110</td>
</tr>
<tr>
<td>D (1.00, 0.25)</td>
<td>0.150</td>
<td>0.1497</td>
<td>0.0014</td>
<td>0.1797</td>
<td>0.0263</td>
<td>1.6187</td>
<td>7.7362</td>
</tr>
<tr>
<td>F (3.50, 0.75)</td>
<td>0.150</td>
<td>0.1518</td>
<td>0.0013</td>
<td>0.6709</td>
<td>0.0958</td>
<td>-2.1372</td>
<td>8.1500</td>
</tr>
</tbody>
</table>

Several preliminary remarks can be made on the CTA experiments. First very low frequency disturbances were noticed in the velocity surveys of the steady state experiments, particularly at low blowing ratios (see Figure 5-13 and Figure 5-14). During these experiments, an air conditioning unit was installed in the wind tunnel room, which did not have air conditioning previously. The experiments are realised at very low wind tunnel velocity, since $U_∞=1.6m/s$ when the range of the wind tunnel is 0 to 30m/s, and very low jet velocity as well since the blowing ratios are under 1. It followed that when the fan of the air conditioning unit kicked on, it disturbed the flow in the
wind tunnel room. Since the wind tunnel is an open loop, these disturbances were felt in the wind tunnel flow. For the experiments where disturbances appeared, the power spectrum was recomputed over the part of the record not influenced. Most of the time the power spectrum was not affected as Figure 5-13 shows. Luckily the frequencies of these disturbances are really low, and do not affect the range of frequency of interest. However a few records were too bad to recover any information and were disregarded (see Figure 5-14). In the following only partial time records will be shown to emphasize on the periodic phenomena related to the JICF, which have higher frequencies than these perturbations.

Figure 5-13: Example of disturbance due to the air conditioning system at BR = 0.150, position F (3.50, 0.75): (a) time record, (b) power spectrum, (c) corrected power spectrum.

Figure 5-14: Example of disturbance due to the air conditioning system at BR = 0.175, position B (0.00, 0.25): (a) time record, (b) power spectrum.

The second remark mainly concerns the position D (1.00, 0.25). At this position situated right behind the jet some CTA records seem rectified as shown on Figure 5-15. This is confirmed by the values of the Skewness and the Kurtosis associated to these time records (see Table 5-6). For a normal/gaussian distribution the value of the Skewness is zero and the Kurtosis value is 3. The fact that these records are rectified confirms the presence of vorticity/recirculation behind the jet. It also compromises the spectra computed from these records, which do not usually show any specific frequencies as it will be seen later on and which will be disregarded.
Finally it has to be noticed that the CTA velocity records are not fully relevant by their values (except for position A (0.00, 0.00) to a certain extent) since single wire probes were used and the flow is 3-dimensional. However, they are relevant with respect to the frequency content, which are related to periodic flow phenomena.

As the color code shows in Table 5-5 and Table 5-6, five cases were set apart, corresponding to five different flow behaviours. For some of these cases, two blowing ratios were chosen to illustrate and this for two reasons: 1) better illustration of the flow behaviour -unexpected events, slightly different flow behaviour- and 2) commonality with the forced JICF spectra and visualization study -BR=0.188 common BR\text{ref} and lowest one; BR=0.365 and BR=0.465 close to the two BR\text{m} (0.35 and 0.45) studied in the forced tests.

The five flow behaviours are divided as follows:

Case 1: BR = 0.150 to 0.200: Kelvin Helmholtz instability.

Case 2: BR = 0.225 to 0.250: Horseshoe vortex transport.

Case 3: BR = 0.275 to 0.300: Detachment behind the jet, horseshoe transport and first ring formation.

Case 4: BR = 0.313 to 0.465: Ring vortex formation.

Case 5: BR = 0.533 to 0.900: Fully detached ring vortex.
5.2.2.2. Case 1: BR = 0.150 and BR = 0.188

Figure 5-16: Unforced vertical jet in cross flow at BR=0.150; Visualizations (f=30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

D_J=25.4mm, U_∞=1.6m/s, δ/D_J=0.59
Figure 5-17: Unforced vertical jet in cross flow at $BR_m=0.188$; Visualizations ($f=30\text{Hz}$) at jet mid-plane, $x$-$z$ (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

$D_J=25.4\text{mm}, U_\infty=1.6\text{m/s}, \frac{\delta}{D_J}=0.59$
Figure 5-16 (1 to 20) shows the evolution of the flow at BR = 0.150 over a period of 20 frames (frame rate \( f_r = 30\text{Hz} \)). The jet is marked on all images by the two white vertical lines representing the walls of the jet. One can see that the flow is very stable and cover is brought to the wall up to 3 diameters behind the jet. The flow is characterised by a horseshoe vortex always present in front of the jet. The jet is highly bent by the cross flow, which is expected since the blowing ratio is very low. About two diameters behind the jet an oscillation develops in the top shear layer of the jet. It is a Kelvin-Helmholtz-like instability which leads to the break up of the jet cover approximately 4 diameters behind the jet.

Figure 5-17 (1 to 20) shows the same evolution at \( BR = 0.188 \). The flow is very similar but small differences can be noticed: 1) the horseshoe vortex is sometimes doubled at this blowing ratio; 2) the jet cover is slightly thicker which is expected since the jet flow rate is higher; 3) the Kelvin-Helmholtz instability and therefore the jet cover break up seem to occur slightly earlier, which can also be expected (higher blowing ratio causes higher shear, which leads to a more unstable flow).

The following images show the positions in reference to the flow where the hot wire probes were placed during the CTA survey.

![Figure 5-18: CTA survey positions for (a) BR = 0.150; (b) BR = 0.188](image)

Figure 5-16 (e) shows the power spectra taken at \( BR = 0.150 \). The spectrum at B does not reveal any discrete frequencies, which is also indicated by the sample of the corresponding time record (Figure 5-16 (b)). It may be explained by the position of B, right at the limit between the jet and the cross flow. If the probe is in the cross flow, which is laminar it may not display any discrete frequencies. The time records at A, D and most importantly F show some oscillation. For F it can be explained by the positioning at the shedding of the flow. The probe is picking up the oscillation due to the Kelvin Helmholtz instability.
Figure 5-17 (e) shows the spectra at the different positions for BR = 0.188. Again, no discrete frequency is seen at position B. A look at Figure 5-17 (c) shows the record at D is rectified. This is confirmed by the Skewness and Kurtosis values available in Table 5-6. The Skewness at D is 4.071 and the Kurtosis is 35 compared to 0 and 3 for a normal distribution. The power spectrum of this record is consequently not relevant and can be disregarded. However this rectification tells us there is some recirculation behind the jet, which was not obvious on the images of the flow and which did not seemed to be the case at BR = 0.150. The F time record (Figure 5-17 (d)) shows an oscillation similar to the one at BR = 0.150, but with multiple discrete frequency content.

Table 5-7 shows the frequencies relevant to the flow at BR = 0.150 and BR = 0.188. The orange filled cell means that the record is rectified. The frequencies at the jet exit are pretty close from one blowing ratio to another, which can be expected since the two blowing ratios are close. The frequency of 160Hz seems to be a frequency of the jet air power supply. The shape of the peak (see Figure 5-16 and Figure 5-17 (e)) reminds the shape of the peaks seen in the spectra of the jet without cross flow (see Figure 5-6 and Figure 5-7). Right above the jet (B) no frequency is picked up. Behind the jet (D) two frequencies are observed which may correspond to a recirculation that is not visible on the images. It can be noticed that one of the frequency of 18Hz is common to BR=0.150 and BR=0.188. In the far field, the frequencies observed vary. As observed on Figure 5-16 (e) and Figure 5-17 (e), the shedding is slightly different between the two BR, which explains the difference on the frequencies. From the time records at this position (Figure 5-16 (d) and Figure 5-17 (d)), at BR=0.150 the oscillation is very regular (almost sinusoidal), when at BR=0.188 more frequencies seems involved, as if there were two alternating modes. This could explain the bulge on the spectrum at F.

<table>
<thead>
<tr>
<th>Position</th>
<th>Frequencies [Hz] at BR = 0.150</th>
<th>Frequencies [Hz] at BR = 0.188</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>29, 42, 60, 160</td>
<td>29, 46, 56, 60, 160</td>
</tr>
<tr>
<td>B</td>
<td>Ø</td>
<td>Ø</td>
</tr>
<tr>
<td>D</td>
<td>18, 28</td>
<td>18, 36</td>
</tr>
<tr>
<td>F</td>
<td>14, 28, 40, 55</td>
<td>9.5, [15-20] bulge</td>
</tr>
</tbody>
</table>

One can notice that the electrically induced frequencies were not introduced in this table. The harmonics of 60Hz (electrical power supply frequency) are not representative of the flow and they are very week.
5.2.2.3. Case 2: BR = 0.250

Figure 5-19: Unforced vertical jet in cross flow at BR=0.250; Visualizations (f=30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

\[ DJ = 25.4\text{mm}, \ U_\infty = 1.6\text{m/s}, \ \delta/D_J = 0.59 \]
The second type of flow is characterised by the appearance of a new phenomenon: the transport of the horseshoe vortex by the jet. It is a transition mode. Two phases can be encountered: either the flow is similar to Case 1, or the horseshoe vortex is blown over the jet. In the first case, which can be illustrated by Figure 5-20, the Kelvin-Helmholtz-like instability appears earlier than in Case 1 and the break up of the jet happens closer to the jet exit too (3 diameters). When the horseshoe vortex gets transported, as shown by the sequence on Figure 5-19, the transported horseshoe interacts with the Kelvin-Helmholtz instability which leads to an even earlier break up (1 ½ diameter behind the jet). This phenomenon does not seem to be regular at this blowing ratio. A zone of recirculation behind the jet is now visible where it was not at lower blowing ratio. There was evidence (rectified hot wire signal) at BR=0.188, but at this blowing ratio it is clearly visible on the visualization images.

Figure 5-20 shows the positions where CTA measurements were taken at BR=0.250, relatively to the visualization of the flow. This image was taken while the horseshoe vortex was stable at the leading end of the jet. It clearly appears that B is in the top shear layer of the jet and if there is a transport of the horseshoe, the hot wire sensor should be affected by it. D is in the rollover region behind the jet, and F is at the break up region of the flow.

Figure 5-20: CTA survey positions at BR = 0.250

Figure 5-19 shows the power spectra (e) at the various locations as well as the associated time records ((a) to (d)). At D, behind the jet, the record is once again rectified. The Skewness and Kurtosis are respectively Sk=2.3011 and Ku=9.1398 indicating a separation region. The record displays more fluctuation than that at BR =
0.188, which can be expected since the blowing ratio is higher. All records display some oscillation. The frequency seems to be different at A than at B, D and F, for which the frequency shown but the sample record seem close. However, only the spectra at B and F show some distinct frequencies.

Table 5-8 displays the significant frequencies of the flow. At the jet exit the spectrum does not deliver any noticeable frequencies. Above the jet, in the shear layer, a frequency of 10.5Hz and its harmonic 21Hz are observed. They are certainly characteristics of the shear layer since it was noticed that the transport of the horseshoe vortex is mostly erratic according to the visualizations. At F the spectrum is pretty similar to the one at BR=0.188 (see Figure 5-17 (e)) and the frequency of 9Hz is common to both spectra. 9Hz could be a characteristic of the Kelvin Helmholtz-like instability for these two blowing ratios.

Table 5-8: Significant frequencies of the flow at BR = 0.250.

<table>
<thead>
<tr>
<th>Position</th>
<th>Frequencies [Hz] at BR = 0.250</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Ø</td>
</tr>
<tr>
<td>B</td>
<td>10.5, 21, 50</td>
</tr>
<tr>
<td>D</td>
<td>Ø</td>
</tr>
<tr>
<td>F</td>
<td>9</td>
</tr>
</tbody>
</table>

5.2.2.4. Case 3: BR = 0.300

This third Case is also a transition between two distinct patterns of the flow. For the first time an asymmetric ring vortex appears at the exit of the jet, as well as a distinct separation and detachment right behind the jet, as can be seen on the sequence of visualization images on Figure 5-21 (1-20). But there are also occurrences of horseshoe vortex transport (see Figure 5-22) as in the previous case. Figure 5-21 (1-20) shows the ring formation process. The front part of the ring appears to be forming inside the jet tube while the back part forms downstream and above the jet. The rear part of the ring gets vorticity from the interaction of the two shear layers bent behind the jet and from the recirculation region. The horseshoe vortex seems to get pulled into the jet occasionally. The asymmetric ring vortex is periodically convected away from the jet, and when the front shear layer rollup is convected downstream, it usually creates a break behind the jet, which leads to a detachment of the flow behind the jet. In the far field the loose ring vortex formation can be seen rotating in a counter-clockwise manner.

