THE EFFECTS OF NOZZLE TRAILING EDGE MODIFICATIONS ON
THE ACOUSTIC FAR FIELD OF A MACH 2 RECTANGULAR JET

A THESIS

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ABSTRACT

An anechoic chamber for use in subsonic and supersonic jet studies was designed and constructed. This chamber operates as a research platform for multiple types of experiments, including acoustic measurements of jet noise, various laser based flow visualization and measurements, and simultaneous acoustic and flow measurements. The design parameters, materials, and final qualification test results for the chamber are presented. The chamber was employed in the verification of a hypothesis formed in previous work on a nozzle with trailing edge modifications in an aspect ratio 3 Mach 2 rectangular high Reynolds number jet. The modifications in the previous study were found to substantially increase mixing and decrease the far field noise, in some instances. A considerable increase in the mixing and reduction in the noise from the baseline case was observed in the underexpanded flow condition. The overexpanded flow condition had a minimal mixing increase, with decreases of the noise in the low frequency range and increases in the high frequency. The modifications had very little to no effect in the ideally expanded flows.

Acoustic measurements completed in the previous research were only qualitative in nature, as they were completed in an open room environment, where the effects of reflections, and background noise would have contaminated the data. The anechoic
chamber allowed for the ideal testing environment for the jet, and acoustic experiments were conducted for single and double side trailing edge modified nozzles using three microphones, placed in a plane at the angles of 90°, 60° and 30° with respect to the axis of the jet. The trailing edge modified nozzles substantially reduced the turbulent mixing noise and the broadband shock associated noise radiation by up to 12 dB for the underexpanded flow regime, and up to 7 dB for overexpanded condition, except in some cases where in the very high frequency range, the noise was increased. Screech tones were either reduced or eliminated for single side nozzle modifications, but amplified for double side-modified cases, with the turbulent mixing noise found to be unaffected by the addition of the cutouts. The modifications did not alter the noise field for the ideally expanded flow condition, as expected.
Dedicated to my parents, sisters and Melani.
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# TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................... ii

DEDICATION ...................................................................................................................................... iv

ACKNOWLEDGMENTS .................................................................................................................... v

VITA .................................................................................................................................................. vi

LIST OF TABLES ................................................................................................................................ x

LIST OF FIGURES ........................................................................................................................ xi

1.0 INTRODUCTION ....................................................................................................................... 1

2.0 BACKGROUND .......................................................................................................................... 4

2.1 DAWN OF JET NOISE RESEARCH ..................................................................................... 4

2.2 SOURCES OF NOISE IN JET FLOWS ............................................................................. 6

2.2.1 Turbulent Mixing Noise ................................................................................................. 7

\hspace{0.5cm} 2.2.1.1 Mach Wave Radiation ...................................................................................... 8
\hspace{0.5cm} 2.2.1.2 Velocity and Temperature Effects ...................................................................... 9

2.2.2 Broadband Shock Associated Noise ........................................................................... 9

\hspace{0.5cm} 2.2.2.1 Broadband Shock Associated Noise Generation Mechanisms ..................... 10
\hspace{0.5cm} 2.2.2.2 Directivity of Broadband Shock Associated Noise .................................... 11
\hspace{0.5cm} 2.2.2.3 Pressure and Temperature Effects .................................................................... 12

2.2.3 Screech Tones ............................................................................................................... 13

\hspace{0.5cm} 2.2.3.1 Generation Mechanisms of Screech in Shock Containing Jets .................... 14
\hspace{0.5cm} 2.2.3.2 Pressure, Temperature and Nozzle Geometry Effects ................................ 15

2.3 TECHNIQUES FOR PASSIVE CONTROL OF JET NOISE ........................................... 16

2.3.1 Asymmetric Nozzle Geometry ...................................................................................... 17

2.3.2 Tabs, Vortex Generators ............................................................................................... 18

2.3.3 Shaping of the Nozzle Trailing Edge ......................................................................... 19
3.0 EXPERIMENTAL TECHNIQUES AND PROCEDURES ........................................ 26

3.1 HOW TO ACCURATELY MEASURE SOUND ................................................. 27
  3.1.1 Chamber Types ................................................................. 27
  3.1.2 Fully Anechoic Chamber Free Field Dimensions ......................... 28
  3.1.3 Dealing with Background Noise ............................................. 29
  3.1.4 Anechoic Wedges ............................................................. 30
  3.1.5 Other Considerations .......................................................... 31

3.2 DESIGN OF AN ANECHOIC SUPERSONIC JET FLOW FACILITY ....................... 32
  3.2.1 Parameters and Specifications ............................................. 33
    3.2.1.1 Wedge Selection ...................................................... 33
    3.2.1.2 Anechoic Jet Facility Design ................................... 34
    3.2.1.3 Entrainment and Exhaust ......................................... 37
    3.2.1.4 Simultaneous Flow and Acoustic Measurements .................. 37
  3.2.2 Evaluation of the Anechoic Chamber ..................................... 38
    3.2.2.1 Measurement Errors ................................................. 39
    3.2.2.2 Data Reduction Technique ....................................... 39

3.3 EXPERIMENTAL MEASUREMENT TECHNIQUES .............................................. 42
  3.3.1 Jet Facility ................................................................. 43
  3.3.2 Nozzle Modifications ...................................................... 43
  3.3.3 Microphone Placement ...................................................... 44
  3.3.4 Microphone Calibration .................................................... 46
  3.3.5 Data Errors from Microphones .......................................... 46
  3.3.6 Data Acquisition System .................................................. 47

4.0 EXPERIMENTAL RESULTS AND DISCUSSION .............................................. 63

4.1 STREAMWISE VORTICITY ................................................................. 64

4.2 EXPERIMENTAL ERROR IN JET NOISE DATA ........................................... 65

4.3 SPECTRA ............................................................................. 67
  4.3.1 Ideally Expanded Spectra ..................................................... 68
  4.3.2 Overexpanded Spectra ........................................................ 69
    4.3.2.1 90° Measurement Location ......................................... 70
    4.3.2.2 60° Measurement Location ......................................... 71
    4.3.2.3 30° Measurement Location ......................................... 71
    4.3.2.4 Comparisons of the Spectra for the Overexpanded Flow Regime . 72
  4.3.3 Underexpanded Spectra ........................................................ 74
    4.3.3.1 90° Measurement Location ......................................... 74
    4.3.3.2 60° Measurement Location ......................................... 75
    4.3.3.3 30° Measurement Location ......................................... 75
    4.3.3.4 Comparisons of the Spectra for the Underexpanded Flow Regime . 76
4.4 OASPL ..................................................................................................................... 77
  4.4.1 90° Measurement Location ............................................................................. 78
  4.4.2 60° Measurement Location ............................................................................. 78
  4.4.3 30° Measurement Location ............................................................................. 79
  4.4.4 OASPL Comparisons ...................................................................................... 80

4.5 PERCEIVED NOISE LEVEL ................................................................................. 81
  4.5.1 Scaling of Jet Noise Data ................................................................................. 81
  4.5.2 Converting Decibels to Noys ......................................................................... 82
  4.5.3 PNL Measurement Locations ........................................................................ 83
  4.5.4 PNL Comparisons .......................................................................................... 84

4.6 MIXING AND ACOUSTIC MEASUREMENT COMPARISONS ......................... 84

4.7 COHERENCE BETWEEN THE MICROPHONES .............................................. 86

4.8 MICROPHONE COMPARISONS ........................................................................ 88

5.0 CONCLUSIONS .................................................................................................... 129

APPENDIX A ............................................................................................................... 134

APPENDIX B ............................................................................................................... 173

LIST OF REFERENCES ............................................................................................... 212
LIST OF TABLES

Table  Page
4.1 Nozzle modifications with coherence above 0.5 or 50% for mic1 and mic3, at the 90°, 60° and 30° measurement locations, taken at both overexpanded (OE) and underexpanded (UE) flow conditions for single (SS) and double (DS) sided nozzle modifications. ................................................................. 87
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The three sources of supersonic jet noise, shown for an overexpanded Mach 2 aspect ratio 3 rectangular nozzle.</td>
<td>21</td>
</tr>
<tr>
<td>2.2</td>
<td>Schematic of the turbulence and shock structure noise sources in a non-ideally expanded jet.</td>
<td>22</td>
</tr>
<tr>
<td>2.3</td>
<td>The turbulent mixing noise generated by an ideally expanded Mach 2 aspect ratio 3 rectangular nozzle. The arrow points in the direction of increasing amplitude and decreasing peak frequency, showing that the preferential radiation direction is at 30°.</td>
<td>23</td>
</tr>
<tr>
<td>2.4</td>
<td>Displays the angle of the Mach wave radiation as can be calculated using Eqn. 3 in section 2.2.1.1. (Seiner, 1991).</td>
<td>24</td>
</tr>
<tr>
<td>2.5</td>
<td>Broadband Shock Associated Noise for an underexpanded Mach 2 aspect ratio 3 rectangular nozzle. At 90°, the peak in amplitude is seen at 6500 Hz, but disappears into the turbulent mixing noise at 30°.</td>
<td>25</td>
</tr>
<tr>
<td>2.6</td>
<td>Screech tones for a Mach 2 aspect ratio 3 rectangular nozzle. Notice that as the measurement angle decreases, the screech tones do not change their frequency of radiation, unlike the other two jet noise components.</td>
<td>26</td>
</tr>
<tr>
<td>3.1</td>
<td>Image of the current anechoic facility at the Ohio State University Gas Dynamics and Turbulence Laboratory.</td>
<td>48</td>
</tr>
<tr>
<td>3.2</td>
<td>The minimum free field size for accurate measurements in an anechoic chamber. The total dimensions are 180 cm by 120 cm.</td>
<td>49</td>
</tr>
<tr>
<td>3.3</td>
<td>The acoustic wedge in the current facility designed and manufactured by Eckel Industries to a cutoff frequency of 250 Hz.</td>
<td>50</td>
</tr>
<tr>
<td>3.4</td>
<td>Exploded view of the anechoic chamber, showing all of the removable sections, including the door, windows and floor. Notice the windows, the removable floor, and the main front door.</td>
<td>51</td>
</tr>
</tbody>
</table>
3.5 (a) Image from the right side of the chamber showing a removed window. (b) Image showing the 2nd floor section partially removed through the main door. ................................................................. 51

3.6 An assembled view from the bottom of the anechoic chamber with the exoskeletal supports clearly visible. Notice the removed wall sections, outlined by dashed lines, so that the Ventilation opening and the wedges could be seen................................................................. 52

3.7 Plot displaying the transmission loss through the 3.2 mm aluminum wall. Notice that at the lower frequencies, there is less attenuation of the incident sound wave. 0° is considered perpendicular incidence to the wall, with the angles measured from this reference......................................................... 53

3.8 A not to scale plan view of the chamber showing the ventilation openings, wedges, jet location, and bell-mouth................................................................. 53

3.9 Image of the bell-mouth in the current facility................................................. 54

3.10 Not to scale plan view schematic showing the possible chamber setup for a simultaneous flow visualization and acoustic measurement experiment......... 54

3.11 Image of a possible laser optics setup in the anechoic chamber............................. 55

3.12 Image of the sound source as it appeared in the chamber during the qualification testing. Notice the 8 microphone paths......................................................... 55

3.13 Schematic of the microphone paths used in the qualification testing. Path 1 is from the source to the front wall, path 2 is from the source to the back wall, path 5 is from the source to the front left upper corner, etc........................................ 56

3.14 (a) Path 1 is from the source to the front wall. (b) Path 2 is from the source to the bell-mouth. (c) Path 3 is from the source to the left wall. (d) Path 4 is from the source to the right wall......................................................... 57

3.15 (a) Path 5 is from the source to the front upper left corner. (b) Path 6 is from the source to the front lower left corner. (c) Path 7 is from the source to the back upper right corner. (d) Path 4 is from the source to the back lower right corner......................................................... 58