Figure 5-22 shows the CTA survey points taken at BR = 0.300. G appears out of the jet flow on this image but as the vortex ring moves by it, the probe is inside the jet fluid flow.
Figure 5-21: Unforced vertical jet in cross flow at $BR_m=0.300$; Visualizations ($f_r=30\text{Hz}$) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

$D_J=25.4\text{mm}, U_\infty=1.6\text{m/s}, \delta/D_J=0.59$
Figure 5-22 (e) shows the power spectra at the various locations showed on Figure 5-22. A look at the time record shows (see Figure 5-21 (a) to (d)) that the signal behind the jet (C) is rectified ($Sk=2.3167$, $Ku=9.4398$) in the separation region. The signals from A and C show clear oscillations at similar frequencies (10 oscillations in a second at A, 8 at C). The records at D and G also present oscillations. They are not so clear as the ones at A and C. This could be because of the position behind the jet, in a zone of recirculation and sometimes detachment, and in the far field where the mixing is more important between the jet flow and the cross flow. The spectra of the non-rectified (from A, C, and G) signals do not all present clear peaks at the discrete frequencies that are observable in the time-records. For example the signal from G clearly shows two discrete frequency peaks, while the spectra from A and C do not. This is so because a general inspection of the full time-records reveals that the periodic behavior in A and C is intermittent, while that in G is more regular (see Figure 5-23). This intermittency is evident in the time-records of other cases and warrants analysis using a wavelet transform analysis rather than a Fourier analysis. It is recommended that this is done in the future extension of this work.

Table 5-9 displays the frequencies observed at the different positions. At the jet exit a slight bulge is noticed between 7Hz and 14Hz. When the horseshoe vortex seems to get inside the jet during the formation of the ring vortices, the center of the jet is close to the shear layer and the probe could pick up frequencies present in this shear layer. Over the jet, the spectrum shows a large bump centered around 10Hz. This may be linked to the ring formation on one hand and to the fact that the probe can get fully into the wind tunnel flow (see Figure 5-22). In the
far field, it seems the frequencies are linked to the shedding of the ring vortex of the jet flow. Indeed, the frequencies found are comparable to the ones found in the two previous cases.

Figure 5-23: CTA time records at BR=0.300 at (a) A, (b) C, (c) G.

Table 5-9: Significant frequencies of the flow at BR = 0.300.

<table>
<thead>
<tr>
<th>Position</th>
<th>Frequencies [Hz] at BR = 0.300</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>[7-14] bulge</td>
</tr>
<tr>
<td>C</td>
<td>10 bump</td>
</tr>
<tr>
<td>D</td>
<td>Ø</td>
</tr>
<tr>
<td>G</td>
<td>9, 15, [23-29] bulge</td>
</tr>
</tbody>
</table>

5.2.2.5. Case 4: BR = 0.365 and BR = 0.465

This fourth case is characterised by constant ring formation at the exit of the jet, whether part of it is inside the jet or outside. Figure 5-24 (1 to 20) shows the formation of ring vortices at BR=0.365. If compared to Figure 5-21 (1 to 20) this formation is pretty close to the one in the third case at BR=0.300. However the horseshoe vortex entrainment over the top of the jet is no-longer observed. The front of the ring vortex appears to be forming mostly inside the jet tube with a prominent rear part outside. Figure 5-24 (2-3 or 7-8 among others) shows a counter-clockwise rotation of the ring vortex in the far field, but much weaker than what was already observed in Case 3.

At BR=0.465 the flow is pretty similar to BR=0.365 as can be seen on Figure 5-25 (1 to 20). The ring vortices are injected a little higher into the free-stream and the dome of the jet is slightly flatter. More importantly the leading part of the rings starts forming slightly outside of the jet (Figure 5-25 2, 7, 12). The back part of the ring is still very prominent. It will be interesting to see if the tests at BRm = 0.35 and BRm = 0.45 will also be similar. It can be noticed that at these blowing ratios, in spite of the rings, the jet still brings a fair cover to the surface. It is not a full cover like in Cases 1, 2 or 3 (sometimes), but coverage still exists. Further study would tell if it is enough or not. One can notice that the protection at 0.465 seems slightly better than at 0.365 at least from the visualizations presented here.
Figure 5-24: Unforced vertical jet in cross flow at $BR_m=0.365$; Visualizations ($f_r=30\text{Hz}$) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

$D_J=25.4\text{mm}$, $U_\infty=1.6\text{m/s}$, $\delta/D_J=0.59$
Figure 5-25: Unforced vertical jet in cross flow at $BR_m=0.465$; Visualizations ($f_v=30\text{Hz}$) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

$D_j=25.4\text{mm}$, $U_\infty=1.6\text{m/s}$, $\delta/D_j=0.59$
An interesting point is that higher blowing ratios are known to give a better spread on the y-z plane. A few visualizations were made on this plane but the flow meter system was not yet in place. The flow conditions not being precisely known, those tests have not been included here.

Figure 5-26 shows again the similarity between the two blowing ratios 0.365 and 0.465 and displays the positions of the CTA surveys presented on Figure 5-24 and Figure 5-25.

![Figure 5-26: CTA survey positions at (a) BR = 0.365; (b) BR = 0.465](image)

Figure 5-24 (e) displays the power spectra at the various locations for BR=0.365. The study of the time records (see Figure 5-24 (a) to (d)) shows time record in the separation region behind the jet (D, (c)) is rectified which is confirmed by the Skewness (Sk=1.2667) and the Kurtosis (Ku = 4.2693). The four time records present oscillating profiles. At A and C the oscillations are clean and comparable to the ones shown at BR=0.300 for the same positions. D and H show the presence of smaller scales, which is indicative of the generation of turbulent fluctuations. D is a zone of recirculation and separation, H is in the mixing region.

Samely Figure 5-25 shows the power spectra (e) at the different locations for BR = 0.465 as well as partial time records ((a) to (d)) at those locations. The time record behind the jet appears rectified but in this case the Skewness (0.9579) and the Kurtosis (3.4117) do not really corroborate this fact. The partial time records show oscillations at all positions. The sample at C (Figure 5-25 (b)) shows a clean oscillation which looks like the one at BR=0.365 (and as BR=0.300) but is actually different (almost inverted). Other than that the samples seem different from BR=0.365. However, a look at the spectrum displays a good similarity between the two cases, except maybe as the position A is concerned. The spectra have the same trend but there is more energy in the spectrum at BR=0.465, which translates it to the right. This is to be expected since the velocity of the jet is higher leading to higher shear,
which produces fluctuations at smaller scales (i.e. higher frequencies). Case 4 covers a broad range of blowing ratio compared to the other cases.

Table 5-10 shows the distinctive frequencies of these spectrum tests. Most tests do not actually reveal much in terms of discrete frequencies, but this can be deceiving due to intermittency, and warrants wavelet analysis as mentioned before. The spectra move toward higher frequencies, there is more turbulence and the spectra get consequently broader. Very broad peaks can be noticed rather than clear discrete frequencies. The spectra show once again the similarity between BR=0.365 and BR=0.465 as the frequencies right above the jet exit (at C) are comparable. The broad peak is slightly smaller at the higher blowing ratio. These frequencies are around 11 to 17Hz and are linked to the ring vortex formation and shedding in these cases as well as the cross flow. At BR = 0.465 they are found back in the far field of the jet.

Table 5-10: Significant frequencies at BR = 0.365 and BR = 0.465.

<table>
<thead>
<tr>
<th>Position</th>
<th>Frequencies [Hz] at BR = 0.365</th>
<th>Frequencies [Hz] at BR = 0.465</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>[10-12] bulge</td>
<td>Ø</td>
</tr>
<tr>
<td>C</td>
<td>[11.5-17] bulge</td>
<td>[12-16.5] bulge</td>
</tr>
<tr>
<td>D</td>
<td>Ø</td>
<td>Ø</td>
</tr>
<tr>
<td>H</td>
<td>Ø</td>
<td>[10-17] bulge</td>
</tr>
</tbody>
</table>

5.2.2.6. Case 5: BR = 0.600

The fifth and last Case of the JICF flow in steady state is a fully detached ring flow. Figure 5-27 (1 to 20) shows ring vortex formation at BR=0.600 which was the highest blowing ratio studied through visualizations for the unforced case and which is right below the highest high blowing ratio used in the forced cases (BR_{hmax} = 0.7125 (nominal value)). Different kinds of rings can be noticed. Some rings are big and flat as on Figure 5-27 9, 10, 16, whereas other rings are small and have less space between each other like Figure 5-27 2, 19, 20. In both situations the rings are more distinct and more symmetrical than before. The front part and the back part are of comparable size, while in Case 4, the ring is highly disproportionate with a very prominent back part. In comparison with Case 4, it can also be said that the flow in Case 5 is fully detached and does not bring cover to the wall. On some of the images (Figure 5-27 12, 17 among others) one can notice evidence of wake vortices (evoked in 1.3) behind the jet. The jet is seen like a cylinder by the cross flow. The sequence of images on Figure 5-27 (1 to 20) also displays a clockwise rotation of the ring vortices while they make their way in the far field.
Figure 5-27: Unforced vertical jet in cross flow at $BR_m = 0.600$; Visualizations ($f_r = 30\text{Hz}$) at jet mid-plane, $x$-$z$ (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

$D_J = 25.4\text{mm}$, $U_\infty = 1.6\text{m/s}$, $\delta/D_J = 0.59$
Figure 5-28 shows the various CTA positions studied for this case. The C position is seeing passing ring vortices. D was in the other cases in the zone of recirculation behind the jet. It seems right out of it in this case. As for the I position, it is on the path of the rotating ring vortexes in the far field.

Figure 5-28: CTA survey positions at BR = 0.600

Figure 5-27 (e) shows the power spectra at various locations. The study of the time records (see Figure 5-27 (a) to (d)) shows that the flow involves higher levels of velocity fluctuations, which the RMS (Table 5-6) corroborates. Above the jet and behind it the records are slightly rectified (indicating strong intermittency or flow reversals). Looking at the Skewness and the Kurtosis the survey above the jet (Sk = 1.0566, Ku = 5.1970) is actually more rectified than the one downstream of the jet (Sk = 0.4188, Ku = 2.5358). This confirms that that the position C is on the front ring vortex way, and that the position D is now almost out of the recirculation. The partial time records of A and C at BR=0.600 can be compared to those of A and C at BR=0.465 (Figure 5-25 (a) and (b)). Even if the profiles at BR=0.600 seem to have higher frequencies, the shapes of the oscillations have common features.

Table 5-11: Significant frequencies of the flow at BR = 0.600

<table>
<thead>
<tr>
<th>Position</th>
<th>Frequencies [Hz] at BR = 0.600</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>25, 50</td>
</tr>
<tr>
<td>D</td>
<td>Ø</td>
</tr>
<tr>
<td>I</td>
<td>Ø</td>
</tr>
</tbody>
</table>
Table 5-11 shows that there is no frequency, which is prominent downstream of the jet (position D and I) as the spectra on Figure 5-27 (e) show. However in the whereabouts of the front ring vortex formation (A, C) a frequency around 20Hz, which is associated with the ring vortex. Since the spectra survey at C is not fully reliable, that is all that can be said.

5.3. Forced Jet in Cross Flow

5.3.1. Presentation

The forced JICF was first surveyed using CTA with an X-probe. However these tests were run without the flow meter system. The actual conditions of the flow were not known well enough for the results to be presented in this thesis. Once the flow meter system was implemented, LASER sheet visualizations of the x-z plan were done, followed by CTA surveys at four positions in the flow, the selection of which was guided by the visualizations.

The parameters for the forced tests are defined in Chapter 2. Two mean blowing ratios $BR_m$ were studied: (1) $BR_m = 0.35$ and (2) $BR_m = 0.45$. For (1) one low blowing ratio ($BR_l = 0.1875$) and two peak-to-peak blowing ratios (respectively $BR_{pp} = 0.15$ and $BR_{pp} = 0.25$) were explored with visualizations for three duty cycles ($DC = 0.25$, $DC = 0.50$, $DC = 0.70$) and four forcing frequencies ($f_f = 0.5Hz$, $f_f = 1.0Hz$, $f_f = 5.0Hz$, $f_f = 10.0Hz$). For (2) visualizations were conducted at one low blowing ratio ($BR_l = 0.1875$) for two duty cycles ($DC = 0.50$ and $DC = 0.70$) and four forcing frequencies ($f_f = 0.5Hz$, $f_f = 1.0Hz$, $f_f = 5.0Hz$, $f_f = 10.0Hz$); and at one peak-to-peak blowing ratio ($BR_{pp} = 0.25$) also for two duty cycles ($DC = 0.25$ and $DC = 0.50$) and four forcing frequencies ($f_f = 0.5Hz$, $f_f = 1.0Hz$, $f_f = 5.0Hz$, $f_f = 10.0Hz$). The choice of parameters for (2) was made keeping in mind that too high a $BR_h$ is not in the best interest for film cooling. This reduced the field of study and the time spent on the experiments as well as the amount of data to process.

The forced JICF visualizations were run differently from the unforced cases. For each set of parameters phase locked images were taken at precise positions in the forcing cycle. For low forcing frequencies (0.5 and 1.0Hz) a set of 10 phase-locked images was taken at 10 positions equally spaced in the forcing cycle. For high forcing frequencies (5.0 and 10.0Hz) a set of 10 phase-locked pictures was taken at 50 positions equally spaced in the cycle. Phase averaging can be applied on these pictures to get an idea of the cover behaviour of the flow. However single pictures are better to study the flow phenomena.

The flow meter system was used to set the high and low blowing ratios corresponding to each selected case. It was also used to monitor the actual flow conditions during the tests. The valve signal and the flow meters’ signals
were recorded for each set of parameters. Using the valve signal, a precise phase averaging of the flow meters signals was computed to display a phase average cycle with the actual position in the cycle where the picture was taken. This phase average cycle was used to compute the actual mean, low, high and peak-to-peak blowing ratios as well as the actual duty cycle during the test.

After studying the pictures obtained during these visualizations, four positions in the flow were chosen to conduct CTA surveys. These four positions were identical for all the sets of experiments to make experimentation easier. They were chosen in order to cover as best as possible the range of settings. The positions (see Figure 5-12) were chosen as follows: 1) A (0.00, 0.00) at the jet exit; 2) C (0.00, 0.50) above the jet exit; 3) D (1.00, 0.25) behind the jet; 4) H (3.50, 1.25) in the far field.

Figure 5-12 and Figure 5-13 respectively show the flow conditions during the visualization experiments as well as the parameters sets for which CTA surveys were taken. One can appreciate the precision of the system. It can be noticed that at high forcing frequency the flow conditions differ slightly from the nominal conditions. Indeed at high forcing frequency, especially for DC = 0.25 and DC = 0.70, the solenoid valve is operating close to its limitations (30Hz). Moreover at these frequencies, as will be shown later on, the flow does not have time to settle, and acoustic frequencies of the system play a role. Overall, the precision of the system is quite good as Table 5-12, Table 5-13, and Table 5-14 illustrate by comparing actual values of BR<sub>m</sub> to the nominal ones.

### Table 5-12: Flow conditions of the visualizations at BR<sub>m</sub> = 0.35

<table>
<thead>
<tr>
<th>(f_0) [Hz]</th>
<th>BR&lt;sub&gt;m&lt;/sub&gt;</th>
<th>BR&lt;sub&gt;f&lt;/sub&gt;</th>
<th>BR&lt;sub&gt;h&lt;/sub&gt;</th>
<th>BR&lt;sub&gt;pp&lt;/sub&gt;</th>
<th>DC to get</th>
<th>DC to set</th>
<th>CTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aim at 0.350</td>
<td>0.1875</td>
<td>0.8375</td>
<td>0.650</td>
<td>0.250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.388</td>
<td>0.1832</td>
<td>0.9407</td>
<td>0.758</td>
<td>0.270</td>
<td>0.25</td>
<td>No</td>
</tr>
<tr>
<td>1.0</td>
<td>0.396</td>
<td>0.1830</td>
<td>0.9213</td>
<td>0.738</td>
<td>0.289</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>0.389</td>
<td>0.1878</td>
<td>0.7623</td>
<td>0.574</td>
<td>0.350</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>0.377</td>
<td>0.1902</td>
<td>0.6145</td>
<td>0.424</td>
<td>0.440</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Aim at 0.350</td>
<td>0.1875</td>
<td>0.5125</td>
<td>0.325</td>
<td>0.500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.355</td>
<td>0.183</td>
<td>0.520</td>
<td>0.337</td>
<td>0.510</td>
<td>0.25</td>
<td>Yes</td>
</tr>
<tr>
<td>1.0</td>
<td>0.358</td>
<td>0.183</td>
<td>0.520</td>
<td>0.337</td>
<td>0.520</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>0.351</td>
<td>0.185</td>
<td>0.518</td>
<td>0.333</td>
<td>0.500</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>0.350</td>
<td>0.193</td>
<td>0.512</td>
<td>0.318</td>
<td>0.492</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Aim at 0.350</td>
<td>0.1875</td>
<td>0.4196</td>
<td>0.232</td>
<td>0.700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.354</td>
<td>0.189</td>
<td>0.422</td>
<td>0.233</td>
<td>0.709</td>
<td>0.25</td>
<td>No</td>
</tr>
<tr>
<td>1.0</td>
<td>0.357</td>
<td>0.190</td>
<td>0.422</td>
<td>0.232</td>
<td>0.718</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>0.352</td>
<td>0.202</td>
<td>0.419</td>
<td>0.217</td>
<td>0.690</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>0.365</td>
<td>0.233</td>
<td>0.419</td>
<td>0.186</td>
<td>0.711</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-12 cont.
The CTA surveys were made with the same sampling conditions as in the unforced JICF cases: sampling frequency 5kHz with a low pass filter of 2kHz over 20s (or 100,000 points). The hot wire probe signal was recorded along with the solenoid valve signal and the flow meters’ signals. Using the valve signal a precise phase averaging of the signals was done to get a phase-averaged cycle of the blowing ratio and of the hot wire velocity measurement. Mean, high, low and peak–to-peak blowing ratios were computed as well as the mean, the high and the low velocity and the actual duty cycle. It should be noted that the velocity measurement is only valid in terms of amplitude at the jet exit. However the velocity measurement profiles at the other positions can be interesting. The power spectra of the velocity measurement, the power spectra of the phase averaged velocity measurement cycle and the power
spectra of the velocity measurement without the phase-averaged component of the signal were computed for each set of parameters.

Table 5-13: Flow conditions of the visualizations at BR\(_m\) = 0.45

<table>
<thead>
<tr>
<th>(f_t) [Hz]</th>
<th>BR(_m)</th>
<th>BR(_l)</th>
<th>BR(_h)</th>
<th>BR(_{pp})</th>
<th>DC to get</th>
<th>DC to set</th>
<th>CTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aim at</td>
<td>0.450</td>
<td>0.1875</td>
<td>0.7125</td>
<td>0.525</td>
<td>0.500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.460</td>
<td>0.196</td>
<td>0.715</td>
<td>0.519</td>
<td>0.510</td>
<td>0.25</td>
<td>Yes</td>
</tr>
<tr>
<td>1.0</td>
<td>0.466</td>
<td>0.197</td>
<td>0.716</td>
<td>0.519</td>
<td>0.519</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>0.456</td>
<td>0.203</td>
<td>0.713</td>
<td>0.510</td>
<td>0.495</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>0.458</td>
<td>0.221</td>
<td>0.707</td>
<td>0.486</td>
<td>0.488</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

| Aim at         | 0.450     | 0.1875  | 0.5625  | 0.375      | 0.700     |           |     |
| 0.5            | 0.457     | 0.180   | 0.571   | 0.391      | 0.708     | 0.25      | Yes |
| 1.0            | 0.458     | 0.182   | 0.568   | 0.387      | 0.716     | 0.25      |     |
| 5.0            | 0.451     | 0.199   | 0.570   | 0.372      | 0.680     | 0.15      |     |
| 10.0           | 0.471     | 0.246   | 0.568   | 0.321      | 0.700     | 0.05      |     |

| Aim at         | 0.450     | 0.3875  | 0.6375  | 0.250      | 0.250     |           |     |
| 0.5            | 0.434     | 0.363   | 0.635   | 0.272      | 0.262     | 0.25      | Yes |
| 1.0            | 0.436     | 0.361   | 0.632   | 0.271      | 0.274     | 0.25      |     |
| 5.0            | 0.428     | 0.360   | 0.613   | 0.254      | 0.271     | 0.15      |     |
| 10.0           | 0.428     | 0.359   | 0.596   | 0.237      | 0.290     | 0.05      |     |

| Aim at         | 0.450     | 0.3250  | 0.5750  | 0.250      | 0.500     |           |     |
| 0.5            | 0.442     | 0.309   | 0.570   | 0.261      | 0.511     | 0.25      | Yes |
| 1.0            | 0.444     | 0.308   | 0.568   | 0.260      | 0.521     | 0.25      |     |
| 5.0            | 0.438     | 0.310   | 0.564   | 0.254      | 0.505     | 0.15      |     |
| 10.0           | 0.436     | 0.311   | 0.557   | 0.246      | 0.510     | 0.05      |     |

Table 5-14: Mean and standard deviation of BR\(_m\)

<table>
<thead>
<tr>
<th></th>
<th>Number of tests</th>
<th>BR(_m)</th>
<th>StdDev of BR(_m)</th>
<th>Nominal BR(_m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visualizations</td>
<td>36</td>
<td>0.3593</td>
<td>0.0112</td>
<td>0.35</td>
</tr>
<tr>
<td>CTA</td>
<td>80</td>
<td>0.3554</td>
<td>0.0044</td>
<td>0.35</td>
</tr>
<tr>
<td>Total</td>
<td>116</td>
<td>0.3566</td>
<td>0.0074</td>
<td></td>
</tr>
<tr>
<td>Visualizations</td>
<td>16</td>
<td>0.4478</td>
<td>0.0138</td>
<td>0.45</td>
</tr>
<tr>
<td>CTA</td>
<td>64</td>
<td>0.4583</td>
<td>0.0066</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>0.4562</td>
<td>0.0094</td>
<td></td>
</tr>
</tbody>
</table>

The harmonic frequencies of perfectly square signals corresponding to our forcing conditions (forcing frequency \(f_t\) and duty cycle DC) were computed theoretically (see Table 5-15). Frequencies corresponding to a forcing set are in the flow for whatever position the probe is set and show up on the spectra (see for example Figure
These frequencies can hide other frequencies, which can be related to the structures of the flow. That is why the spectrum of the phase-averaged cycle is taken off the raw spectrum to give the spectrum of the record without the forcing linked components.