3.16 (a) Schematic of the air supply system. (b) Detail of the stagnation temperature......................................................... 59

xii
3.17 Schematic of the nozzle and its modifications.......................... 60
3.18 The rectangular nozzle used in the experiment, showing the double side RS nozzle modification........................................... 61
3.19 The three microphone array locations for the experiment, at 90°, 60° and 30°. The microphones were placed in the far field at 40 D_{eq}, or 74.5 cm........ 61
3.20 Wedge mounted wooden standoffs used to hold the microphones........ 62
3.21 Oscilloscope display showing the calibration peaks of the microphone. .... 62
4.1 Flow visualizations displaying average cross sectional images at the x/D_{eq}=1 for the three flow conditions. Taken from Kim (1998)...................... 90
4.2 Flow visualizations displaying average cross sectional images at the x/D_{eq}=2 for the three flow conditions. Taken from Kim (1998)...................... 91
4.3 Flow visualizations displaying average cross sectional images at the xD_{eq}=4 for the three flow conditions. Taken from Kim (1998). ....................... 92
4.4 Flow visualizations displaying average cross sectional images at the xD_{eq}=8 for the three flow conditions. Taken from Kim (1998). ....................... 93
4.5 Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for an SS case measured by microphone 1.................. 94
4.6 Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for a DS case measured by microphone 2.................. 95
4.7 Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for an SS case measured by microphone 3................. 96
4.8 Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for an SS case measured by microphone 1.................. 97
4.9 Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for a DS case measured by microphone 1................. 98
4.10 Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for an SS case measured by microphone 1................. 99
4.11 Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for a DS case measured by microphone 1. .................................................. 100

4.12 Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for an SS case measured by microphone 1. ................................. 101

4.13 Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for a DS case measured by microphone 1. ................................. 102

4.14 Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for an SS case measured by microphone 1................................. 103

4.15 Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for a DS case measured by microphone 1................................. 104

4.16 Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for an SS case measured by microphone 1................................. 105

4.17 Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for a DS case measured by microphone 1................................. 106

4.18 Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for an SS case measured by microphone 1................................. 107

4.19 Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for a DS case measured by microphone 1................................. 108

4.20 Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for an SS case measured by microphone 3................................. 109

4.21 Overall sound pressure level plots for the 90° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.................................................. 110

4.22 Overall sound pressure level plots for the 60° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.................................................. 111

xiv
4.23 Overall sound pressure level plots for the 30° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.

4.24 Perceived noise level plots for the 90° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.

4.25 Perceived noise level plots for the 60° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.

4.26 Perceived noise level plots for the 30° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.

4.27 Normalized mixing area curves for the (a) Overexpanded flow condition, and (b) Underexpanded flow condition. Taken from the flow visualization images of Kim (1998) for several double side modified nozzle configurations, at several downstream locations. Displays the mixing increase or decrease due to the nozzle modification.

4.28 Coherence curves for a double sided RC nozzle at 90°, running in the overexpanded flow condition.

4.29 Coherence curves for a double sided OC nozzle at 60°, running in the overexpanded flow condition.

4.30 Coherence curves for a double sided OC nozzle at 30°, running in the overexpanded flow condition.

4.31 Coherence curves for a single sided OC nozzle at 60°, running in the underexpanded flow condition.
4.32 Coherence curves for a single sided RC nozzle at 30°, running in the underexpanded flow condition ................................................................. 121

4.33 Coherence curves for a single sided OC nozzle at 30°, running in the ideally expanded flow condition ................................................................. 122

4.34 Differences between the three microphones for the single side modified cases taken and 90°, 60° and 30° for the overexpanded flow condition .......... 123

4.35 Differences between the three microphones for the double side modified cases taken and 90°, 60° and 30° for the overexpanded flow condition .......... 124

4.36 Differences between the three microphones for the single side modified cases taken and 90°, 60° and 30° for the ideally expanded flow condition .......... 125

4.37 Differences between the three microphones for the double side modified cases taken and 90°, 60° and 30° for the ideally expanded flow condition .......... 126

4.38 Differences between the three microphones for the single side modified cases taken and 90°, 60° and 30° for the underexpanded flow condition .......... 127

4.39 Differences between the three microphones for the double side modified cases taken and 90°, 60° and 30° for the underexpanded flow condition .......... 128

A.1 Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for an SS case measured by microphone 2 .............. 135

A.2 Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for an SS case measured by microphone 3 .............. 136

A.3 Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for a DS case measured by microphone 1 .............. 137

A.4 Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for a DS case measured by microphone 2 .............. 138

A.5 Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for a DS case measured by microphone 3 .............. 139

A.6 Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for an SS case measured by microphone 1 .............. 140

xvi
| A.7 | Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for an SS case measured by microphone 2. | 141 |
| A.8 | Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for an SS case measured by microphone 3. | 142 |
| A.9 | Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for a DS case measured by microphone 1. | 143 |
| A.10 | Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for a DS case measured by microphone 3. | 144 |
| A.11 | Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for an SS case measured by microphone 1. | 145 |
| A.12 | Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for an SS case measured by microphone 2. | 146 |
| A.13 | Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for a DS case measured by microphone 1. | 147 |
| A.14 | Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for a DS case measured by microphone 2. | 148 |
| A.15 | Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for a DS case measured by microphone 3. | 149 |
| A.16 | Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for an SS case measured by microphone 2. | 150 |
| A.17 | Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for an SS case measured by microphone 3. | 151 |
| A.18 | Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for a DS case measured by microphone 2. | 152 |
| A.19 | Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for a DS case measured by microphone 3. | 153 |
| A.20 | Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for an SS case measured by microphone 2. | 154 |
A.21 Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for an SS case measured by microphone 3. ........................................... 155

A.22 Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for a DS case measured by microphone 2. .............................. 156

A.23 Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for a DS case measured by microphone 3. .............................. 157

A.24 Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for an SS case measured by microphone 2. .............................. 158

A.25 Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for an SS case measured by microphone 3. .............................. 159

A.26 Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for a DS case measured by microphone 2. .............................. 160

A.27 Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for a DS case measured by microphone 3. .............................. 161

A.28 Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for an SS case measured by microphone 2......................... 162

A.29 Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for an SS case measured by microphone 3......................... 163

A.30 Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for a DS case measured by microphone 2......................... 164

A.31 Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for a DS case measured by microphone 3......................... 165

A.32 Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for an SS case measured by microphone 2......................... 166

A.33 Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for an SS case measured by microphone 3......................... 167

A.34 Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for a DS case measured by microphone 2......................... 168
A.35 Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for a DS case measured by microphone 3.....................169

A.36 Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for an SS case measured by microphone 2.....................170

A.37 Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for a DS case measured by microphone 2..........................171

A.38 Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for a DS case measured by microphone 3..........................172

B.1 Coherence curves for a single sided BB nozzle at 90°, running in the overexpanded flow condition.................................................................174

B.2 Coherence curves for a single sided RS nozzle at 90°, running in the overexpanded flow condition.................................................................175

B.3 Coherence curves for a single sided OC nozzle at 90°, running in the overexpanded flow condition.................................................................176

B.4 Coherence curves for a double sided OS nozzle at 90°, running in the overexpanded flow condition.................................................................177

B.5 Coherence curves for a double sided RS nozzle at 90°, running in the overexpanded flow condition.................................................................178

B.6 Coherence curves for a single sided BB nozzle at 60°, running in the overexpanded flow condition.................................................................179

B.7 Coherence curves for a single sided RC nozzle at 60°, running in the overexpanded flow condition.................................................................180

B.8 Coherence curves for a single sided OC nozzle at 60°, running in the overexpanded flow condition.................................................................181

B.9 Coherence curves for a single sided RS nozzle at 60°, running in the overexpanded flow condition.................................................................182

B.10 Coherence curves for a single sided OS nozzle at 60°, running in the overexpanded flow condition.................................................................183
B.11 Coherence curves for a double sided RC nozzle at 60°, running in the overexpanded flow condition..................................................................................184
B.12 Coherence curves for a double sided RS nozzle at 60°, running in the overexpanded flow condition..................................................................................185
B.13 Coherence curves for a double sided OS nozzle at 60°, running in the overexpanded flow condition..................................................................................186
B.14 Coherence curves for a single sided BB nozzle at 30°, running in the overexpanded flow condition..................................................................................187
B.15 Coherence curves for a single sided RC nozzle at 30°, running in the overexpanded flow condition..................................................................................188
B.16 Coherence curves for a single sided OC nozzle at 30°, running in the overexpanded flow condition..................................................................................189
B.17 Coherence curves for a single sided RS nozzle at 30°, running in the overexpanded flow condition..................................................................................190
B.18 Coherence curves for a single sided OS nozzle at 30°, running in the overexpanded flow condition..................................................................................191
B.19 Coherence curves for a double sided RC nozzle at 30°, running in the overexpanded flow condition..................................................................................192
B.20 Coherence curves for a double sided RS nozzle at 30°, running in the overexpanded flow condition..................................................................................193
B.21 Coherence curves for a double sided OS nozzle at 30°, running in the overexpanded flow condition..................................................................................194
B.22 Coherence curves for a single sided BB nozzle at 60°, running in the underexpanded flow condition..................................................................................195
B.23 Coherence curves for a single sided RS nozzle at 60°, running in the underexpanded flow condition..................................................................................196
B.24 Coherence curves for a double sided RC nozzle at 60°, running in the underexpanded flow condition..................................................................................197
B.25 Coherence curves for a double sided OC nozzle at 60°, running in the underexpanded flow condition.................................................. 198

B.26 Coherence curves for a double sided OS nozzle at 60°, running in the underexpanded flow condition.................................................. 199

B.27 Coherence curves for a single sided BB nozzle at 30°, running in the underexpanded flow condition.................................................. 200

B.28 Coherence curves for a single sided OC nozzle at 30°, running in the underexpanded flow condition.................................................. 201

B.29 Coherence curves for a single sided RS nozzle at 30°, running in the underexpanded flow condition.................................................. 202

B.30 Coherence curves for a single sided OS nozzle at 30°, running in the underexpanded flow condition.................................................. 203

B.31 Coherence curves for a double sided RC nozzle at 30°, running in the underexpanded flow condition.................................................. 204

B.32 Coherence curves for a double sided OC nozzle at 30°, running in the underexpanded flow condition.................................................. 205

B.33 Coherence curves for a double sided RS nozzle at 30°, running in the underexpanded flow condition.................................................. 206

B.34 Coherence curves for a double sided OS nozzle at 30°, running in the underexpanded flow condition.................................................. 207

B.35 Coherence curves for a single sided BB nozzle at 60°, running in the ideally expanded flow condition........................................... 208

B.36 Coherence curves for a single sided RC nozzle at 60°, running in the ideally expanded flow condition........................................... 209

B.37 Coherence curves for a single sided BB nozzle at 30°, running in the ideally expanded flow condition........................................... 210

B.38 Coherence curves for a single sided OS nozzle at 30°, running in the ideally expanded flow condition........................................... 211
CHAPTER 1

INTRODUCTION

The noise radiated by supersonic nozzles of jet aircraft prevent the wide use of supersonic commercial transports, cause property values around airports to lower, and limit economic development in these area. Sonic fatigue in supersonic aircraft effects nozzle lips, engines, and tail fins by the upstream propagation of sound, which in time can lead to failure of these structures through cyclic vibration of the part. Proven methods for reducing jet noise do exist, but at great expense to the aircraft's overall performance. These methods use large bypass air ducts and acoustic shielding, further increasing the weight and drag of the vehicle. In light of this, and the fact that researchers have been developing methods for increasing mixing in jet flows, simple, possibly cost-effective ways of reducing noise without large penalties have surfaced. Such methods rely on modifications applied to the nozzle, causing measurable reductions in the noise while increasing mixing. The addition of tabs, beveled cuts, the coaxial flows and trailing edge modifications are among the few mixing devices that have been found to both increase the mixing and decrease the noise.
Reducing turbulent mixing noise and shock associated noise of a jet flow has proven to be a difficult task, considering our limited understanding of turbulence, turbulent structures, and sound generating mechanisms in supersonic flows. However, some of the factors in the evolution of jet noise are understood, such as the creation of Mach waves by turbulent structures, and the interaction of turbulent structures with shock cells to form shock associated noise. In addition, the velocity of the flow plays a major role in the production of noise. In general, the slower the flow, the less noise produced. To date no firm theoretically or computationally based solutions have been formulated to accurately model the noise from these turbulent flows. Gharib (1996) explained that all simulations of turbulent fluid flows with a Reynolds number of $10^5$ or greater do not have the resolution required to capture the necessary information for understanding. Although empirical models have been developed, they are only reliable for similar types of nozzle flows, from which they were based.

Trailing edge modified nozzles have been recently examined for their ability to increase the mixing in supersonic jets for underexpanded flow conditions, with some possible large reductions in the downstream-radiated noise. After a detailed investigation of the flow physics of such nozzles, it was time to perform an in-depth analysis of the noise field in these jets. The objectives of this research were to first construct an anechoic jet flow facility where accurate sound measurements of supersonic jet flows could be conducted. Second, the effects of nozzle trailing edge modifications on an aspect ratio 3, high Reynolds number, $1.3 \times 10^5$, rectangular supersonic nozzle were
for its effects on far field noise in various flow regimes. An attempt was also made at relating the radiated noise to the flow physics.
CHAPTER 2

BACKGROUND

2.1 Dawn of Jet Noise Research

The founder of jet noise research, the Sir James Lighthill, published his first papers (Lighthill 1952, 1953, 1954) in 1952, thus establishing the field of Aeroacoustics. In these papers, he introduces his now famous jet noise equation, the Acoustic Analogy Theory, as

\[
\frac{\partial^2 \rho}{\partial t^2} - a_\infty^2 \nabla^2 \rho = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}
\]  

(1)

where \( \rho \) and \( a_\infty \) are the density and the speed of sound in the ambient, respectively. The right hand side of this equation is considered the source of the sound emitted by a jet flow. The Lighthill stress tensor, \( T_{ij} = \rho u_i u_j + \{(p-p_\infty) - c_0^2 (\rho-\rho_\infty)\}\delta_{ij} \), where \( u \), \( p \), and \( c \) are the velocity, pressure, and speed of sound, and \( \delta_{ij} \) is the Kronecker delta, is considered the dominant noise producing term is the first term. In order to solve this equation, the Lighthill tensor either must be measured, or obtained theoretically or computationally, none of which has yet to be accomplished. However, the Acoustic Analogy Theory does
present a starting point for the reduction of jet noise, as Lighthill found after performing a
dimensional analysis, concluding that the radiated noise from subsonic jets is
proportional to the velocity of the jet raised to the eighth power.

Numerous researchers have built upon Lighthill’s work, either experimentally or
theoretically. Moore (1953) and Ribner (1954, 1955) theoretically examined the
interaction of jet flow with shock waves, noting that shock noise had a preferential
radiation direction upstream. Powel (1953 a and b) took the research further, finding
what he termed screech tones, formed by the unsteady interaction of shock waves with
turbulent structures. The process proceeds as follows, a feedback loop forms when
instabilities in the flow create sound waves, which travel upstream and encounter the
nozzle, reflecting back into the flow setting off further instability waves, thus closing the
loop, and causing the generation of distinct harmonic frequencies. According to Raman
(1998), Merle (1956) found experimentally that screech tones had five different
characteristic modes, which were later classified by Davis and Oldfield (1962 a and b).
Kramer (1955) took Lighthill's research on turbulent mixing noise and discovered that he
could calculate a convective Mach number from Schlieren images, after finding distinct
pressure waves radiating from the jet. Later, Phillips (1960), who coined the term Mach
wave radiation, improved upon the theory. Pao (1973), inspired by Phillips, studied and
improved upon his convective wave equation. Ffowcs-Williams (1963) refined
Lighthill’s Acoustic Analogy theory by relating the work to high-speed jet flows. He
stated that the acoustic power of the noise radiated by a supersonic jet is proportional to
the velocity of the jet cubed. A few years later Ffowcs-Williams and Maidanik (1965)
pushed the Lighthill Acoustic Analogy theory further by developing an approximate theory for predicting Mach wave radiation. Lilley (1972) contributed to the analytical approaches by introducing a connective wave solution for looking at turbulent structures.

2.2 Sources of Noise in Jet Flows

From the basic understanding that has been formulated through countless experiments and theoretical investigations, jet noise sources can be divided into three types. The most dominant of these noise sources, turbulent mixing noise or Mach wave radiation, occurs in all flow regimes of a jet. In the imperfectly expanded flow regimes, shock associated noise also occurs in the forms of broadband shock associated noise and screech tones, a special case of the latter. The shock associated noise sources arise when convecting turbulent structures in the shear layer of the flow interact with the shock cell structures of the jet.

Figure 2.1 is a frequency spectrum of the noise produced from the baseline rectangular nozzle studied in this experiment, operating in the overexpanded flow regime and taken at a measurement angle of 90° to the jet axis. The three components of jet noise are indicated. The turbulent mixing noise is in the lower frequency region of the figure, the screech tones appear as the prominent narrow-band peaks in the spectrum, and the broadband shock associated noise peak can also be seen just before the second harmonic of screech. In Fig. 2.2 the source locations and directivity of the three jet noise components are displayed. The shock noise produces the broadband shock associated noise and screech tones, which has upstream directivity, and are generated by the interaction of turbulent structures in the shear layer with the shock cell structure of the
jet. The turbulent structures create two kinds of noise, that from small scale turbulence, which has sideline and upstream directivity, and that from large scale turbulence and or Mach wave radiation, which has downstream directivity. Broadband shock associated noise and screech tones may be dominant in the upstream direction, though Raman (1998) stated that in the far field, screech tones, when they occur, become the dominant noise in all directions, because it radiates with high intensity.

2.2.1 Turbulent Mixing Noise

Occurring in all flow regimes of subsonic and supersonic jet nozzles, turbulent mixing noise is the most studied and modeled jet noise component. In general, this noise component is produced by the mixing mechanisms present in the jet. Tam (1995) believes that the source of turbulent mixing noise is made up of two distinct components, large-scale turbulent structures and fine-scale turbulent structures. However, little is known about the breakdown or growth of large scale structures to or from fine scale structures. In this thesis, this process will be termed the cascading of large scale structures, where the turbulent mixing noise will be considered as the sum of all of the noise generated by large scale and cascading structures. The larger scale structures are believed to radiate in the lower frequency range and in the downstream, where as the cascading structures radiate to the sideline and at higher frequencies, as suggested by Mollo-Christensen et al. (1964). Figure 2.3 shows the peak radiation direction of the turbulent mixing noise being generated in the ideally expanded flow regime. In this figure, the peak of the spectra increases in amplitude and decreases in peak frequency, as
the measurement angle is decreased, signifying that the turbulent mixing noise radiates in the downstream direction.

2.2.1.1 Mach Wave Radiation

Papamoschou and DeBiasi (1999) state that in jets with exit velocities in excess of the speed of sound, i.e. convective velocities of the structures of the jet greater than the speed of sound, Mach wave radiation plays an integral part in the overall radiated noise. This turbulent mixing related noise could account for as much as 20 dB of the total sound pressure level measured from the jet. The convection of large scale turbulent structures, formed by shear layer instabilities propagating supersonically relative to the ambient, have been found to cause Mach waves, and are believed to be the most dominant of the three supersonic jet noise components (Washington and Krothapalli 1999), along with turbulent mixing noise.

Mach waves are generated near the edge of the jet flow, in the region of the jet surrounding the potential core (Tam 1995 and 1998a, Seiner 1991). They are directional in the downstream direction of the flow, and only occur if the structures in the flow are at sonic speed or faster. Increased temperatures also have a major effect on the Mach waves. As the temperature increases, so does the speed, size and radiation direction of the large-scale structures. The angles of radiation of the Mach waves are determined by

\[ \theta = \cos^{-1} \left( \frac{1}{M_c} \right) = \cos^{-1} \left( \frac{a_s}{\alpha V_j} \right) \]  \hspace{0.5cm} (2)
where \( \alpha = V_c / V_j \). The terms \( a_0 \), \( V_j \), \( V_c \), and \( M_c \) are the speed of sound in the ambient, velocity of the jet, turbulence convection velocity and the convective Mach number. As shown in Fig. 2.4, Eqn. 2 can be used to calculate the angle theta (Seiner 1991).

2.2.1.2 Velocity and Temperature Effects

The intensity, spectral distribution and directional characteristics of the turbulent mixing noise in supersonic jets depend heavily on the temperature ratio with the ambient and Mach number at the jet exit (Tam, 1995). Tanna (1977a) performed an in depth analysis of jet noise while varying the jet exit velocity and the temperature. He used several nozzles, both converging and converging-diverging, to obtain different velocities, and operated them only in the perfectly expanded flow regime, as to not introduce any shock associated noise. Tanna found what the Lighthill Acoustic Analogy theory stated, that the velocity of a jet directly effects the intensity of the sound measured. In all of the cases he examined, the intensity of the noise increased for every increase in jet velocity. When he increased the temperature, an increase in the intensity of sound was most significant in the downstream directions. One other notable fact was that as the temperature was increased and the jet operated at lower velocities, an increase in the overall intensity of the noise was observed, where as when the jet was operated at higher velocities and temperatures, decreases in the overall sound intensity were noticed.

2.2.2 Broadband Shock Associated Noise

Supersonic aircraft operate in off design conditions, either in the overexpanded or underexpanded flow regime, for a large portion of their flight envelope. For converging
nozzles operated at pressures above their design and converging-diverging nozzles operated in off design conditions, shock cells form in the flow (Tanna 1977b). Turbulent structures passing through the cells interact with shock waves to generate shock-associated noise, which has two distinguishable parts, broadband shock associated noise and screech tones. Each of these two components has a preferential radiation direction upstream or towards the nozzle and similar generation mechanisms, dependent on the shock cell spacing and operating pressures of the nozzle (Seiner 1991). Broadband shock associated noise and its generation mechanisms will be discussed in the following section, followed by the second shock associated noise component, screech tones.

2.2.2.1 Broadband Shock Associated Noise Generation Mechanisms

Theoretical and experimental evidence from several researchers, as reported by Seiner (1984 & 1991), have found that broadband shock associated noise has a direct connection to the convecting turbulent structures moving and interacting with the shock cells in the jet plume (Harper-Bourne and Fisher 1974). Shock cells form in supersonic flows when compression waves in overexpanded jets or expansion waves in underexpanded jets form to equalize the pressure of the jet with that of the surroundings. The waves reflect back into the flow as they encounter the subsonic air at the jet boundary in the shear layer. When turbulent structures interact with the shock cells, pressure waves are emitted from each cell in the flow creating broadband noise. The intensity and spectral content of the generated noise depends on the interference patterns for each set of the emitted waves (Kim et al. 1992). These waves coalesce to form a discrete peak frequency associated with a broad spectral range. Seiner (1984) reports that
the most intense noise is generated at the interface between the sonic and subsonic region, where the shock waves are terminated and reflected back into the flow. Norum and Seiner (1982) reported that the noise sources of broadband shock associated noise could be modeled as stationary acoustic sources placed on the ends of each shock cell.

2.2.2.2 Directivity of Broadband Shock Associated Noise

Figure 2.5 shows the broadband shock associated noise generated for an underexpanded flow condition without screech at the three measurement angles for this experiment. The dominant and most intense broadband peak can be seen in the 90° direction, as compared to the other measurement angles. This gives rise to the fact that the noise generated by turbulence interacting with the shock cells travels in the upstream direction. In the 60° direction, the peak moves to a higher frequency. At this point, the broadband shock associated noise begins to merge with the turbulent mixing noise, dominant in the downstream directions. For the 30° direction, the broadband peak has become less dominant than the turbulent mixing noise, which as a result, can no longer be identified in the spectra. Seiner (1991) states that the shock noise is greater than the turbulent mixing noise at the larger measurement angles, and as seen from the Fig. 2.5, it loses its influence on the noise at smaller, downstream angles. Seiner (1984) also points out that as the jet becomes increasingly underexpanded, the broadband shock associated noise becomes omnidirectional. The shift of the peak frequency, which was noticed in the Fig. 2.4 as the measurement angle is increased, has been explained by Tanna (1977b), and Norum and Seiner (1982) as a Doppler effect in the flow. The Doppler effect varies
with the turbulence convection speeds and the shock cell spacing in the jet plume (Kim et al. 1992).