**Table 5-15: Harmonic frequencies [Hz] of perfect forced signals at the various forcing conditions.**

<table>
<thead>
<tr>
<th>$f_l$ [Hz]</th>
<th>DC = 0.25</th>
<th>DC = 0.50</th>
<th>DC = 0.70</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.5, 1, 1.5, 2.5, 3, 3.5, 4.5…</td>
<td>0.5, 1.5, 2.5, 3.5, 4.5, 5.5…</td>
<td>0.5, 1, 1.5, 2, 3, 3.5, 4…</td>
</tr>
<tr>
<td>1.0</td>
<td>1, 2, 3, 5, 6, 7, 9…</td>
<td>1, 3, 5, 7, 9, 11…</td>
<td>1, 2, 3, 4, 6, 7, 8…</td>
</tr>
<tr>
<td>5.0</td>
<td>5, 10, 15, 25, 30, 35, 45,…</td>
<td>5, 15, 25, 35, 45, 55,…</td>
<td>5, 10, 15, 20, 30, 35, 40,…</td>
</tr>
<tr>
<td>10.0</td>
<td>10, 20, 30, 50, 60, 70, 90…</td>
<td>10, 30, 50, 70, 90, 110…</td>
<td>10, 20, 30, 40, 60, 70, 80…</td>
</tr>
</tbody>
</table>

Similarly to the unforced tests, the forced tests are also grouped in cases using flow pattern characteristics at low forcing frequency. At high forcing frequency, the flow does not really have time to settle. That is the reason why low frequencies were used to separate the cases. Three cases were singled out at BR$_m$=0.35 and two at BR$_m$=0.45. Table 5-16 shows the grouping. High and low flow are characterised by their similarity with a case of unforced JICF. The couples (BR$_{app}$, DC) corresponding to each case are also reported. For each case, except Case 1 of BR$_m$, four figures presenting an overview of a set of parameters (BR$_m$, BR$_{app}$, DC, $f_l$) will be shown and discussed. Each figure will feature: 1) a sequence of 10 instantaneous pictures taken during phase-locked
visualizations and representing a forcing cycle; 2) partial time records at the four positioned explored with CTA; 3) the corresponding power spectra with and without the phased-average component of the cycle.

Table 5-16: Case definition for forced JICF

<table>
<thead>
<tr>
<th>BR_m</th>
<th>Case #</th>
<th>Low flow</th>
<th>High flow</th>
<th>Related tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>1</td>
<td>Case 1</td>
<td>Case 5</td>
<td>(BR_l = 0.1875, DC = 0.25)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Case 1/(2)</td>
<td>Case 4</td>
<td>(BR_2 = 0.1875, DC = 0.50)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(BR_3 = 0.1875, DC = 0.70)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(BR_pp = 0.25, DC = 0.50)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(BR_pp = 0.25, DC = 0.70)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Case (2)/3</td>
<td>Case 4</td>
<td>(BR_pp = 0.25, DC = 0.25)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(BR_pp = 0.15, DC = 0.25)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(BR_pp = 0.15, DC = 0.50)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(BR_pp = 0.15, DC = 0.70)</td>
</tr>
<tr>
<td>0.45</td>
<td>1</td>
<td>Case 1</td>
<td>Case (4)/5</td>
<td>(BR_l = 0.1875, DC = 0.50)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Case 3/4</td>
<td>Case 4/5</td>
<td>(BR_pp = 0.25, DC = 0.25)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(BR_pp = 0.25, DC = 0.50)</td>
</tr>
</tbody>
</table>

5.3.2. BR_m = 0.35

5.3.2.1. Case 1

Case 1 has only one occurrence in our test matrix for a nominal low blowing ratio of 0.1875 and a nominal duty cycle of 0.25. It is characterised (see Figure 5-30) by a low flow like the Case 1 of the unforced tests (very stable flow covering the wall with developing Kelvin Helmholtz-like instability leading to vortex shedding) and a high flow as in Case 5 of the unforced tests (fully detached ring vortices). These were the two extreme cases encountered in our study of the unforced jet. The presence of those two types of flow in one experiment is due to the fixed low blowing ratio parameter and to the duty cycle (25%). To ensure a mean blowing ratio of 0.35 the high blowing ratio must be consequent. Therefore the nominal peak to peak is important. On top of that there is a big overshoot of these values in the actual test. No CTA survey was taken at these overshoot values because of observations, which showed that this case was extreme and the nominal settings could not be met by the system. The study of this case is therefore purely based on visualizations.

Figure 5-30 (a) shows a fully settled high flow with ring vortices rotated clockwise while moving into the far field. The flow behind the jet is fully detached, and wake-like vortices can be observed. Figure 5-30 (b) shows the flow covering the wall during the low part of the cycle, with a well-identified horseshoe vortex upstream of the jet and Kelvin-Helmholtz-like instability in the far field. A zone of recirculation situated behind the jet is clearly
visible which is not the case in the unforced study at BR=0.188. At the transition between these two phases of flow separated by such a high peak to peak blowing ratio the jet flow seems to almost shut off as Figure 5-31 illustrates.

![Blowing Ratio vs Time for BR=0.1875, DC = 0.25, f = 0.5Hz](image)

**Figure 5-30**: High (a) and low (b) flow characteristics (BR = 0.1875, DC = 0.25, f = 0.5Hz)

![Phase-averaged images at various positions in the forcing cycle at a forcing frequency of 5Hz.](image)

**Figure 5-31**: Jet shut off

If at low frequency (Figure 5-30) the high and low flows have time to settle, it is not the case at higher frequency. Figure 5-32 displays phase-averaged images at various positions in the forcing cycle at a forcing frequency of 5Hz. (a) and (f) show that the low flow does not manage to fully settle like an unforced Case 1 situation. However, the horseshoe vortex is clearly visible and the flow is attached behind the jet. (b) and (c) show the growth of a ring vortex puff with a prominent back part. This is different from what was observed in Case 5 of the unforced cases. At such high blowing ratio in steady state, as at the low forcing frequencies, the ring vortex is less asymmetric with even a prominent front part sometimes. The forcing at high frequency prevents the flow from settling in such a way and it actually brings some cover during the ring formation. A second ring seems to be
forming but it is broken when the solenoid valve is shut as shown on (d). The first ring-like vortex rotates in a clockwise fashion, while the second one not fully formed is pushed in a counter clockwise manner. (d) and (e) illustrate the jet shut off. The cross flow almost gets inside the jet orifice.

Figure 5-32: Phase averaged cycle (BR$_l$ = 0.1875, DC = 0.25, $f_t$ = 5.0Hz)

Figure 5-33 shows two instantaneous pictures during a 10Hz cycle. The high and low flows have even less time to settle. During the high flow (a) a ring like vortex puff is building while the previous puff is being convected and dispersed by the cross flow in the far field. The low flow does not have time to develop any of the characteristics of the unforced Case 1. On (b) it seems that a horseshoe vortex is being blown up by a forming ring like vortex. But this ring like vortex does not display the usual convexity. On the contrary it displays a concavity, which may be due to the fact that it is being pushed down by the cross flow.
5.3.2.2. Case 2

Figure 5-33: Puff build up (a) and low flow (b) \((BR_t = 0.1875, DC = 0.25, f_t = 10.0Hz)\)

Figure 5-34: Similarity of \((BR_t = 0.1875, DC = 0.50)\) (top) and \((BR_{pp} = 0.25, DC = 0.50)\) (bottom) at \(f_t = 1.0Hz\) (phase averaged pictures)
Case 2 is characterised by a low flow part similar to the unforced Case 1 or 2 (stable covering layer with Kelvin-Helmholtz-like instability and horseshoe vortex transport occurrences) and a high flow part similar to the unforced Case 4 (partially attached RLV formations). Four conditions of this Case are examined: \((\text{BR}_l=0.1875, \text{DC}=0.50), (\text{BR}_l=0.1875, \text{DC}=0.70), (\text{BR}_{pp}=0.25, \text{DC}=0.50), (\text{BR}_{pp}=0.25, \text{DC}=0.70)\). They can be grouped in pairs by duty cycles. Indeed, if one looks at Table 5-12 the nominal and actual values of the parameters for the pairs are close (<7% except for \(\text{BR}_l\) for the DC = 0.50 pair). Figure 5-34 and Figure 5-35 confirms these similarities by comparing phase-averaged pictures of the cycles. This similarity is useful because no CTA survey was taken at \((\text{BR}_l=0.1875, \text{DC}=0.70)\).

Figure 5-35: Similarity of \((\text{BR}_l=0.1875, \text{DC}=0.70)\) (top) and \((\text{BR}_{pp}=0.25, \text{DC}=0.70)\) (bottom) at \(f_f = 5.0\text{Hz}\) (phase averaged pictures)

Figure 5-34 and Figure 5-35 also show in the phased-averaged time record of the blowing ratio that oscillations occur. When measured, the period of this oscillation in both cases \((f_f = 1.0\text{Hz} \text{ and } f_f = 5.0\text{Hz})\) is between 20 and 25 ms \((\approx 22.5\text{ms})\) which gives a frequency of approximately 45 Hz. It will be seen later that this oscillation is
always present when the system is pulsed. 45Hz is an acoustic frequency of the system (Helmholtz mode) and it is observed at steady state (e.g. see Figure 5-16(e)) outside the energetic envelope of the flow. Figure 5-36 to Figure 5-39 present an overview of Case 2. They show a comprehensive review of the results for the four following sets of parameters: Figure 5-36 ($BR_m=0.35$, $BR_{pp}=0.25$, $DC=0.70$, $f_f=0.5Hz$); Figure 5-37 ($BR_m=0.35$, $BR_{pp}=0.25$, $DC=0.50$, $f_f=1.0Hz$); Figure 5-38 ($BR_m=0.35$, $BR_{pp}=0.25$, $DC=0.70$, $f_f=5.0Hz$); and Figure 5-39 ($BR_m=0.35$, $BR_{l}=0.1875$, $DC=0.50$, $f_f=10.0Hz$).

The phase-locked instantaneous images show the evolution of the flow over a cycle while the blowing ratio phase-averaged time record illustrates when each image was taken during the cycle. The phase-averaged signals help figure out what the probes are seeing and when. The time records corroborate the phase-averaged signal shapes. First it can be noticed that the oscillation frequency is evoked before it appears at the jet exit in all cases. It is the most visible on Figure 5-38 (b). At C and H at the 0.5Hz and 1Hz, the phase-averaged signals show that during the high part of the cycle, the probe is in the jet flow, but at low flow it is in the wind tunnel flow (more stable, less fluctuation). At higher frequencies (5Hz and 10Hz) it is hard to tell, but the signals at C and H are also inverted compared to A. The signal at D (behind the jet), whatever the frequency or set seems to be rectified, which means there is flow-reversal in this region. This seems particularly true during the low flow. A look at the visualization images confirms this fact. One can notice that all the partial time signals of all the sets of parameters show their corresponding forcing frequency. It means the forcing frequency has a persistent influence in the flow. The presence of this frequency is confirmed by the raw velocity spectra, which clearly display the forcing frequencies and their harmonics as was discussed earlier.

The visualization images of the four sets show different structures during a forced cycle. At low frequency during the low part of the cycle an unforced Case 1 settles (see Figure 5-36 1, 9, 10 and Figure 5-37 1, 9, 10). At higher frequency it does not really have the time to settle. During the high flow part at low frequency the ring vortex formation similar to Case 4 of the steady flow tests can be recognized with a front part forming inside the jet and a back part more prominent. One can also notice the presence of a horseshoe vortex being blown over on Figure 5-36 8 and Figure 5-37 8. The forcing is intermingling the characteristics, which were distinct in the steady state cases. More importantly this pattern of horseshoe blown over is also present at higher frequencies (see Figure 5-38 10, 29 and Figure 5-39 5), while the characteristics of the steady Case 1 are not present and the ones of the steady Case 4 are modified.
Figure 5-36: Forced vertical jet in cross flow at $BR_m=0.35$, $BR_{pp}=0.25$, $DC=0.70$, $f=0.5$Hz; Visualizations at jet mid-plane, x-z (1-42); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 5-37: Forc d vertical jet in cross flow at BR\textsubscript{m}=0.35, BR\textsubscript{pp}=0.25, DC=0.50, f\textsubscript{c}=1.0Hz: Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 5-38: Forced vertical jet in cross flow at $BR_m=0.35$, $BR_{pp}=0.25$, $DC=0.70$, $f_c=5.0\text{Hz}$; Visualizations at jet mid-plane, x-z (2-46); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

$D_j=25.4\text{mm}$, $U_\infty=1.6\text{m/s}$; $\delta/D_j=0.59$
Figure 5-39: Forced vertical jet in cross flow at $BR_m=0.35$, $BR_l=0.1875$, $DC=0.50$, $f_c=10.0\,\text{Hz}$; Visualizations at jet mid-plane, $x$-$z$ (1-47); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

$D_J=25.4\,\text{mm}$, $U_\infty=1.6\,\text{m/s}$; $\delta/D_J=0.59$
The set of parameters of Figure 5-38 (BR\textsubscript{m}=0.35, BR\textsubscript{pp}=0.25, DC=0.70, f\textsubscript{f}=5.0Hz) actually bring a fair cover during most part of the cycle. But the characteristics of the flow are no longer those of steady Case 1 or 4. This is what one looks for by pulsing the JICF: change the behavior of the flow and bring more cover, with less mixing. The set presented at 10Hz (see Figure 5-39) shows a ring like vortex trying to set in a puff. When the valve shuts, it creates a significant break up in the flow.