2.2.2.3 Pressure and Temperature Effects

Harper-Bourne and Fisher (1974), and Tanna (1977b), as reported by Kim et al. (1992), both found that the intensity of the broadband shock associated noise appears to be a function of the jet pressure and temperature ratios. Tanna (1977b) noted several findings from his experiments, which are significant to the understanding of broadband shock associated noise. In his experiments, he isolated the component of interest by removing the screech from the nozzle, when necessary, with a tab inserted into the flow. He found that when a jet was operated at a fixed temperature and at a fixed measurement location with rising pressure, the broadband shock associated noise becomes more dominant than the turbulent mixing noise. If the pressure and measurement angle were held fixed, with the temperature being increased, Tanna (1977b) found that the turbulent mixing noise grows and becomes more dominant than the broadband shock associated noise. Finally, he varied the measurement angle with the pressure and temperature being fixed at supercritical values, finding that the broadband shock associated noise radiated in the upstream direction was most dominant beyond 90°. He concluded that the broadband shock associated noise was the most significant when the jet was operated at pressure ratios other than one, with low temperatures, and when the upstream noise was of interest.
2.2.3 Screech Tones

As mentioned in section 2.2.2, the third jet noise component, screech tones, are generated under the same jet operating conditions as broadband shock associated noise, namely in imperfectly expanded supersonic jet flows. Unlike its counterpart, broadband shock associated noise, screech has been widely studied both theoretically and experimentally. Screech tones can be identified as prominent peaks in the spectral plots, present in Fig. 2.6. Notice that there are several harmonics to screech, and that changes to the measurement angle do not affect the frequency, at which the tones radiate, where as the peak in broadband component in the same figure shifts to higher frequencies with the decreasing measurement angle. However, the intensity of the screech tones change with the measurement location just as the intensity of the broadband shock associated noise, decreasing at smaller angles, signifying a more preferential upstream radiation direction. One other noticeable fact from Figure 2.6 is that screech effects the turbulent mixing and broadband shock associated noise through what Tam (1996) has termed, broadband amplification. This can be seen as the raised sections highlighted in Figure 2.6. Screech tones are also the most destructive of the three jet noise components (Raman, 1997). Due to its high amplitude at fixed frequencies and upstream propagation, screeching aircraft suffer from what is termed sonic fatigue. Failures in the British VC-10, and in the U.S. F-15 and B1-B have prompted a renewed effort to study the mechanisms that cause screech tones and methods to reduce or eliminate them.
2.2.3.1 Generation Mechanisms of Screech in Shock Containing Jets

Powel discovered screech in the 1950's when he started researching the phenomena emanating from converging nozzles. He explained the development of screech as embryonic or minute disturbances that originate at the nozzle lip, growing as they propagate downstream, and interacting with the multiple shock cells in the flow to produce sound at a resonant frequency, dependent on the nozzle (Powel 1953b). The sound was found to have preferential directivity upstream, towards the nozzle, traveling outside the jet flow (Tam 1995), which sets off further instabilities, thus creating a sustained feedback loop. Raman (1998), in a review paper, discussed that the instabilities in the flow could be explained by looking at the oscillatory modes in the jet flow caused by screech. There are four types of oscillatory modes, which are present when a jet is screeching, causing it to oscillate in one or all four of these modes, switching between them in a random manner. The first of these screeching modes has two parts, A1 and A2, which are axisymmetric. The second and third modes, B and C, are both helical, and the fourth, D, was found to be a sinuous mode. These oscillation modes are related to instability modes occurring in the shear layer of jet flows. Raman (1998) states that the growth rate of these instability modes in the shear layer are exponential for all types of jet flows, but in shock containing flows, the instability wave modes become altered, causing non-linear propagation. The non-linear propagation causes the waves to interact with the unsteady shocks in the supersonic flow, creating screech tones.

The screech tones radiate according to the strength of the turbulent structures and the shock cells for which they pass through, and they radiate at the frequency equivalent
to the length of each individual cell, hence multiple harmonics. Seiner (1991) has surmised that the shock cell spacing must be at or near an integer multiple of the wavelength of the strongest fixed frequency or instability wave in the shear layer, to send the shock cells into oscillation at that frequency, producing screech. He also states that the acoustic feedback loop to the nozzle lip must be maintained in order for sustained screeching. Rice and Taghavi (1992) have found that the sources of screech noise in a rectangular nozzle are closely related to the shock cell structure in the jet plume. In their experiments, they found "islands" of high amplitude sound radiating from the flow, which they say can be related to the noise peaks observed slightly downstream of each of the shocks contained in the flow. Rice and Taghavi (1992) also notice that the screech tones appear to cancel themselves in the downstream directions, thereby accounting for the supposed upstream propagation.

2.2.3.2 Pressure, Temperature and Nozzle Geometry Effects

Several variables effect the screeching of a nozzle, including the pressure and temperature of the jet, as well as the way the nozzle was designed. Powel (1953b) found that by increasing the nozzle pressure ratio, the intensity of the screech tones increased. Tam (1995) has reported that this increase is due to mode switching, discussed earlier, and thus causing non-linearity in the instability waves. Temperature increases have been found to have the opposite effects on the intensity of screech tones, causing weakened instability waves and a frequency mismatch between the turbulent structures and the shock cells, thus reducing the screech noise (Tam 1995).
Screech tones are altered significantly with small changes to the nozzle geometry and with objects surrounding the nozzle. Raman (1998) explains several cases where changes to the environment around a supersonic screeching flow may alter the screech tones. Differences in the nozzle geometry, i.e. a thicker nozzle lip, can cause the screech tones to send the jet into random oscillation, and increase the amplitude of the screech tones by orders of magnitude, also increasing the mixing of the jet. The presence of surfaces near the jet exit can also magnify the screech tones, making them the dominant noise source. However, if these surfaces are placed in just the right positions, the screech tones will be canceled, and the flow will steady. Twin or coupled jets, as on the F-15, can also cause an increase in the amplitude of the screech tones, through a sound generation mechanism called screech tone coupling.

2.3 Techniques for Passive Control of Jet Noise

Minimizing the sound generated in supersonic jets due to mixing and shock associated noise has several benefits. These include reducing the impacts of jet noise on the environment and reducing the effects of sonic fatigue on the aircraft. Several penalties exist when implementing devices that reduce noise emanating from jet engines, including increased weight, size and drag of the airframe and nacelles, and reduced thrust from the engines due to bulky bypass flows and acoustic liners. These factors play a large part in the overall functionality of the aircraft, and have to be dealt with in the design process.

Most techniques that are being developed to decrease noise in supersonic flows rely on the velocity cubed law from Ffowcs-Williams (1963), which states that the
intensity of the noise emanating from a supersonic nozzle is proportional to the velocity of the flow raised to the third power. Current noise control techniques work on the premise that by increasing the mixing of the flow and thereby reducing the velocity of the structures in the flow, noise will be reduced. However, it must be noted that not all methods of increasing the mixing of a jet flow will decrease the noise. With this in mind, there are two methodologies used to increase the mixing in a jet, either active or passive control techniques. In order to determine the best method for reducing the noise, the costs and penalties of the modification need to be weighed. The active control method alters the jet flow by actively deforming the nozzle or changing the chemistry of the flow by adding heat, inducing ionization of the air particles or other methods, such as reducing or increasing the air pressure immediately around the nozzle exit. The passive methods increase the mixing by applying some static change to the nozzle, such as a mixer ejector, co-flow, tabs, or a change in the nozzle geometry, such as trailing edge modifications. For the remainder of this paper, passive control methods will be examined for their noise reduction capabilities in supersonic jet flows.

2.3.1 Asymmetric Nozzle Geometry

Non-axisymmetric nozzle shapes, such as rectangular, elliptic and lobed nozzles have been extensively studied (Gutmark et al., 1990; Seiner, 1991; Kinzie and McLaughlin, 1995; Raman, 1997; Tam, 1998b; Tam, 2000), because they are believed to decrease the noise from supersonic jet nozzles due to increased mixing and spreading rates. Kinzie and McLaughlin (1995) studied elliptic cold air, and simulated heated jet nozzles, where helium was used to help imitate the lower density of air in heated jets and
increase the velocity of the large-scale structures in the flow. They found that the cold air jets somewhat decreased the noise on the major axis plane, but the simulated heated elliptic jets are much greater in their noise reduction on both axis planes as compared to data from axisymmetric nozzles. Kinzie and McLaughlin (1995) also concluded that it is possible to misinterpret cold jet data, which does not include the effects of Mach wave radiation in heated jets. In heated jets, the larger scale structures travel at higher Mach numbers, hence radiating Mach waves at greater amplitudes and peak frequencies.

A recent study by Tam (1998b), reported that turbulent mixing noise in cold jets is not affected by changes to nozzle geometry. He observed this by conducting measurements on several simple, asymmetric nozzles, and comparing them to his similarity spectra (Tam et al. 1996) for circular nozzles at the same operating conditions. Asymmetric nozzles are also seen to weaken screech tones, as Raman (1997) reports, due to the development of spanwise oblique shock cells. The shock cells change to fit the nozzle exit dimensions, which effects the source locations and screech generation mechanisms. He also reports that supersonic flows from asymmetric nozzles screech over a limited Mach number range.

2.3.2 Tabs, Vortex Generators

Streamwise vortex generating devices, such as tabs, are placed at or near the nozzle exit, substantially increasing the mixing in the shear layer, and have been found to reduce the generated noise. Many researchers have studied their effects on subsonic flows (Ahuja and Brown, 1989; Samimy et al., 1993; Rogers and Parekh, 1994; Surks et al., 1994; Reeder and Samimy, 1996; Bohl and Foss, 1999; Tam and Zaman, 1999; Tam,
2000) and in supersonic jet flows (Ahuja and Brown, 1989; Samimy et al., 1993; Zaman et al. 1994; Zaman, 1999; Ibrahim and Nakamura, 2000). The main effects of tabs are similar in both subsonic and supersonic flows, where a pair of strong streamwise vortices are generated, and grow in the downstream direction. These vortices help to entrain ambient air into the jet, and enhancing the mixing with the ambient fluid.

Tabs have been shown to eliminate or reduce screech noise, and can substantially reduce mixing and shock associated noise at lower frequencies, but in some instances, increases at the noise have been seen in higher frequencies (Ahuja and Brown, 1989; Samimy et al., 1993; Zaman et al., 1994; Ibrahim and Nakamura, 2000). Vortex generating tabs are effective, in all flow regimes for mixing enhancement and noise reduction, with exception to the increased high frequency noise, the effects of which are not clear at this point. Unfortunately, tabs appear to cause a substantial thrust penalty (Zaman et al., 1994; Zaman, 1999; Ibrahim and Nakamura, 2000).

2.3.3 Shaping of the Nozzle Trailing Edge

Due to the thrust penalties associated with tabs, other types of nozzle modifications, which do not exhibit these negative characteristics, have been pursued (Kim, 1998; Kim and Samimy, 1999 and 2000). Some limited work in shaping of the trailing edge (Wlezien and Kibens, 1988; Tam, 2000) in circular nozzles and beveling the trailing edge (Rice and Raman, 1993; Raman, 1997; Tam, 2000) in rectangular nozzles has shown promise in mixing enhancement and reductions in noise. Verma and Rathakrishnan (1999) have shown that mixing enhancements and noise reductions are
seen in the flow of a circular nozzle with notches cut out of the nozzle lip, much like trailing edge modifications.