As mentioned earlier, the raw spectra show the harmonics of the forcing frequencies for each case. At the jet exit (A) the 45Hz frequency that was determined to be the acoustic frequency of the pulsing system is present as well as one of its harmonics (135Hz) at 0.5Hz and 1.0Hz. At 5.0Hz, the harmonic frequency can be noticed but the 45Hz frequency is lost in the energetic part of the flow power spectrum as it is at the 10Hz-forcing frequency. The 400Hz peak (also present on the spectra without the phase-averaged part of the cycle) is also observed at A is a longitudinal mode coming from the air supply system.

When the phase-averaged signal is taken off of the spectra, one can start distinguishing distinctive frequencies characteristic of the flow apart from the forcing frequencies and harmonics. At (BR\textsubscript{m}=0.35, BR\textsubscript{c}=0.1875, DC=0.50, f\textsubscript{f}=10.0Hz) and (BR\textsubscript{m}=0.35, BR\textsubscript{pp}=0.25, DC=0.70, f\textsubscript{f}=5.0Hz) the forcing frequencies still rise up. Since the flow does not have time to settle the probe picks up the frequency of the puffs which is the forcing frequency. At the lower frequency a small bulge appears on the spectra at C and H (D has a rectified signal which bias the spectra). It is around 10-15Hz. Since C and H do not seem to see the low flow part of the jet, this bump is linked to the jet at high flow. If one refers to the unforced Case 4 it can be noticed that this frequency corresponds to the ones picked up in that case (see Table 5-10). The CTA picks up the frequency linked to the ring like vortices during the high part of the cycle.

5.3.2.3. Case 3

The third and last case at BR\textsubscript{m}=0.35 is characterised by a low flow similar to unforced Case 2/3 (horseshoe transport and stable thick cover or in-jet ring formation) and a high flow part like unforced Case 4 (RLV formation). There were four occurrences of this case: (BR\textsubscript{pp}=0.25, DC=0.25), (BR\textsubscript{pp}=0.15, DC=0.25), (BR\textsubscript{pp}=0.15, DC=0.50), (BR\textsubscript{pp}=0.15, DC=0.70). One can be surprised that the whole set of BR\textsubscript{pp}=0.15 fits in this case but since the peak to peak blowing ratio is very low, the difference between highs and lows does not vary much and consequently the flows are very similar in features. Figure 5-40 shows phase-averaged images taken at the very beginning of the cycle for every DC and f\textsubscript{f} at BR\textsubscript{pp}=0.15. This way one can see the influence of the forcing frequency and duty cycle.
Figure 5-40: Phase averaged cycle evolution with DC (left to right DC = 0.25, 0.50, 0.70) and $f_t$ (top to bottom $f_t = 0.5, 1.0, 5.0, 10.0$Hz) for $BR_{pp} = 0.15$
First the similarity of the flows can be noticed as it was just mentioned in spite of the different forcing (and therefore flow) conditions. Then if one looks at the blowing ratio profile, several remarks can be made. As noticed earlier, the forcing system induces an acoustic frequency in the flow which is visible at every (DC, f<sub>f</sub>). The higher the forcing frequency gets, the more influence the acoustics have on the flow, since the acoustic frequency stays the same as the period of a cycle gets shorter. A manual measure on these records gives a frequency of 45Hz. It is believed this acoustic phenomenon is due to the needle valves. Indeed only the very low range of the valve system is used. The needle valves are almost fully closed, which creates a high impedance element.

The time at which these images were taken is the time right before the solenoid valve opens, i.e. the low flow is at its most settled point. For a fix duty cycle, increasing the forcing frequency disturb the flow and the low flow cannot fully settled anymore. For a fixed frequency DC = 0.50 seems to be the duty cycle for which the low flow settle the best. One can wonder why since DC = 0.25 would offer more time to the low flow to settle. DC = 0.50 combine enough time to settle with a lower BR<sub>h</sub> than DC = 0.25. A higher BR<sub>h</sub> is a disturbance factor for the low flow to settle. That is why DC = 0.50, which equilibrate high and low around the mean blowing ratio is best to help high and low flow settle.

Figure 5-41 to Figure 5-44 present an overview of Case 3. They show a comprehensive review of the results for the four following sets of parameters: Figure 5-41 (BR<sub>m</sub>=0.35, BR<sub>pp</sub>=0.25, DC=0.25, f<sub>f</sub>=0.5Hz); Figure 5-42 (BR<sub>m</sub>=0.35, BR<sub>pp</sub>=0.15, DC=0.50, f<sub>f</sub>=1.0Hz); Figure 5-43 (BR<sub>m</sub>=0.35, BR<sub>pp</sub>=0.25, DC=0.25, f<sub>f</sub>=5.0Hz); and Figure 5-44 (BR<sub>m</sub>=0.35, BR<sub>pp</sub>=0.15, DC=0.50, f<sub>f</sub>=10.0Hz). One can ask why no set of the occurrences (BR<sub>pp</sub>=0.15, DC=0.25) and (BR<sub>pp</sub>=0.15, DC=0.70) were used. The CTA experiments have been done after the visualizations. The visualizations showed those cases were similar to (BR<sub>pp</sub>=0.15, DC=0.50) as was mentioned beforehand. Those cases were consequently disregarded since they can be covered by a similar test. It also made the work load lighter.

The images on Figure 5-41 to Figure 5-44 show the flow characteristics of Case 3. Figure 5-41 8, Figure 5-42 1, Figure 5-43 35 and Figure 5-44 15 show horseshoe vortex transport at all frequencies. At 0.5, 1.0 and 5.0 Hz this transport occurs during the low part of the cycle which confirms a similarity to Case 2/3 of the steady state. At 10Hz it occurs during the high flow part of the cycle. As explained before at high frequency high and low flow parts have difficulties to settle and characteristics of the flow change. During the low part of the cycle Figure 5-41 1, 10 and Figure 5-42 10 also show the similarity to Case 2 of the steady state: these images show a flow bringing a thick cover to the wall which does not has time to settle at high frequency it seems.
Figure 5-41: Forced vertical jet in cross flow at $BR_m=0.35$, $BR_p=0.25$, $DC=0.25$, $f_0=0.5$Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 5-42: Forced vertical jet in cross flow at $BR_m=0.35$, $BR_{pp}=0.15$, $DC=0.50$, $f=1.0\,\text{Hz}$: Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j). $D_J=25.4\,\text{mm}$, $U_\infty=1.6\,\text{m/s}$; $\delta/D_J=0.59$
Figure 5-43: Forced vertical jet in cross flow at BR_m=0.35, BR_pp=0.25, DC=0.25, f_c=5.0Hz; Visualizations at jet mid-plane, x-z (1-46); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

\[ D_J = 25.4 \text{mm}, U_\infty = 1.6 \text{m/s}; \delta/D_J = 0.59 \]
Figure 5-44: Forced vertical jet in cross flow at $BR_m=0.35$, $BR_{pp}=0.15$, $DC=0.50$, $f_c=10.0\,Hz$; Visualizations at jet mid-plane, $x-z$ (2-48); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

$D_J=25.4\,mm$, $U_\infty=1.6\,m/s$; $\delta/D_J=0.59$
At low flow ring like vortices are also noticed like on Figure 5-41 7, 9 (0.5Hz). The back part is prominent which is characteristic of cases 3 or 4 ring like vortices. On Figure 5-43 46 (5.0Hz) such vortex is also formed during the high part of the cycle Case 4 like ring like vortex develop at low forcing frequencies such as on Figure 5-41 2,3 and Figure 5-42 4, 5. At higher frequencies (Figure 5-43 and Figure 5-44) such vortices try to form but do not have enough time before the solenoid valve shuts. Since the peak to peak blowing ratio in this case is very small, the break up of the flow is less significant than in Case 2. Once again at 5.0Hz the cover is still pretty fair during the whole cycle.

As far as the phase-averaged time records are concerned, they show again in some inversion between the records at A and the records at C and H (for example Figure 5-42 (b)). However it is not the same reason as in Case 2. The record stay perturbated during most of the cycle, which means it stays in the jet flow. There is just a time delay between the flow passes at each position. All the time records display the corresponding forcing frequency. The records behind the jet still present rectification, sign that there is a recirculation behind the jet in any case.

At A the phase-averaged records as well as the partial time records show the presence of the acoustic frequency of 45Hz already mentioned several times. However this frequency appears only slightly on the spectra at the position A on Figure 5-41 (g), (i) and Figure 5-42 (g). At higher frequency it disappears in the forcing frequency. Additionally these sets of parameters imply a higher blowing ratio during the cycle than during Case 2, which also explains the difference of low part characteristic and the ring like vortices in the low part of the cycle. As a consequence there is more energy in the signal and the power spectrum is broader. At A the air supply acoustic frequency of 400Hz is still visible at all frequencies.

At all frequencies the raw time records show the associated forcing frequencies. At the high frequencies (5.0Hz and 10.0Hz) the spectra without the phase-averaged part of the cycle also display those frequencies. It was explained why in Case 2. At (BRm=0.35, BRpp=0.25, DC=0.25, f=0.5Hz) at A and C a slight bulb is visible between 10Hz and 14Hz on Figure 5-41 (i); and at D and H a slight bulb is also visible between 10Hz and 20Hz on Figure 5-41 (j). At Figure 5-42 (BRm=0.35, BRpp=0.15, DC=0.50, f=1.0Hz), small bulbs are also present at A (around 10Hz), C (around 10-14Hz), D (around 9Hz) and H (around 10-14Hz). These frequencies as was said in Case 2 are close to the one detected in the steady state Case 4, but also 3 and 2 actually. One can wonder why there is so little to see on the spectra in the forced cases: the forcing (and the effect increases with frequency) has for effect to break
down the characteristic flow patterns of the JICF. It has for consequence the creation of new phenomena, or the
disparition of others, or the apparition of phenomena where they should not be.

5.3.3. $BR_m = 0.45$

5.3.3.1. Case 1

The first case at $BR_m=0.45$ is distinguished by its low flow similar to unforced Case 1 (stable flow covering
the wall with a developing Kelvin Helmholtz like instability in the far field) and its high flow similar to unforced
Case 4/5 (ring like vortex formation). It is a bit similar to Case 1 at $BR_m=0.35$, except that CTA surveys were taken.
Two occurrences of this Case 1 happen: ($BR_r=0.1875$, DC=0.50) and ($BR_r=0.1875$, DC=0.70). It can be notice that
($BR_r=0.1875$, DC=0.25) was not taken because of a too important peak to peak blowing ratio which would make this
experiment extreme. If it had been, this test would most probably be a part of this case (higher $BR_h$ and identical $BR_l$).

Figure 5-45 to Figure 5-48 present an overview of Case 1. They show a comprehensive review of the
results for the four following sets of parameters: Figure 5-45 ($BR_m=0.45$, $BR_r=0.1875$, DC=0.50, $f_l=0.5\text{Hz}$); Figure
5-46 ($BR_m=0.45$, $BR_r=0.1875$, DC=0.70, $f_l=1.0\text{Hz}$); Figure 5-47 ($BR_m=0.45$, $BR_r=0.1875$, DC=0.70, $f_l=5.0\text{Hz}$); and
Figure 5-48 ($BR_m=0.45$, $BR_r=0.1875$, DC=0.50, $f_l=10.0\text{Hz}$).

The images for low frequencies show the cycle characteristics for high and low flow. At high flow ring like
vortices are observed either slightly detached (see Figure 5-45 3), or forming closer the exit of the jet (Figure 5-46
4). Figure 5-45 2 shows an increase in seed which can be explained by the pulse when the solenoid valve opens. At
low $f_l$ during the low flow seed tends to accumulate in the jet pipe because of the low velocity. When the solenoid
valve opens and the high flow kicks in this seed is expelled from the jet which gives a higher intensity in the image.
Contrary to what may be expected this high flow brings some cover to the wall through the break up of the back
shear layer of the jet (Figure 5-46 2, 4) and wake vortices. During the low flow a steady state Case 1 like situation is
mostly observed (Figure 5-45 1, 9, 10; Figure 5-46 1, 10): the flow is very stable along the wall and brings a good
cover, a horseshoe vortex is present upstream of the jet exit and two or three diameters behind the jet the flow is
shedding due to a Kelvin Helmholtz instability. Sometimes the Kelvin Helmholtz instability develops earlier or the
horseshoe vortex interacts with it (Figure 5-46 9) which can lead to a flow break up. It happened too that the flow
almost detached from the wall right after the jet.
Figure 5-45: Forced vertical jet in cross flow at $BR_m = 0.45$, $BR_l = 0.1875$, $DC = 0.50$, $f_l = 0.5$ Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

$D_J = 25.4$ mm, $U_\infty = 1.6$ m/s; $\delta/D_J = 0.59$
Figure 5-46: Forced vertical jet in cross flow at BR\textsubscript{m}=0.45, BR\textsubscript{r}=0.1875, DC=0.70, f\textsubscript{c}=1.0Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

D\textsubscript{j}=25.4mm, U\textsubscript{∞}=1.6m/s; 8/D\textsubscript{j}=0.59
Figure 5-47: Forced vertical jet in cross flow at BR_m=0.45, BR_l=0.1875, DC=0.70, f=5.0Hz; Visualizations at jet mid-plane, x-z (1-49); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 5-48: Forced vertical jet in cross flow at $BR_m=0.45$, $BR_l=0.1875$, $DC=0.50$, $f=10.0$Hz; Visualizations at jet mid-plane, x-z (1-44); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
At higher frequencies (5.0Hz and 10.0Hz), the low flow does not have time to settle (see Figure 5-47 and Figure 5-48). The high flow does not fully settle either. However characteristics of a steady state Case 4/5 can still be observed (Figure 5-47 17). One can observe that the higher the frequency gets, the more prominent the back part of the ring like vortices is. Figure 5-45 2, 3 (0.5Hz) is close to a steady state Case 5, when Figure 5-48 16, 22 shows more the formation of a steady state high Case 4. On Figure 5-48 various phenomena created by the forcing can be observed: horseshoe vortex transport (6, 12), creation of a secondary ring like vortex by break up of the bulge of the first ring like vortex (22, 25, 29, 36).

Similarly to Case 1 at BR_m = 0.35, the high peak to peak linked to these tests can induce a break up or shut off of the jet after the transition between high and low flow as it is illustrated by Figure 5-45 7, Figure 5-46 9, Figure 5-47 49, Figure 5-48 44 for instance. Figure 5-47 12 shows the high flow starting to get out while the previous puff is being transported in the far field by the cross flow. Figure 5-48 36 and 44 show an almost blown out jet: the cross flow almost gets in the jet pipe.

The phase-averaged time records of the CTA experiments (Figure 5-45 to Figure 5-48 (b)) show once again the acoustic frequency of the jet at the jet exit. It also shows the delay between when each points see the flow passing. Each time record (Figure 5-45 to Figure 5-48 (c) to (f)) displays the corresponding forcing frequency, and at the jet exit (A), the acoustic frequency of the jet as well. Behind the jet (D) the records still present strong oscillations and rectification characteristic of recirculation.

The raw power spectra (Figure 5-45 to Figure 5-48 (g), (h)) mainly show the forcing frequencies and their harmonics present in the flow. The spectra without the phase-averaged part of the cycle (Figure 5-45 to Figure 5-48 (i), (j)) are more revealing. At (BR_m=0.45, BR_l=0.1875, DC=0.50, f_r=0.5Hz), a frequency close to 30Hz is picked up at A (28Hz), C (30Hz) and D (30Hz). At C a frequency of 65Hz is also picked up. The frequency of 30Hz was present in the spectra in Case 1 of the steady state (see Table 5-7: Significant frequencies of the flow at BR = 0.150 and BR = 0.188.). The frequency picked up seems to be a frequency characteristic of the low flow part of the cycle. At (BR_m=0.45, BR_l=0.1875, DC=0.70, f_r=1.0Hz), at the jet exit a frequency of 19Hz is picked up. Above the jet (C) a small bulge around 20 with a peak at 24 can be noticed and in the far field (H) there is a very small bulge around between 10Hz and 20Hz. In Case 5 of the steady state a frequency of 20Hz was noticeable at the jet exit and it was 25Hz above the jet (see Table 5-11). In the higher case of Case 4 there was a bulge around the same frequency as noticed here in the far field (see Table 5-10). The flow presents characteristics of the Case 5 and 4 of the steady state.
not only in the visualizations but also in the spectra. At \((BR_m=0.45, BR_l=0.1875, DC=0.70, f_r=5.0\,\text{Hz})\) at the jet exit (A) one can notice a bulge between 10Hz and 14Hz, which can be linked to the Case 4 again. As mentioned earlier as the frequency goes up the flow characteristics slightly become more like Case 4 and less 5. At \((BR_m=0.45, BR_l=0.1875, DC=0.50, f_r=10.0\,\text{Hz})\) no frequency singles out except the forcing frequency. Finally it can be noticed that on all spectra (raw and without the phase-averaged part of the signal) at the jet exit the acoustic frequency of the air supply system (400Hz) is still present.

5.3.3.2. Case 2

Case 2 is characterized by an unforced Case 3/4 like low flow (horseshoe transport and RLV formation) and an unforced Case 4/5 like high flow (RLV). There are two occurrences of this case: \((BR_{pp}=0.25, DC=0.25)\) and \((BR_{pp}=0.25, DC=0.50)\). Figure 5-49 to Figure 5-52 present an overview of Case 2. They show a comprehensive review of the results for the four following sets of parameters: Figure 5-49 \((BR_m=0.45, BR_{pp}=0.25, DC=0.50, f_r=0.5\,\text{Hz})\); Figure 5-50 \((BR_m=0.45, BR_{pp}=0.25, DC=0.25, f_r=1.0\,\text{Hz})\); Figure 5-51 \((BR_m=0.45, BR_{pp}=0.25, DC=0.50, f_r=5.0\,\text{Hz})\); and Figure 5-52 \((BR_m=0.45, BR_{pp}=0.25, DC=0.25, f_r=10.0\,\text{Hz})\).

These figures show various structures during the low flow part of the cycle. It appears to be very eclectic. The flow seems pretty unstable. Various ring formations (Figure 5-49 8; Figure 5-50 7, 9) can be observed as well as horseshoe transport (Figure 5-49 1, 10) and even it seems Kelvin Helmholtz instability flow (Figure 5-50 10) which should not be occurring at this BR\(_l\). It results a pretty good cover of the wall.

During the high flow part of the cycle, two kinds of vortices formations are noticed: 1) steady state Case 5 like ring like vortices (Figure 5-49 2; Figure 5-50 2, 3) usually at the beginning of the high flow part; and 2) steady state Case 4 like ring like vortices (Figure 5-49 4, 5). At higher frequencies \((5.0\,\text{Hz and } 10.0\,\text{Hz})\) the high flow does not have time to fully settle. On Figure 5-51 the build up of the puff is comparable to a steady state Case 4 but the result (26) is more like a steady state Case 5. At the beginning, the back part of the ring is prominent but when formed, the ring is actually equilibrated. One can notice as well that at 5.0Hz and 10.0Hz the cover offered by the flow stays good during all the cycle. This is particularly true for 10.0Hz (Figure 5-52) with DC=0.25. The high flow does not have time to settle at all. There is a small break up in the cover between puffs but the cover stays pretty thick.
Figure 5-49: Forced vertical jet in cross flow at $BR_m=0.45, BR_w=0.25, DC=0.50, f_j=0.5$Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

$D_j=25.4$mm, $U_\infty=1.6$m/s; $\delta/D_j=0.59$
Figure 5-50: Forced vertical jet in cross flow at $BR_v=0.45$, $BR_p=0.25$, $DC=0.25$, $f_c=1.0$Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

$D_J=25.4$mm, $U_\infty=1.6$m/s; $\delta/D_J=0.59$
Figure 5-51: Forced vertical jet in cross flow at BRw=0.45, BRpp=0.25, DC=0.50, f=5.0Hz; Visualizations at jet mid-plane, x-z (1-42); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

Dj=25.4mm, Uw=1.6m/s; δ/Dj=0.59
Figure 5-52: Forced vertical jet in cross flow at BR\text{ave}=0.45, BR\text{pp}=0.25, DC=0.25, f=10.0Hz; Visualizations at jet mid-plane, x-z (2-49); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

\(D_J=25.4\text{mm}, U_\infty=1.6\text{m/s}; \delta/D_J=0.59\)
The study of the phase-averaged time records and of the partial time records brings up the same as precedently. At A the acoustic frequency of the jet has an influence. This is particularly true at (BR_m=0.45, BR_pp=0.25, DC=0.25, f_f=10.0Hz): a high forcing frequency and a small duty cycle reduces emphasize the influence of the acoustics (45Hz). It is even more flagrant on the blowing ratio record. The phase-averaged records show the delay of time between the moments when the flow is passing at each position. It is of the order of 0.1s between the jet exit position A and the far field position H. This seems good since it gives a velocity of the flow of around 1m/s. The cross flow is at U_∞=1.6m/s and the jet is slower and its flow interact with the boundary layer of the wind tunnel (slower than U_∞=1.6m/s). This is a logical number.

The partial time records confirm the shape of the phase-averaged records and display at all position and in all cases the appropriate forcing frequency. Same can be said of the raw power spectra. It is more marked at the jet exit and right above the jet of course since the frequency dissipates with the mixing of the jet in the cross flow. The spectra without the phase-averaged part of the signal are more informative. At (BR_m=0.45, BR_pp=0.25, DC=0.50, f_f=0.5Hz), there is a small bulge at the jet exit (A, Figure 5-49 (i)) between 18Hz and 21Hz. Above the jet exit (C, Figure 5-49 (i)), behind the jet (D) and in the far field (H) (Figure 5-49 (j)) small peaks respectively at 24Hz, 21Hz and 18Hz are noticed. If one looks at Table 5-11 the frequencies at A and C can be linked to the Case 5 of the steady state. As for at D and H they can be a reminiscence of the frequencies at A and C. At (BR_m=0.45, BR_pp=0.25, DC=0.25, f_f=1.0Hz) (Figure 5-50 (i), (j)) a frequency is picked of 25Hz above the jet and behind the jet which can also probably be linked to the steady state Case 5. At (BR_m=0.45, BR_pp=0.25, DC=0.50, f_f=5.0Hz) (Figure 5-51 (i), (j)) three slight bulbs can be seen respectively at A (jet exit) between 2Hz and 14Hz, at C (above jet) with a peak at 10Hz (maybe harmonics of the forcing frequency) and H (far field) between 7Hz and 20Hz. At (BR_m=0.45, BR_pp=0.25, DC=0.25, f_f=10.0Hz) a similar bulb is found at H (Figure 5-52 (j)) between 5Hz and 20 Hz. With caution this values can be compared to the Case 4 of the steady state study (see Table 5-10). Also on Figure 5-52 (i) the forcing frequency still shows up (10Hz) but also a peak at 18Hz which is not dependent of the harmonics of the forcing frequency since it also appears on the raw spectrum (Figure 5-52 (g)) and the harmonics do not.
Chapter 6: Conclusion

An experimental setup of a jet in cross flow has been built and two methods of measurements have been developed to study it: a precise and automated constant temperature anemometry system using hot-wire sensors and a 3-axis traverse; a system of LASER sheet visualization. Both systems integrated flow meters to ensure a proper correlation of the CTA and visualizations experiments with pulsing of the jet flow rates. The experimental setup was characterized. The boundary layer at the jet exit is laminar and $\delta/D_J=0.59$ for the chosen cross flow velocity. The unforced and the forced jet in a cross flow at $U_\infty=1.6m/s$ have been investigated respectively from blowing ratios ranging from $BR=0.150$ to $BR=0.600$ and for two mean blowing ratios $BR_m=0.35$ and $BR_m=0.45$. For each set of parameters visualizations were taken along the jet central (x-z) plane and CTA measurements were taken at four positions in the flow, the selection of which was guided by the visualizations.