In rectangular jets, trailing edge modifications have been shown to substantially increase the mixing in underexpanded cases and slightly increase the mixing in overexpanded cases, with preliminary noise measurements showing reductions in the overall sound pressure level (Kim, 1998; Samimy et al., 1998; Kim et al., 1998; Kim and Samimy, 1999 and 2000). In the aforementioned references, mixing enhancement was induced in the flow by streamwise vortices generated by a spanwise pressure gradient over the modified trailing edges in the underexpanded flow regime. In the overexpanded flow regime the flow separates due to an adverse pressure gradient, thus only a very small mixing enhancement was seen. For the ideally expanded cases, a mixing enhancement was not noticed, due to the lack of a pressure gradient.

The limited noise measurements conducted by Kim (1998) and an in-depth acoustic study by Kerechanin et al. (1999) on a trailing edge modified rectangular jet, exhibited promise in reducing the radiated noise from a jet without causing a thrust penalty. This prompted the larger study at several downstream positions of the noise radiating from these types of modified nozzles. In the following text, the design of the test facility and the results of the experiments will be explained. In short, an anechoic test facility was designed, and acoustic measurements on the trailing edge modifications was completed to find that the screech was reduced or eliminated in the overexpanded cases, and turbulent mixing noise was substantially reduced in the underexpanded flow regime.

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Figure 2.1: The three sources of supersonic jet noise, shown for an overexpanded Mach 2 aspect ratio 3 rectangular nozzle.
Figure 2.2: Schematic of the turbulence and shock structure noise sources in a non-ideal expanded jet.
**Figure 2.3:** The turbulent mixing noise generated by an ideally expanded Mach 2 aspect ratio 3 rectangular nozzle. The arrow points in the direction of increasing amplitude and decreasing peak frequency, showing that the preferential radiation direction is at 30°.
Figure 2.4: Displays the angle of the Mach wave radiation as can be calculated using Eqn. 3 in section 2.2.1.1. (Seiner, 1991)

Figure 2.5: Broadband Shock Associated Noise for an underexpanded Mach 2 aspect ratio 3 rectangular nozzle. At 90°, the peak in amplitude is seen at 6500 Hz, but disappears into the turbulent mixing noise at 30°.
Figure 2.6: Screech tones for a Mach 2 aspect ratio 3 rectangular nozzle. Notice that as the measurement angle decreases, the screech tones do not change their frequency of radiation, unlike the other two jet noise components.
CHAPTER 3

EXPERIMENTAL TECHNIQUES AND PROCEDURES

The original acoustic measurements taken on the trailing edge modified nozzles by Kim (1998) were completed in an open room. At that time, care was taken to treat some of the surrounding surfaces with acoustical foam, but spurious data from reflected acoustic waves and background noise could still have affected the measurements. To quantitatively test the trailing edge modified nozzles for the hypothesized noise reductions, an anechoic test facility was designed and constructed to be compliant with the ANSI Standard S12.35 (ANSI, 1990). Figure 3.1, shows the chamber as it appears today. The theory behind anechoic chambers will first be discussed in the following section, after which, the parameters and design of the current facility will then be detailed, as well as the qualification test results for the chamber.

Once the chamber was known to act as a free field, preparations for the first acoustical experiment in the chamber were completed. The nozzle trailing edge modifications, which have been previously discussed, were tested in the chamber to verify the preliminary noise measurements, and to gather more information on the
acoustic field from these nozzles. The experimental setup for this experiment will be discussed after the anechoic chamber.

3.1 How to Accurately Measure Sound

An anechoic chamber or a "no echo" room is the state of the art for accurately measuring noise in the laboratory. Past publications on the design of anechoic chambers include Ingerslev et al. (1967) and Duanqi et al. (1990). These chambers create a free field environment, meaning that the sound absorbing surface area is much greater than any reflective surface area in the room. This could be compared to an echo that would occur by yelling into a canyon, where the surface area of the reflecting surfaces are large, and to the absence of an echo if one were to yell at 10,000 feet off the ground, an idealized free field. A free field means that the sound pressure level from a spherically radiating sound source decays according to the inverse radius squared law, dissipating six decibels for every doubling of the distance traveled (Duda, 1977 and 1998). There are very few publications or texts on the design and construction of anechoic chambers, so the following discussion will try to clarify the main points.

3.1.1 Chamber Types

Duda (1977), discussed several points that need to be considered when designing an anechoic chamber, including the type of chamber desired, the inner dimensions from wedge tip to tip, wall construction, ambient background sound levels, ventilation requirements, the type of floor desired and wedge selection. There are two types of anechoic chambers, fully anechoic and hemi-anechoic. In a fully anechoic chamber, all
surfaces are covered with sound absorbing material, effectively eliminating the reflection of sound waves. Rooms such as these are excellent for highly accurate maps of acoustic intensity from a source. Hemi-anechoic rooms are not fully anechoic, having all surfaces, except the floor, covered in sound absorbing material. This allows for testing of the sound power coming from a sound source in actual situations, such as a piece of machinery mounted on a concrete floor to simulated the noise as it would radiate in a factory setting, or an idling automobile on asphalt, as in someone's driveway. Most chambers which are designed to be fully anechoic, can with very slight modifications to the floor, be converted to an hemi-anechoic room.

3.1.2 Fully Anechoic Chamber Free Field Dimensions

The internal, wedge tip-to-tip, dimensions of a fully anechoic chamber depend on the lowest frequency of interest and the physical dimensions of the sound source to be used in the room, such as the diameter of a speaker. In the case of the current study, large scale turbulence structures are the noise sources, which have been determined to have sizes comparable to the nozzle exit diameter. According to Duda (1977), the minimum distance from wedge tip to tip in a chamber would be

$$D_{\text{min}} = 4S_d + \frac{\lambda}{2} \quad (3)$$

where $D_{\text{min}}$ is the wedge tip-tip distance, $S_d$ is the dimension of the source or 30 cm, whichever is greater, and $\lambda$ is the wavelength of the lowest desired frequency or 120 cm, whichever is greater. The $4S_d$ limits the so-called measurement sphere around a source to a minimum radius of 60 cm from the center of the source, which is the location of any
microphones or wedge tips. The $\lambda/2$ accounts for the distance a microphone placed on the edge of the measurement sphere needs to be away from the wedge tips, which was limited to a minimum of 60 cm. Therefore, in Fig. 3.2, the smallest size free-field measurement area can be 180 cm by 120 cm from wedge tip to tip, with one microphone measurement location, ensuring that half of a period of the lowest sound wave of interest will be present. The microphone and source placement has been idealized by the measurement sphere diameter to $\frac{1}{2}$ of a wavelength of the lowest desired frequency, but one can place either device at a minimum distance of $\frac{1}{4}$ of a wavelength away from the walls (Duda, 1977). Doing so can decrease the overall size of the chamber, or increase the measurement area.

3.1.3 Dealing with Background Noise

The background noise must be sufficiently low in an anechoic chamber in order to obtain accurate measurements. According to the ANSI (1990) standard, any measured background noise within 15 dB below any measured noise source spectra at a specified frequency needs to be corrected by subtracting a given correction factor. In order to prevent this unwanted step, anechoic chambers should be designed so that they are shielded from outside noise sources. The simplest way of solving this problem is to construct the walls of the chamber out of a material with adequate transmission loss, usually a dense material such as masonry block or prefabricated acoustical panels. The reduction of the background noise through a wall may be found for most materials by employing the perfectly limp plate theory (Pierce, 1991), where the specific impedance is
obtained directly from the inertia of the material used in the wall construction. The transmission loss is

$$ R_{TL} = 10 \log_{10} \left[ 1 + \left( \frac{2\pi m_{pl}}{\rho \lambda} \right)^2 \cos^2 \theta \right] $$

(4)

where \( m_{pl} \) is the plate mass per unit area, found from the density times the thickness of the plate, \( \rho \) is the density of the fluid, i.e. air, \( \lambda \) is the wavelength of the sound incident on the wall and \( \theta \) is the angle of incidence of the wave, as long as it is not close to the grazing angle (total reflection angle), or where \( \cos(\theta) \) is small. Double walls with an air gap in-between them may be used where highly accurate measurements are desired. Other types of background noise may arise as vibrations through the floor, or from the channeling of outside noise through ventilation ducts. In most cases where sensitive measurements are being taken, any vibrations or spurious noise sources that are transferred from the surroundings, through the floor or walls of the chamber can be detected by the microphones. To isolate these sources, anechoic rooms are usually built with foundations separate from the building in which they are housed, and mounted on spring or rubber pads, or a combination of both. Ventilation ducts must be designed as long channels leading into and out of the chamber, and lined with sound absorbing materials, to help dampen background noise (Duda, 1977).

### 3.1.4 Anechoic Wedges

The acoustical wedges are the most important part of an anechoic chamber; and are the determining factor for the cutoff frequency, also called the acoustical floor of the
chamber. Without well-designed wedges, the sound waves in the room would reflect back towards the microphones, disrupting measurements. In order to achieve the highest performance out of a chamber, wedge materials with a coefficient of absorption closest to the theoretical value of 1.0 are desired. To obtain low cutoff frequencies, the wedge must be sized appropriately, the longer the wedge the lower the cutoff frequency that can be reached. Commercially available wedges range in length from 15 cm to 1.2 m. For most wedge materials, a cutoff frequency of 250 Hz with a coefficient of absorption of 0.99 can be obtained with a wedge length of 50 cm or more. Higher frequencies are more readily attenuated by most anechoic wedges and are therefore not a major concern. Foam wedges are used for most chamber designs, but in situations where fire or high temperatures may be a factor, fiberglass wedges are used. Newer wedge designs use perforated metal plating shaped into a wedge and filled with a sound absorbing material, promoting excellent high temperature ratings and durability, but at a much higher cost.

3.1.5 Other Considerations

The floor of an anechoic chamber depends on the types of experiments that are being conducted. Construction materials of the floor usually consist of a wire mesh, or grating, which is used because it is acoustically transparent and can be suspended over the wedges. To make entering a chamber and experimental setup easier, the floor wedges are usually sunk into the floor of the laboratory with the suspended wires or grating level to the lab floor.

Several other factors help in the creation of a free field in an anechoic chamber. Additional modifications to the wedges, such as including air spaces behind them, give
the benefit of a lower cutoff frequency without an increase in length or materials. Surfaces in a chamber such as microphone stands, test subject stands, etc., should be covered with acoustical foam, to prevent any unwanted or spurious data points. Open-ended hollow tubes or channels should be closed at both ends, or avoided altogether. Standing waves can form in these cavities during testing, causing a resonate frequency to form, generating unwanted noise and disrupting measurements.

3.2 Design of an Anechoic Supersonic Jet Flow Facility

In order to measure jet noise, a standard anechoic chamber needs to be modified for the high flow rates and temperatures common in this field of study. Papers by Iyengar and Krothapalli (1991), written solely on the design of such a facility, and Quartararo and Lauchle (1985), on inlet wall design in order to overcome entrainment problems, touch on the difficulties associated in designing these types of chambers. The inlet wall of a chamber needs to be designed so that any noise created outside of the chamber will be eliminated before traveling into the free field environment with the entrained air. The bell-mouth, used to channel and exhaust the jet air from the chamber, also needs to be covered by sound absorbing material, due to it being the largest flat surface in a chamber, and the largest uncovered opening. In some cases, high temperature flows may be examined, and the materials of the chamber need to be chosen to withstand the extreme temperatures of heated jets.
3.2.1 Parameters and Specifications

Davidz (1997) initiated the design of the anechoic chamber for the current experiments. From her initial observations and suggestions, the design parameters for the chamber were used and modified as follows. An adaptable and modular thin walled room was planned for easy experimental setup for both acoustic and non-acoustic testing. High temperature wedges were needed for future heated jet experiments. A high flow rate acoustically lined ventilation system was needed, as well as an acoustically lined exhaust. Finally, the chamber must be built for a reasonable price, without sacrificing the desired acoustic qualities.