The unforced JICF was divided into five cases over the range of blowing ratios explored depending on the characteristics of the flow coming out of the jet: 1) a fully attached flow with a Kelvin-Helmholtz-type instability developing in the far field and with a stable horseshoe vortex in front of the jet; 2) a first transition case with an attached flow presenting the Kelvin-Helmholtz-like instability and the horseshoe vortex of case 1) but with occurrences of this horseshoe vortex being blown away; 3) a second transition case presenting the characteristics of case 2) but with more occurrences of the horseshoe vortex being blown away and also occurrences of asymmetric ring-like vortices formation and flow break up; 4) a flow of partially attached ring-like vortices (asymmetric or equilibrated); and 5) a fully detached flow with jet-mode ring-like vortices. A power spectrum analysis provided frequencies associated with each case.

The study of the forced JICF lead to the division of the forced JICF into five cases depending on the characteristics of the flow during the high and low flow part of the cycle. For each $BR_m$ (0.35 and 0.45) various $BR_i$, $BR_pp$ (0.15, 0.25), DC (0.25, 0.50, 0.70) and $f_f$ (0.5Hz, 1.0Hz, 5.0Hz, 10.0Hz) were studied. The influence of each one of these parameters on the flow was studied. The forcing lead to a perturbation of the flow characteristics and this effect increases with the velocity. At low frequency (0.5Hz and 1.0Hz) the characteristics of the flow at $BR_i$ and $BR_pp$ could be found in the forced cycle. At higher frequency (5.0Hz and 10.0Hz) the low flow and the high flow did not have time to settle and these characteristics disappear. The spectral characteristics were also found back and sometimes were even visible at higher frequency. Several cases at 5.0Hz were noticed to improve coverage. If the
forcing frequency is too high consequent break up appears in the jet. The importance of this break up depends also on the other parameters. The system had four parameters, which all play a role and combine to give more or less coverage to the wall.

Future work will consist of the complementary study of the parameters already explored. Visualizations on the x-y plane parallel to the wall need be performed at different z positions (heights from the wall) to investigate the lateral coverage of the jet depending on the parameters already studied.

Further work will consist in the implementation of a new designed jet with an inclinaison angle of 35 degree and with the possibility of a compound angle. This is a more realistic geometry for the film-cooling application. The influence of the flow density will be studied by replacing the jet flow with another fluid than air. In the meantime the measurement system will be improved. For instance the visualization system will receive a new camera with higher resolution in order to realise Particle Image Velocimetry (PIV) experiments, which combine the advantages of velocity measurements with the advantages of visualizations. All this will hopefully result in a better understanding of the phenomena linked to the forced jet in cross flow and further ahead more efficient ways to do and control film cooling.
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S. M. Coulthard, R. J. Volino, K. A. Flack
Effect of Jet Pulsing on Film Cooling, Part 2: Heat Transfer Results

N. Dupuis, R. Gandy, J. Wyatt
Computer Automated 3-D Travers System
Appendix: Data Processing Matlab Codes

Code for the calibration of a single wire probe

clc
clear all

[A,B]=xlsread('Input_calibration_file');  %%%Read of the file containing the details of the
calibration, A contains all the numeric data of the file,
B contains the character data of the file

Gain=A(1,1);  %%%Gain and offset to apply to the
Offset=A(2,1);  ouput voltage to convert to raw voltages
Numvruns=A(3,1);  %%%Number of files taken during the calibration
Numvpts=A(11,1);  %%%Number of data points taken for each run
Vel_reach=A( 12:45 ,2);  %%%Velocity reached by the calibrator

%%%Read the .txt file containing the data for each run during the calibration process
Out_Volt=cell(1,Numvruns);
for j=1:Numvruns
    Input=[int2str(j-1),'V.','txt'];
    fid=fopen(Input);
    Var=dlmread(Input);
    Out_Volt{j}=Var(2:1025,3);
    Raw_Volt{j}=(Out_Volt{j}./Gain)+Offset;  %%%Apply gain and offset to get the raw
    Mean_Raw_Volt{j}=Mean(Raw_Volt{j});  volatges
    Raw_Volt{j}=cat(Numvruns, Mean_Raw_Volt{j});
end
Raw_Voltages=CELL2MAT(Raw_Volt);
Volt=Raw_Voltages';
%%%Polynomial fit to get the coefficients in the decreasing exponent order
%%%Vel=A4*Volts^4+A3*Volts^3+A2*Volts^2+A1*Volts^1+Ao

p=polyfit(Volt,Vel_reach,4);
%%%Velocity after fitting the polynomial coefficients
F1=polyval(p,Volt);
%%%Plot the calibration curve (which should look like a parabol)
plot(Volt,Vel_reach,'rx',Volt,F1,'b:');
legend('New Daq Bridge voltages',' Curve fit voltages');
xlabel('Raw Bridge voltage');
ylabel('velocity');
title('Calibration curve fit ');
grid on;
hold on

%%%Write the polynomial coefficients in the increasing exponent order
fid=fopen('CALIBRATION COEFFICIENTS FILE.txt ','w');
fprintf(fid,'CALIBRATION COEFFICIENTS

');
fprintf(fid,'%f7.3
fclose(fid);

Code for the X probe calibration
%%%Read Input_calibration_file.xls to get the details of the calibration
clc
clear
[A,B]=xlsread('Input_calibration_file.xls');
%%%Gain and offset to applied to the ouput voltage to convert to raw voltage
Gain1=A(1,1);  %%%Gain of the first wire sensor
Offset1=A(2,1); %%%Offset of the first sensor
Gain2=A(3,1);  %%%Gain of the second sensor
Offset2=A(4,1); %%%Offset of the second sensor
Tmin=A(6,1); %%%Minimal Temperature
Tmax=A(7,1); %%%Maximal Temperature
Topr=A(8,1); %%%Operating Temperature
Tcal=A(9,1); %%%Calibration Temperature
Pcal=A(10,1); %%%Calibration Pressure
Pexp=A(11,1); %%%Experimental Pressure

Numvruns=A(5,1); %%%Number of files taken during the calibration
Numvpts=A(13,1); %%%Number of data points taken for each run

%%%Velocity Reached by the calibrator
Vel_reach=A(14:47,1)*sin(45*pi/180);

YawVelLow=A(48,1);
YawVelMid=A(49,1);
YawVelHigh=A(50,1);

a=A(51:61,1); %%%Angle of the stand of the calibrator
a1=(a+45)*pi/180; %%%Angle of the first wire sensor
a2=(45-a)*pi/180; %%%Angle of the second wire sensor

%%%Read the txt files containing the calibration data
Out_Volt1=cell(1,Numvruns);
Out_Volt2=cell(1,Numvruns);

for j=1:Numvruns
    Input=['E:\Piem\Calibrations\014066_36_05082006\','int2str(j-1),'V.','txt'];
    fid=fopen(Input);
    Var=dlmread(Input);
    Out_Volt1(j)=Var(2:1025,1);
    Out_Volt2(j)=Var(2:1025,2);

    %%Applying gain and offset to get the raw voltages
    Raw_Volt1(j)=(Out_Volt1(j)./Gain1)+Offset1;
    Raw_Volt2(j)=(Out_Volt2(j)./Gain2)+Offset2;
Mean_Raw_Volt1(j) = Mean(Raw_Volt1(j));
Mean_Raw_Volt2(j) = Mean(Raw_Volt2(j));

Raw_Volt1(j) = cat(Numvruns, Mean_Raw_Volt1(j));
Raw_Volt2(j) = cat(Numvruns, Mean_Raw_Volt2(j));

end

Raw_Voltages1 = CELL2MAT(Raw_Volt1);
Raw_Voltages2 = CELL2MAT(Raw_Volt2);

Volt1 = Raw_Voltages1';
Volt2 = Raw_Voltages2';

%% Polynomial curve fit with coefficients in decreasing exponent order
p1 = polyfit(Volt1, Vel_reach, 4);
p2 = polyfit(Volt2, Vel_reach, 4);

%% Velocity obtained from the voltages with the polynomial coefficient
F1 = polyval(p1, Volt1);
F2 = polyval(p2, Volt2);

%%% Plot the calibration curves
subplot(2,1,1);
plot(Vel_reach, Volt1, 'rx', F1, Volt1, 'b:');
legend('New Daq Bridge voltages', 'Curve fit voltages');
ylabel('Raw Bridge voltage');
xlabel('velocity');
title('Calibration curve fit (Ch 1)');
grid on;

subplot(2,1,2);
plot(Vel_reach, Volt2, 'rx', F2, Volt2, 'b:');
legend('New Daq Bridge voltages', 'Curve fit voltages');
ylabel('Raw Bridge voltage');
xlabel('velocity');
title('Calibration curve fit (Ch 2)');

grid on;

hold off;

%%% Compute the yaw coefficients with the experiments done aside the IFA300 calibration process

for j=1:20
    m=5*j;
    if m<10
        file=['00',int2str(m)];
    elseif m<100
        file=['0',int2str(m)];
    else
        file=[int2str(m)];
    end
    for k=1:11
        Input=['E:\Piem\Calibrations\014066_36_05302006\XprobeCalibrationTest',file,'mps\',int2str(k),'Y.txt'];
        fid1=fopen(input);
        V=dlmread(input);
        Num=length(V);
        fs=V(1,1);
        ts=1./fs;
        E1=V(2:Num,1);
        E2=V(2:Num,2);
        TV=V(2:Num,3);
        TV1=(TV*((Tmax-Tmin)/10))+((Tmax-Tmin)/2);
        E1b=(E1/Gain1)+Offset1;
        E2b=(E2/Gain2)+Offset2;
    end
end
E1=E1b.*sqrt((Topr-Tcal)./(Topr-TV1));
E2=E2b.*sqrt((Topr-Tcal)./(Topr-TV1));
V1P= p1(1).*E1.^4 + p1(2).*E1.^3 + p1(3).*E1.^2 + p1(4).*E1 + p1(5);
V2P= p2(1).*E2.^4 + p2(2).*E2.^3 + p2(3).*E2.^2 + p2(4).*E2 + p2(5);
V1(j,k)=mean(V1P.*(Pcal/Pexp));
V2(j,k)=mean(V2P.*(Pcal/Pexp));
U(j)=j*0.5;  %%%Velocity out of the calibrator
UN1(j,k)=U(j)*sin(a1(k));  %%%Velocity normal to the first wire sensor
UT1(j,k)=U(j)*cos(a1(k));  %%%Velocity tangent to the first wire sensor
UN2(j,k)=U(j)*sin(a2(k));  %%%Velocity normal to the second wire sensor
UT2(j,k)=U(j)*cos(a2(k));  %%%Velocity tangent to the second wire sensor

%%%Compute the correction coefficients for each velocity and angle for each wire sensor

k1(j,k)=sqrt((V1(j,k)^2-UN1(j,k)^2)/UT1(j,k)^2);
k2(j,k)=sqrt((V2(j,k)^2-UN2(j,k)^2)/UT2(j,k)^2);

end
end

%%%Corrected normal velocity to each wire sensor
UN1corr=sqrt((V1.^2-k1.^2.*V2.^2)./(1-k1.^2.*k2.^2));
UN2corr=sqrt((V2.^2-k2.^2.*V1.^2)./(1-k1.^2.*k2.^2));

%%%Vertical and horizontal velocity after correction
U=(UN2corr+UN1corr)/sqrt(2);
V=(UN2corr-UN1corr)/sqrt(2);