3.2.1.1 Wedge Selection

Originally in Davidz (1997), the wedge size and cutoff frequencies planned for an acoustic floor in the chamber of 150 Hz. After pricing and rough calculations of the total chamber size and the space available in the high bay laboratory, the cutoff frequency was set to 250 Hz. The wedge material was selected based upon an 800 K operating temperature of the heated jet, to be use in some experiments. Most acoustic wedges are manufactured from foam and are relatively inexpensive, but at high temperatures, the foam tends to release thick black smoke as it decays. In light of this, fiberglass was chosen for the wedge material, at higher cost, but with less of a concern for safety.

The wedges, Fig. 3.3, were manufactured and tested by Eckel Industries of Cambridge, MA. They can withstand sustained temperatures of up to 800 K, and are constructed from fiberglass matting, Owens Corning type 703, and covered with
fiberglass cloth, J.P. Stevens type 1675, to prevent shedding. Wire mesh was used to encase the fiberglass wedges to help maintain the original shape. The wedge dimensions are 20.0 x 61.0 cm at the base, with a height of 43.2 cm. There are three wedges per group, which are mounted on a frame to allow for a 5.0 cm air gap behind the wedges once placed against the wall to help achieve the cutoff frequency. The total dimensions of a wedge group are 61.0 x 61.0 x 46.0 cm.

3.2.1.2 Anechoic Jet Facility Design

Due to the diversity of the types of experiments conducted by the group, acoustic measurements, Planar Doppler Velocimetry, flow visualizations and simultaneous flow and acoustic measurements, the chamber was designed in such a manner as to easily accommodate several different experimental setups. This meant that it needed to have easy camera and laser access as well as fulfilling all of the acoustic requirements for simultaneous tests. The size of the chamber was also limited by the lab space. With these conditions in mind, the general size of the chamber was determined by a simple calculation involving Eqn. 3. Multiplying the second term on the right by two in order to account for two microphone measurement locations in a single plane, one microphone on either side of the nozzle.

\[ D_{\text{min}} = 4S_d + \lambda \]  

(5)

Since the cutoff frequency was already chosen, \( \lambda \) was found as 136 cm from \( \lambda = \frac{c}{f} \), where \( c \) is the speed of sound and \( f \) is the cutoff frequency. \( S_d \) was less than 30 cm, the jet has a maximum diameter nozzle of 2.54 cm, giving the minimum chamber size, \( D_{\text{min}} = 256 \) cm.
cm. Figuring the number of wedges which would fit in the chamber, without going below the minimum size or over the maximum floor space, the dimensions from wedge tip-to-tip, measure 3.12 m in width and length, and 2.69 m in height.

The chamber was designed to be modular, in that modifications could be made easily, without disassembling the chamber. Figure 3.4 presents an exploded view Pro-E drawing of the basic modular design, where the rectangular sections represent the doors, windows, walls and the removable floor. There are no structural members present in the figure. Each of these exploded pieces can be removed if so desired, however, the windows, floor and doors were designed to be the easiest removable sections. The wall sections could be removed, though with a considerable amount of effort. In order to grant laser and camera access from the outside, windows, consisting of a single wedge group mounted on a modular section, were placed on all four walls of the chamber and can be detached as needed by removing a few screws from the main structure, Fig. 3.5(a). In this manner, cameras could be placed at almost any angle to the jet flow. Two windows were also placed above the jet in the ceiling. The laser beam can be brought in through a window or by a small hole in the side of the chamber. The floor was designed to be completely removable, Fig. 3.5(b), in order to simplify experimental setup, and to allow for easier camera placement when acoustic testing is not taking place. The floor was divided into five sections of five wedge groups each, which can be removed through the main door. The centerline of the jet was placed 1.52 m from the ceiling wedge tips, 1.56 m from both side-wall wedge tips, and 1.17 m from the floor wedge tips. Originally, the plan was to center the jet in the front wall of the chamber, but after physically looking at
the height of the nozzle and the locations of the cameras, the jet nozzle was place at eye level.

An exoskeletal structure was chosen to support the walls of the chamber so as not to interfere with the mounting of the wedges, Fig. 3.6. The beams are extruded aluminum channels, manufactured by Item Products, Livonia, MI, with the entire structure being held together by screws and plates. The walls of the chamber are 3.2 mm (1/8th inch) thick aluminum sheets. Concern has been voiced over the thickness of the walls, because low frequency noise can easily be transmitted through them, causing increased background noise. A simple calculation using Eqn. 4, with \( m_p \) equaling 8.25 Kgm\(^{-2}\), \( \rho \) equaling 1.2 Kgm\(^{-3}\), and \( \lambda \) and \( \theta \) being left as variables gives the curves in Fig. 3.7. At higher frequencies, the thin wall decreases the incident noise by a considerable amount, but at lower frequencies, the transmission of the sound is much greater. Adding another wall or acoustic treatment to the outside of the chamber would improve this value. However, one of the main assumptions made when choosing the wall material, was that the noise generated by the jet would be much greater than the background noise in the chamber, thereby canceling the need for a thick wall. This assumption has held true for most experiments, except in situations where subsonic jet noise is studied. In these instances, the background noise does interfere with measurements near the very high frequency range, greater than 55 kHz. One other concern was the noise from the airport, which is next to the laboratory that could travel into the chamber. The chamber was built within another building, doubly attenuating the noise external to the lab, essentially giving double wall protection from outside noise sources. To dampen floor
vibrations, rubber pads were used as an insulation layer underneath the structure, as removing the existing floor and pouring a separate foundation was not feasible. The outside dimensions of the chamber are 4.11 m wide by 4.71 m long and 3.68 m high.

### 3.2.1.3 Entainment and Exhaust

The jet enters the chamber through an open window in the center of the front wall, Fig. 3.8. For air entrainment by the jet, a variable size ventilation opening, partially blocked by an overhang and lined with acoustical foam, was built into the front wall of the chamber, Figs. 3.6 and 3.8. This simple design allows for the unimpeded flow of air, as well as the dampening of outside noise traveling into the chamber. The variable size comes from the ventilation opening being approximately 65 percent blocked by acoustical foam, which can bend with the increased in entrainment rates at higher jet speeds. On the back wall, across from the jet, a bell-mouth was placed to capture the exhaust and channel it out of the building, as seen in Figs. 3.8 and 3.9. The bell-mouth is 1.2 m in diameter and contracts down to 60 cm in diameter. Because the bell-mouth extends into the chamber, it was treated with sound absorbing fiberglass, cloth and wire mesh, similar to the wedge materials, which helps to prevent reflected noise from disrupting measurements.

### 3.2.1.4 Simultaneous Flow and Acoustic Measurements

During simultaneous flow visualizations and acoustic testing (Hileman, 2000), a schematic of which is shown in Fig. 3.10, the windows can be removed as needed for camera placement without disrupting acoustical measurements. In order to keep the
chamber “anechoic”, special foam inserts were designed to fit into the window opening with each insert having a slot for the camera lens. To simplify camera placement the centerline of these windows coincides with the centerline of the jet. Laser optics can be mounted on a framework connected to the windows in the ceiling, Fig. 3.11. This framework allows for laser sheet placement, in either spanwise or streamwise directions, at a distance of up to 2.0 m from the nozzle exit. The same framework can also be used for mounting the microphones.

3.2.2 Evaluation of the Anechoic Chamber

The chamber was tested for compliance to the ANSI Standard S12.35 (ANSI, 1990). This entailed measuring the decay of the sound pressure level (SPL) generated by a source, Fig. 3.12, suspended in the center of the room in eight radial directions of microphone paths, Fig. 3.13. For reference, in Fig. 3.8, the front wall is where the jet enters the chamber. The sound generator, a B & K type HP1001 with a type 4205 sound source, was set to generate broadband or so called white noise for all measurements from 0 to 10 kHz. A 1/4-inch condenser microphone, B & K type 4135, with a type 2670 preamplifier, attached to a type AO-0416 30 m extension cable, and a type 5935 dual microphone amplifying power source, was placed at several increasing distances away from the generator along each path. The microphone was calibrated using a B & K type 4231 acoustical calibrator before each set of measurements. The SPL was recorded on an HP35665A Digital Signal Analyzer (DSA) and plotted on a PC. Along each path, the SPL was measured every 15 cm starting at 25 cm from the center of the chamber, which coincides with the placement of the source. Measurements were taken until the
microphone was within 10 cm of the wedge tips. Also note that the data taken for the qualification tests were not acoustically weighted.

3.2.2.1 Measurement Errors

All reasonable precautions were taken to reduce spurious noises from entering the chamber. Ventilation and bell-mouth openings were filled with acoustical foam, and all exposed surfaces, except for the sound source, were covered. Further precautions were taken as to conduct the qualification test after normal working hours, so other noises from laboratory work or the airport would not disrupt the data. Problems were found between the lighting system in the chamber and the DSA. ANSI (1990) recommended that during the testing, all electrical equipment in the chamber should be turned off. While initially taking data, the DSA would spike after moving the microphone further up a microphone path. It was determined that by turning on and off the lights, an electrical surge was created causing the DSA to reset the calibration to a higher value, thereby increasing the SPL of the recorded data. To remedy this, the chamber was grounded in several places and the lights were left on, after determining that they did not affect the data.

3.2.2.2 Data Reduction Technique

The information was compared to the theoretical inverse radius squared law for SPL decay in a free field. This law states that for each doubling of distance away from a source in a free field, the SPL will decay 6 dB, a halving of the acoustical power of the sound source. The spherical spreading rule of a sound source (Pierce, 1991) was used to calculate this theoretical curve. In Eqn. 6, the term $I_{av}$ is the average acoustical intensity
at a specified radius, $P_{av}$ is the average power, $r$ is the spherical surface radius, $(P)^2_{av}$ is the rms pressure, $\rho$ is the density of the fluid, i.e. air, and $c$ is the speed of sound.

$$I_{r,av} = \frac{P_{av}}{4\pi r^2} = \frac{(P)^2_{av}}{\rho c} \quad (6)$$

Taking Eqn. 5 and setting it equal to the average reference power at a distance of 100 cm along a microphone path equal to the value of the average reference power at each other location for the average pressure terms gives,

$$P_{100} = \frac{4\pi r^2 (P)^2_{100}}{\rho c} = P = \frac{4\pi r^2 (P)^2}{\rho c} \quad (7)$$

$$P^2_{100} r^2_{100} = p^2 r^2 \quad (8)$$

Dividing by the reference pressure, $p^2_{ref}$, and $r^2_{100}$, then taking the log of base ten of both sides and multiplying by ten,

$$10 \log_{10} \left( \frac{P^2}{p^2_{ref}} \right) = 10 \log_{10} \left( \frac{P_{100}^2}{p^2_{ref}} \right) = 10 \log_{10} \left( \frac{r_{100}^2}{r^2} \right) + 10 \log_{10} \left( \frac{P_{100}^2}{p^2_{ref}} \right) \quad (9)$$

where the reference pressure is $20 \times 10^{-6} \text{ Pa}$. Finally,

$$SPL = 20 \log_{10} \left( \frac{r_{100}}{r} \right) + SPL_{100} \quad (10)$$

where SPL is the sound pressure level that should be measured at the $r$ measured distance from the source, at the reference values for 100 cm, if the chamber is a true free field.

Results from the qualification tests were in good agreement with this theoretical prediction. The measured data followed the theoretical values within the required tolerance for frequencies of 250 Hz and above, over the distances along the microphone paths at each measured frequency between 0 to 10 kHz, which is the calibrated range of
the sound generator. Figure 3.14(a-d), displays the results for paths 1 through 4, for a horizontal measurement plane parallel with the jet centerline, and Fig. 3.15(a-d), displays the results for paths 5 through 8 for a vertical measurement plane cutting from the back right corner to the left front corner of the chamber.