%%%Magnitude of the velocity corrected, and measured by the sensor
MAG1=sqrt(U.^2+V.^2);
MAG2=sqrt(V1.^2+V2.^2);
alpha=atan(V1./V2)*180/pi-45;

xlswrite('VelocityCoefficients.xls',[p1;p2]');  %%%Write the velocity coefficients into an excel file
xlswrite('YawCoefficients.xls',[a';k1.^2;k2.^2;MAG1]');  %%%Write the yaw coefficients into an excel file
Code to read a .txt file and extract the data in it

Input=char(strcat(datadir,filename(i),'.txt')); %%%Path to the file
fid=fopen(Input);     %%%Open the file
V=dlmread(Input);    %%%Read the file and put its content in a matrix
Num=length(V);      %%%Read the number of rows in the text file
fs=V(1,1);    %%%Read the forcing frequency on the first line of the file
ts=1./fs;        %%%Time between two samples
E1=V(2:Num,1);      %%%Hotwire Probe Signal
E3=V(2:Num,3);      %%%Temperature Signal
E4=V(2:Num,4);      %%%Jet Flow Flowmeter Signal
E5=V(2:Num,5);      %%%Seeding Flow Flowmeter
E6=V(2:Num,6);      %%%Trigger Signal
fclose(fid);     %%%Close the file
clear V fid Input     %%%Clear the variables which will not be used later

Code to transform the voltages of a hotwire sensor into velocities

UV1=(E1/Gain)+Offset;    %%%Get the raw voltage from the acquired voltages
clear E1
TV1=(E3*((Tmax-Tmin)/10))+((Tmax-Tmin)/2);     %%%Convert the temperature voltage in temperature
clear E3
UV2=UV1.*sqrt((Topr-Tcal)./(Topr-TV1));              %%%Apply temperature correction to the velocity raw voltages
clear UV1 TV1
UP=a00+a01*UV2+a02*UV2.^2+a03*UV2.^3+a04*UV2.^4; %%%Apply the velocity coefficients from the calibration to the raw voltages to get the velocity
clear UV2
U=UP.*(Pcal/Pexp);   %%%Apply pressure correction to get the actual velocity
clear UP
U=U/1.6;   %%%Scale the velocity with the cross flow velocity 1.6m/s
Code to transform the voltages from the flowmeters into blowing ratio

\[
BR_{\text{main}} = \frac{((E4 \times 25) / (60 \times 1000)) / (\pi \times (0.0254 / 2)^2)}{1.6};
\]

%%%Transform the voltages from the jet flow flowmeter into blowing ratio

clear E4

\[
BR_{\text{seeding}} = \frac{((E5 \times 1) / (60 \times 1000)) / (\pi \times (0.0254 / 2)^2)}{1.6};
\]

%%%Transform the voltages from the seeding flow flowmeter into blowing ratio

clear E5

\[
BR = BR_{\text{main}} + BR_{\text{seeding}};
\]

%%%Compute the total blowing ratio of the jet

The formula to change the voltages of the flowmeters to blowing ratios is the result of the following steps. The jet flowmeter provides a linear voltage ranging from 0 to 4V for a range of flow that we set between 0 and 100 StdL/min. Hence we need a 25 gain to pass from the voltage to the flow in StdL/min. Then we transform the StdL/min in m$^3$/s. Hence we divide by 60 and 1000. Considering the density of the jet is the same as the one of the cross flow, the blowing ratio is the ratio between the mean velocity of the jet and the mean velocity of the wind tunnel, which is 1.6 m/s, constant for all our experiments. To get the velocity from the flow rate, we need to divide by the surface of the jet section. The same operation is applied with the seeding flow, the only change being that the seeding flow flowmeter gives a 0 to 10V linear signal for a set range of 0 to 10 StdL/min.

Code to compute the power spectrum of the velocity smooth it and save it in a text file

\[
UF = \text{fft}(U);
\]

%%%Compute the fast Fourier transform of U

\[
Pzz = UF \times \text{conj}(UF) / \text{length}(UF);
\]

%%%Compute the power spectrum of U

\[
Pzz\_smooth50 = Pzz;
\]

%%%Initialize the smoothing procedure

for g = 1:50

%%%Smoothing algorithm

\[
Pzz\_smooth50(3:\text{length}(Pzz\_smooth50)-1,:) = (Pzz\_smooth50(2:\text{length}(Pzz\_smooth50)-2,:)) + 2 \times Pzz\_smooth50(3:\text{length}(Pzz\_smooth50)-1,:) + Pzz\_smooth50(4:\text{length}(Pzz\_smooth50,:)) / 4;
\]

end

clear g

\[
Freq = fs \times (0:\text{length}(UF)-1) / \text{length}(UF)-1;
\]

%%%Creates a vector with frequency
Strou=Freq*.0254/(BRm(i)*1.6); \hspace{1cm} %%%Computes the strouhal number associated to the frequencies

Input=char(strcat(outdir,filename(i),'\_PowerSpectrum.txt')); \hspace{1cm} %%%Path to the file

fid=fopen(Input,'w'); \hspace{1cm} %%%Create and open the file with writing capacity

fprintf(fid,'%2.4e  %2.4e  %2.4e  %2.4e\n',[Freq;Strou;Pzz';Pzz\_smooth50']); \hspace{1cm} %%%Writes the data in the file

fclose(fid); \hspace{1cm} %%%Close the file

clear Input fid UF Freq Strou Pzz Pzz\_smooth50

**Codes to do phase-averaging**

**Code 1**

for j= 1:k-2

Valve\_Cycles(j,1:Tf)=Valve(Valve\_Zeros(1)+(j-1)*Tf:Valve\_Zeros(1)+(j-1)*Tf+Tf-1);

BRmain\_Cycles(j,1:Tf)=BRmain(Valve\_Zeros(1)+(j-1)*Tf:Valve\_Zeros(1)+(j-1)*Tf+Tf-1);

BRseeding\_Cycles(j,1:Tf)=BRseeding(Valve\_Zeros(1)+(j-1)*Tf:Valve\_Zeros(1)+(j-1)*Tf+Tf-1);

BR\_Cycles(j,1:Tf)=BR(Valve\_Zeros(1)+(j-1)*Tf:Valve\_Zeros(1)+(j-1)*Tf+Tf-1);

end

clear j

Valve\_PhAv=mean(Valve\_Cycles,1);

[...]

BRmain\_PhAv=mean(BRmain\_Cycles,1);

BRseeding\_PhAv=mean(BRseeding\_Cycles,1);

BR\_PhAv=mean(BR\_Cycles,1);

**Code 2**

for j= 1:k-2

Valve\_Cycles(j,1:Tf)=Valve(Valve\_Zeros(j):Valve\_Zeros(j)+Tf-1);

BRmain\_Cycles(j,1:Tf)=BRmain(Valve\_Zeros(j):Valve\_Zeros(j)+Tf-1);

BRseeding\_Cycles(j,1:Tf)=BRseeding(Valve\_Zeros(j):Valve\_Zeros(j)+Tf-1);

BR\_Cycles(j,1:Tf)=BR(Valve\_Zeros(j):Valve\_Zeros(j)+Tf-1);

end
clear j
Valve_PhAv=mean(Valve_Cycles,1);
BRmain_PhAv=mean(BRmain_Cycles,1);
BRseeding_PhAv=mean(BRseeding_Cycles,1);
BR_PhAv=mean(BR_Cycles,1);

**Code to find the solenoid valve opening time**

The following code allows to find Valve_Zeros, i.e. the upswings of the time when the valve opens during our experiments. This is our starting point for the phase averaging. Since during our experiments we noticed the presence of undesirable peaks close to these positions, due to the interaction of the solenoid valve with the measurement system, we incorporated a security to be sure to obtain the right upswing. Moreover, as the experience showed us that a peak is most often present on all signals, the other signals are also corrected.

k=1;
for j=1:Num-2
    if (Valve(j)>=Valve_Mean && Valve(j+1)<=Valve_Mean)
        Valve_Zeros(k)=j+1;
        if (k>1 && Valve_Zeros(k)-Valve_Zeros(k-1)<500)
            clear Valve_Zeros(k)
            Valve(j)=Valve(j+1);
            BRmain(j)=BRmain(j+1);
            BRseeding(j)=BRseeding(j+1);
            BR(j)=BR(j+1);
        else
            k=k+1;
        end
    end
end

k-1 %Display the number of actual valve upswings in the record
clear j Valve_Mean
for j=1:k-2
    T(j)=Valve_Zeros(j+1)-Valve_Zeros(j);%%%Compute the period of each cycle found in the record
end
clear j
Tf=round(mean(T))                                             %%%Compute and display the average period of a cycle on a record
clear T

Code to compute the mean, high, low and peak to peak blowing ratio from the phase-averaged data
BRm(i)=mean(BR_PhAv); %%%Compute the mean blowing ratio
[…]
k=1;

%%%The next algorithm computes and positions the time when the blowing ratio signal crosses the mean.
for j=1:Tf-1
    if (BR_PhAv(j)<=BRm(i) && BR_PhAv(j+1)>=BRm(i))  %%%Upswing
        BR_Zeros(k)=j+1;
        k=k+1;
    elseif (BR_PhAv(j)>=BRm(i) && BR_PhAv(j+1)<=BRm(i)) %%%Downswing
        BR_Zeros(k)=j+1;
        k=k+1;
    end
end
Under_BRh(i)=(k-3)/2; %%%Compute the number of times the blwoing ratio goes back under the mean
during the high part of the cycle
clear j
DC(i)=(BR_Zeros(k-1)-BR_Zeros(1))/Tf; %%%Compute the duty cycle, knowing that the first
        crossing of the mean is the beginning of the high flow
        part of the cycle, and the last one the beginning of the
        low flow part of the cycle
l=1;
h=1;

%%%Separate the high and the low flow parts of the cycle to compute the different blowing ratios.

for j=1:Tf-1
    if j<BR_Zeros(1) || j>=BR_Zeros(k-1)
        BR_Low(l)=BR_PhAv(j);
        l=l+1;
    elseif j>=BR_Zeros(1) && j<BR_Zeros(k-1)
        BR_High(h)=BR_PhAv(j);
        h=h+1;
    end
end
clear j k l h
BRl(i)=mean(BR_Low);  %%%Compute the low blowing ratio
BRh(i)=mean(BR_High);  %%%Compute the high blowing ratio
BRpp(i)=BRh(i)-BRl(i);  %%%Compute the peek to peek blowing ratio
clear U_PhAv BR_PhAv BR_Zeros BR_Low BR_High

Example of Code to process images
A=imread(Input1,'tif');  %%%Read tif image A
[…]
B=imread(Input2,'tif');  %%%Read tif image B
B(167:1016,1:1008)=B(1:850,1:1008);  %%%Move part of the image B down
B(1:504,1:1008)=A;  %%%Paste A on the top part of B
B(975:1016,85:91)=uint8(255);  %%%Set a white line at the upstream limit of the jet
B(975:1016,239:245)=uint8(255);  %%%Set a white line at the downstream limit of the jet
[…]
imwrite(B,Output,'tif');  %%%Write the modified image B in tif format
Pierre-Emmanuel Bouladoux was born in Longjumeau, France, in the suburbs of Paris, from the union of Marie-Christine and Pascal Bouladoux, in the morning of the 8th of May 1982. He spent his childhood in Epinay-sur-Orge, Essonne, with his older sister and brother Anne-Sophie and Nicolas.

He obtained his Baccalauréat with Honors in June 2000 at the Lycée Jean-Baptiste Corot in Savigny-sur-Orge, named after the famous 19th century French impressionist painter. He then joined the preparatory classes for engineering schools during two years in the same school.

He entered the Ecole Nationale Supérieure d’Ingénieurs de Constructions Aéronautiques in September 2002 in Toulouse for two years, where he took his private pilot license and helped organize an air show, featuring the French Air Force Demonstration Team, and an aeronautical competition. He was sent to Louisiana State University in August 2004 to complete a Master of Science in Mechanical Engineering under the supervision of Dr Dimitris E. Nikitopoulos in the Department of Mechanical Engineering. He submitted his research named Pulsed Vertical Jet in Cross Flow at Mean Blowing Ratio 0.35 and 0.45 to be graduated in December 2006 and received the engineering diploma from his French school in September 2006.