In Figs. 3.14 and 3.15, the solid lines represent the inverse r-squared theory and the dotted lines with the data point markers represent the collected data. The data is presented such that nine measurement points or path lengths of 145 cm away from the center of the chamber are viewed. This measurement sphere was larger than the theoretical measurement sphere calculated in section 3.2.1.2, so as to obtain the most accurate picture of the acoustic far field in the chamber. The frequencies listed above each measurement curve are representative of the calibrated range of the sound source. Each curve was shifted 20 dB from the previous in each plot. The paths correspond to those in Fig. 3.13. Microphone paths 1, 3, 4, and 5 are considered critical, because most measurements will be taken around these locations. In Figs. 3.14(a, c, and d) and Fig.3.15(a) there is excellent agreement, as the data deviates less than the 1 to 1.5 dB range as specified by ANSI (1990). However, there are two exceptions, the 1000 Hz case in Fig. 3.14(c), and the 250 Hz case in Fig. 3.15(a) near the 150 cm mark. The measurement locations deviated from the theoretical curve, but are outside of the measurement sphere, within a ¼ wavelength distance of the cutoff frequency from the wedge tips, so these discrepancies will not interfere with the effective use of the chamber as microphone will not be placed in this location.
The other plots display excellent agreement between the data and the theory, less two exceptions. In Fig. 3.14(b), path 2, from the source to the bell-mouth, there appears to be a large discrepancy from the theory, but this has been discounted, because sound data cannot be gathered in the bell-mouth area due to the jet flow. Lastly, in Fig. 3.15(a), at 250 Hz, there is deviation away from the theoretical curve. This signifies that in the ventilation-opening region, due to the absence of wedges, there are some reflections of sound waves back to the microphone. This also should not be a problem, because, as mentioned before, this measurement location occurs outside of the measurement sphere, and is within 1/4 wavelength from the wedge tips, where microphones will not be placed.

3.3 Experimental Measurement Techniques

The experimental setup evolved through the course of this experiment, because this was the first time the chamber was used to collect sound data from the jet, and most of the equipment was new. It was found that the chamber, computer cart and microphones needed to be grounded in order to eliminate noise in the data. Frequent calibration of the microphones was required, as the temperature and humidity would change readings almost hourly. The frequency filters, were found to oscillate and caused several sets of data to be invalid, these were replaced with new equipment. One original microphone location would cause noise in the data, and had to be moved from the ceiling location, to the floor. Lastly, the protective screens on the microphones were found, after several trials, to cause noise in the spectra, so they were removed during testing. These problems and their solutions will be examined in the following section as well as the final experimental procedure.
3.3.1 Jet Facility

The experiments were conducted in the Gas Dynamics and Turbulence Laboratory at Don Scott Airport on the Ohio State University Campus. Two four-stage compressors supply the air for the jet facility, which is filtered, dried, and stored in two cylindrical tanks with a total capacity of 42.5 m$^3$ at 16.5 MPa. The air is delivered to the laboratory through a 10.2 cm (4 in) diameter main line, with a 5.1 cm (2 in) diameter line providing air to the primary jet. This line passes through a pressure regulator, which is controlled by the user, who sets a specified pressure in the stagnation chamber. Once in the primary stagnation chamber, the air is expanded from the supply line to a 24.1 cm diameter pipe that is 91.4 cm long for flow conditioning. The air passes through a perforated plate (37% porosity), two mesh screens, and finally converges to a 6.0 cm pipe that is 40.6 cm long. After passing through this pipe, it enters an aspect ratio 3 rectangular nozzle, which is positioned so the major axis is vertical. The nozzle is attached to the pipe by an adapter, which takes the circular pipe cross-section smoothly down to the nozzle shape. The jet used in has a Reynolds number on the order of 1.3 x 10$^6$. Figure 3.16(a) shows a schematic of the air supply system, and Fig. 3.16(b) details the jet stagnation chamber. This jet facility was constructed completely from stainless steel in order to prevent severe expansion problems while running with heated air.

3.3.2 Nozzle Modifications

The aspect ratio 3 Mach 2 rectangular nozzle used in the present experiments was the smaller of the two nozzles studied by (Kim, 1998; Samimy et al., 1998; Kim et al.,
1998; Kim and Samimy, 1999 and 2000). The nozzle dimensions are 0.95 cm high and 2.68 cm wide (3/8 inches by 1-1/8 inches). The equivalent diameter, \( D_{eq} \), for the nozzle was found to be 18.6 mm (0.733 inches) using \( D_{eq} = (4A_{ne}/\pi)^{1/2} \), where \( A_{ne} \) is the area at the nozzle exit. The nozzle was designed with a nominal Mach number of 2.0, and a measured Mach number of 1.93. The modifications are placed on trailing edge extensions, to allow the flow to fully develop before being introduced to the cutouts, Fig. 3.17(a). Based on the flow visualization, mixing and preliminary acoustic results presented in Kim (1998), eight modified nozzles were tested against a baseline case for a total of nine nozzles at three flow conditions of ideally expanded (\( M_j = 2.00 \)), overexpanded and underexpanded (\( M_j = 1.75 \) and \( M_j = 2.50 \)). These modifications are shown in Fig. 3.17(b and c). The nozzle-naming scheme will use the abbreviations introduced in Fig. 3.17, where the baseline nozzle will be called BB and modifications as RC, RS, OC and OS. An image of the nozzle employed in this study can be seen in Fig. 3.18.

3.3.3 Microphone Placement

Far-field acoustic measurements were carried out, using three 1/4-inch condenser microphones, B & K type 4135, with a type 2670 preamplifier, and two type 5935 dual microphone amplifying power source. The three microphones, two positioned along the minor axis and one on the major axis of the nozzle, were placed perpendicular to the flow in the same plane at 90°, 60° and 30° angles, measured from the jet axis, Fig. 3.19. The signals from the microphones were passed through a low pass frequency filter, DL Instruments, LLC model 4302, set at a cutoff frequency of 125 kHz. This was done to
remove any high frequency anomalies from the microphones and eliminate any potential aliasing. The microphones were placed in the far field, 40 \( D_{eq} \) (74.5 cm) from the nozzle centerline. Wooden standoffs, Fig. 3.20, designed to fit over a single wedge held adjustable length metal rods used as microphone stands. The standoffs were anchored in place by four hooks, also attached to the wedges. Two 10 m and one 30 m microphone extension cables, B & K type AO-0415 and AO-0416 respectively, were used to reach the microphone power supplies on the computer cart.

The spherical spreading rule (Pierce, 1991) was used to determine the lowest usable far field frequency at the measurement location. This rule states that for all values of \( kr \), much greater than one, where \( k \) is the wave number and \( r \) is the measurement distance away from the source, the measurement position occurs in the far field. Taking the wave number so as to make it a function of the wavelength, \( \lambda \), and using the relations in Eqn. 11,

\[
k = \frac{\omega}{c} \quad \omega = 2\pi f \quad \lambda = \frac{c}{f} \quad (11)
\]

where \( c \) is the speed of sound in air and \( f \) is the frequency, a basic relation can be found where \( f \) is a function of \( kr \). Then, choosing \( kr \approx 10 \) as an order of magnitude greater than 1,

\[
f = \frac{5c}{r\pi} \quad (12)
\]

Substituting \( c = 340 \text{ ms}^{-1}, \) and \( r = 74.5 \text{ cm} \), the domain that can be used to obtain far field data was determined to include all frequencies measured above 726 Hz.
3.3.4 Microphone Calibration

The microphones were calibrated using a B & K type 4231 acoustical calibrator before each set of measurements, to ensure that the data being gathered was consistent with changes in temperature and humidity. The procedure for calibration was to first set all microphone power supply gains to 20 dB, thereby ensuring that the complete sensitivity of the microphones was used. The signal output of one of the microphones was then attached to a HP 54501A Digitizing Oscilloscope after passing it through the frequency filter. The calibration device was placed on the microphone and was set to produce a constant 114 dB sound wave. The difference between trough and peak of the sine like signal displayed on the oscilloscope, Fig. 3.21, was then determined. Recording the value, the calibrator was placed on the next microphone, and the oscilloscope was set to read its output. The difference between the reading and the known signal was then calculated and the fine gain sensitivity was adjusted if need be in order to match the first two signals. The procedure was then repeated for the last microphone.

3.3.5 Data Errors from Microphones

In some experiments, the protective grids on the microphones, which protect the pressure transducer from damage, need to be removed. The screens should be removed during high frequency measurements where the amplitude of the wavelengths at certain frequencies matches the grid size or when ½ of a wavelength matches the distance from the grid to the pressure transducer. When either of these conditions occur, usually between 25 kHz and 60 kHz, distortions are seen in the data. The grid may block some
frequencies from being measured, and the space between the grid and the pressure transducer can cause a standing wave to form at several harmonic frequencies. Distortions were in the spectra for the current, which study prompted removal of the protective grids.

Care was taken to ground all equipment. Electrical surges occurring anywhere in the chamber or on the computer cart, cause spikes and or amplitude increase in the microphone signals. The chamber and computer cart were grounded to the air and water lines in the lab. The microphones were also indirectly grounded in several places, the metal rods used to hold the microphones were wrapped in electrical tape for extra insulation, and the connections between the microphone cables and the extension cables were carefully placed as to prevent contact with any metal in the chamber. Lastly, the microphone power supplies and frequencies filters had their internal grounds turned on.

3.3.6 Data Acquisition System

The acoustic data was gathered using a National Instruments PC-416 Analog-to-Digital (A/D) board, with a sampling rate of 190 kHz. The Labview data acquisition program sampled 100 blocks of 8192 points for each microphone, with a total sampling time of 8.192 seconds, and saved the data to the hard disk of a Pentium III personal computer. The frequency resolution or bandwidth is 23.19 Hz. The acoustic data was then averaged using a Fast Fourier Transform in the signal processing toolbox of Matlab to find the OASPL, spectra, phase angles, and microphone coherence.
Figure 3.1: Image of the current anechoic facility at the Ohio State University Gas Dynamics and Turbulence Laboratory.
Figure 3.2: The minimum free field size for accurate measurements in an anechoic chamber. The total dimensions are 180 cm by 120 cm.
Figure 3.3: The acoustic wedge in the current facility designed and manufactured by Eckel Industries to a cutoff frequency of 250 Hz.
Figure 3.4: Exploded view of the anechoic chamber, showing all of the removable sections, including the door, windows and floor. Notice the windows, the removable floor, and the main front door.

Figure 3.5: (a) Image from the right side of the chamber showing a removed window. (b) Image showing the 2nd floor section partially removed through the main door.
Figure 3.6: An assembled view from the bottom of the anechoic chamber with the exoskeletal supports clearly visible. Notice the removed wall sections, outlined by dashed lines, so that the Ventilation opening and the wedges could be seen.
**Figure 3.7:** Plot displaying the transmission loss through the 3.2 mm aluminum wall. Notice that at the lower frequencies, there is less attenuation of the incident sound wave. 0° is considered perpendicular incidence to the wall, with the angles measured from this reference.

**Figure 3.8:** A not to scale plan view of the chamber showing the ventilation openings, wedges, jet location, and bell-mouth.
Figure 3.9: Image of the bell-mouth in the current facility.

Figure 3.10: Not to scale plan view schematic showing the possible chamber setup for a simultaneous flow visualization and acoustic measurement experiment.
Figure 3.11: Image of a possible laser optics setup in the anechoic chamber.

Figure 3.12: Image of the sound source as it appeared in the chamber during the qualification testing. Notice the 8 microphone paths.
Figure 3.13: Schematic of the microphone paths used in the qualification testing. Path 1 is from the source to the front wall, path 2 is from the source to the back wall, path 5 is from the source to the front left upper corner, etc.
Figure 3.14: (a) Path 1 is from the source to the front wall. (b) Path 2 is from the source to the bell-mouth. (c) Path 3 is from the source to the left wall. (d) Path 4 is from the source to the right wall.
Figure 3.15: (a) Path 5 is from the source to the front upper left corner. (b) Path 6 is from the source to the front lower left corner. (c) Path 7 is from the source to the back upper right corner. (d) Path 8 is from the source to the back lower right corner.
Figure 3.16: (a) Schematic of the air supply system. (b) Detail of the stagnation temperature.
a. The nozzle block. Notice the location of the nozzle modifications. Not to scale.

Nozzle Modifications

Baseline | Rectangular Center Cut | Rectangular Side Cut | Oblique Center Cut | Oblique Side Cut

b. The nozzle modifications, notice the abbreviations in each diagram. Not to scale.

c. Single and double sided nozzle configurations using the RC modification as an example. The BB modification is used in the single side modified case. Not to scale

Figure 3.17: Schematic of the nozzle and its modifications.
Figure 3.18: The rectangular nozzle used in the experiment, showing the double side RS nozzle modification.

Figure 3.19: The three microphone array locations for the experiment, at $90^\circ$, $60^\circ$ and $30^\circ$. The microphones were placed in the far field at $40 \, \text{D}_{\text{eq}}$, or $74.5 \, \text{cm}$. 

61
Figure 3.20: Wedge mounted wooden standoffs used to hold the microphones.

Figure 3.21: Oscilloscope display showing the calibration peaks of the microphone.
CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSION

The main goals of this research were to determine what, if any effect, the production of streamwise vortices by the trailing edge modifications had on the radiated noise field of the jet, and to relate any findings to the flow physics, studied in the previous work (Kim, 1998). The experiments were completed in the anechoic chamber at three microphone positions, three measurement angles, with nine different nozzles, for a total of 81 data sets. The spectra are compared to the baseline cases for each microphone and at each measurement location, in an attempt at determining the low, mid and high frequency differences and similarities between the nozzles. The OASPL (overall sound pressure level) was calculated, to obtain an overall view of the effect of the modifications on the flow. Relationships, which were discovered between the mixing increases measured by Kim (1998) and the noise reductions viewed through the spectra, in the underexpanded 30° cases, will be discussed. Other results of interest include the calculated perceived noise level (PNL) after scaling to a larger actual size diameter nozzle, possible asymmetry between microphones in the downstream directions where
symmetry of the radiated noise was expected (Tam, 1996, 1998a and 2000), and acoustic radiation coherency.

4.1 Streamwise Vorticity

The streamwise vortices, as discussed in section 2.3, are formed when tabs or cutouts are placed in the flow or on the nozzle trailing edges. These types of vortices substantially increase the mixing in the shear layer through the creation of large-scale streamwise structures. The overexpanded and ideally expanded flow regimes were not expected to yield significant reductions in the jet noise, due to the lack of streamwise vortices in the flow, however. the underexpanded case was expected to show considerable deviations from the BB case, due to the strong mixing from streamwise vorticity. The three potential types of streamwise vorticity generated in the rectangular nozzle by the modifications as quoted from Kim (1998) are the vortices being convected downstream in the boundary layer on the inside wall of the nozzle, a spanwise pressure gradient in the nozzle, and baroclinic torque. It was shown that the spanwise pressure gradient was the dominant source of streamwise vorticity (Kim and Samimy, 1994).

The previous works of Kim (1998), and Kim and Samimy (1999) on the mixing enhancement of nozzles using trailing edge modifications showed, that the various nozzle modifications altered the mixing in the shear layer, either by entraining the ambient air into the jet or expelling the jet fluid. Fig. 4.1 shows the effect of the modifications in the $x/D_{eq} = 1$ position, where $x$ is the distance from the nozzle exit, and $D_{eq}$ is the equivalent nozzle diameter. Fig. 4.2, 4.3 and 4.4 show the mixing for the three flow conditions at $x/D_{eq} = 2, 4$ and 8, respectively. Notice in these figures that the underexpanded flow
regime experiences the greatest increase in the mixing, where as the over and ideally expanded regimes show only a slight increase in mixing. Also notice reduced mixing for the RS and OS nozzle modifications, as compared to the RC and OC cases for increasing measurement distance through all flow conditions, Fig. 4.1-4.4. The RS and OS nozzle modifications generate ‘kidney’ shaped streamwise vortices that entrain ambient air into the jet. These vortices have a strong early development, but tend to decay further down stream, due to the destructive interaction between the vortices. RC and OC nozzle modifications generate ‘mushroom’ shaped streamwise vortices that eject the jet fluid into the ambient. These vortices grow gradually from the nozzle exit, increasing in size as they traverse downstream.

4.2 Experimental Error in Jet Noise Data

Tam (2000) discusses that jet noise data measured at different facilities varies slightly in quality, as would be expected. When noise measurements are completed, the spectra gathered are rarely, if ever, smooth lines, and contain so called “wiggles”. Tam (2000) states that wiggles of 0.5 to 1.0 dB along the entire spectra for jet noise measurements can be considered good data. In this experiment, it was found that the data has a range of wiggle values, from 0.1 to 2.5 dB, depending upon the sample frequency. In the low frequency range, from 0 to 9 kHz, the wiggle was measured to be 0.1 to 0.7 dB, the wiggle in the mid frequency range, 9 to 12 kHz, was measured as 0.7 to 1.5 dB, and in high frequency range, above 12 kHz, the wiggle was 1.5 to 2.5 dB. Therefore, any deviations less than 2.5 dB from the BB in the spectra plots, will be thought of as within
the measurement error and can not be determined as caused by the modifications themselves.

The reason for the varying amount of wiggle in the spectra became clear after comparing the above measurements to the microphone calibration curves, provided by B & K, with the protective screen removed. These calibrations at the factory were completed in a controlled environment, showing that a microphone, at 10 kHz, was seen to lose up to 0.5 dB of amplitude, and at 50 kHz, the microphone could lose up to 2.0 dB of amplitude. The results are similar for the other two microphones. From the calibration curves, it seems that wiggles would still be present in the data, even in ideal condition. The varying ambient pressure, temperature and humidity could have caused the increased wiggle seen in the experimental results, which are impossible to control and change on a daily basis. The reduced sensitivity at higher frequencies seen in the experimental data and in the factory calibration curves also implies that to reach lower wiggle values, very high quality microphones need to be purchased to prevent a drop off of the amplitude at these high frequencies. An environmentally controlled anechoic chamber should be used to lessen the deviations. One last possible way reducing the wiggles would be to acquire more blocks, as only 100 blocks were averaged, would reduce the wiggle in the spectral results.

Other errors, which could have disrupted the data, include the placement of the microphones, even though great care was taken to measure the downstream distances and angles, the air currents formed in the chamber could shift their positions. The air leaking from the seams around the nozzle modifications, due to repeated use. The leaking of air
was first noticed when the nozzle was frosted over, and small areas between the interface point between the nozzle block and the modifications did not frost due to air jetting from small openings. Vacuum grease was used to seal the contact edges, which appeared to stop all leaks. Reflections of sound and air from the bell-mouth may also have affected the measurements.

4.3 Spectra

Examination of the modified nozzle spectra as compared to the baseline case has held several surprising results. For the ideally expanded cases, the spectra behaved in much the same manner as discussed in Kim (1998) where it was determined that due to the lack of a spanwise pressure gradient in the nozzle there was an insignificant mixing increase from the BB configuration. For the overexpanded cases, Kim (1998) found that there was only a slight pressure gradient and a negligible to small increase in the mixing. However, the preliminary noise results did find that the screech for the overexpanded flow regime was reduced or eliminated for most of the single sided modifications applied to the nozzle, which has been confirmed in the present study. Underexpanded cases had the greatest spanwise pressure gradient causing the greatest increase in the mixing. Preliminary measurements found that the OASPL was considerably reduced for all modifications, which were again confirmed by the measurements in the anechoic chamber.

For all spectra plots, the BB (baseline) cases are plotted as they were measured, meaning the curves were not amplitude shifted. However, the modification spectra have been amplitude shifted, starting from the BB, and then from each other by the amount
specified in the title bar above each plot. This was done for ease of presentation and comparison. To better compare each modification to the BB, one further step was taken to plot a Butterworth filtered BB spectrum over each modification spectrum. The reader must also note that the limits of the figures are not held constant, changing to fit as much of the curves on the page as possible. Other information on the plot includes: OE, PE, UE, in the title bar, which stand for overexpanded, ideally expanded and underexpanded, respectively. SS and DS, which stand for single side modified nozzles and double side modified nozzles, respectively, the measurement direction, 90°, 60° and 30°, and the microphone number, as mic1, mic2 and mic3. Sample spectra from all of the flow conditions will be discussed in detail, however, due to the large volume of information gathered, some of the measurements were found to be similar and not included in the main text, but for completeness, are presented in Appendix A for interested readers.

4.3.1 Ideally Expanded Spectra

For the ideally expanded flow condition there was little to no change from the BB. Figs. 4.5-4.7 displays select choices from the data set, which will be discussed for content. The rest of the ideally expanded spectra gathered can be viewed in Figs. A.1-A.15. As mentioned in the background, the turbulent mixing noise was shown to be dominant in this flow regime due to the lack of shock structures in the jet. Mach wave radiation was also thought to occur, as it is known to occur in the 30° downstream directions where the convective Mach number is greater than 1.00. Kim (1998) calculated the theoretical convective Mach number for the present jet to be 0.83, which is less than 1.00, but Mach waves could still occur. Thuow et al. (2000), using an
advanced imaging technique measured a much higher convective velocity, 340 m/s, in a Mach 1.30 jet than they calculated, 209 m/s. Knowing that there could be such a difference between the theoretical and measured values, it may be possible to have some Mach wave radiation in this case, where the jet was at much higher velocities.

In Fig. 4.5, the spectra shown are for a single side modified nozzle at 90° at mic1, which was above the modification on the minor axis, Fig. 3.19. The spectra does not exhibit any strong peak frequencies or dominant features, Mollo-Christensen et al. (1964) stated that cascading structures radiate in the sideline directions, and are dominant in this direction. Fig. 4.6 displays the overexpanded spectra at 60° for mic2, the sideline or major axis microphone, for double side modified nozzles. Notice the peak radiation frequency occurs around 6500 Hz, with an increase in amplitude over Fig. 4.5 of 4dB. This peak hints at the turbulent mixing noise, but there are still the effects of the cascading structures in the spectra. In Fig. 4.7 the microphone at the measurement angle of 30°, was in the radiation path of the noise generated by large-scale structures, for the single side modified nozzles. A large low frequency broadband peak at 104 dB was over 12 dB above the previous figure, with a peak frequency of 3500 Hz.

4.3.2 Overexpanded Spectra

For the overexpanded flow condition, Figs. 4.8-4.13 give a representative sample at the spectral modification due to the trailing edge modifications. Only microphone 1 will be discussed here, because of its location directly above the modification side, for single side modified nozzles, and over both modifications for double side modified nozzles. The other two microphone positions are presented in Figs. A.16-A.27. Just to
note, microphone 2 shows shifts in the broadband shock associated noise and reduced screeching, compared to that of microphone 1. Microphone 3 was found to be almost identical to that of microphone 1, within the measurement error of 2.5 dB. Features of the spectra will first be pointed out for each measurement location, followed by a comparison relating the features and possible explanations of why they occur.

4.3.2.1 90° Measurement Location

For the 90° location, the single side modified nozzles in Fig. 4.8 eliminated the screech for OS, RC and OC, and reduced the intensity for RS, as compared to BB. Fig. 4.9, the double side modified nozzle for the same location sees an increase in the intensity of screeching over BB for RC and OC, and an up-shift in the screech tone frequency by $\sim 3400$ Hz, to 11 kHz. A reduction in the intensity and number of harmonics of the screeching occurs for OS, as well as a downshift in the screeching frequency by 500 Hz, to 7100 Hz seen in both single and double side modified cases. RS has an increase in the screeching intensity and an up-shift in screeching frequency of 500 Hz, to 8100 Hz. Low frequency decreases in amplitude from BB are evident for all spectra in Fig. 4.8 and 4.9. The broadband shock associated noise peak seen in the BB spectrum between 10 kHz and 20 kHz, appears to be eliminated in Fig. 4.8 for RC and OC, but only slightly reduced for RS and OS. The broadband peak in Fig. 4.9 appears to be amplified by the increased screeching in RS, RC and OC, causing an increase in the high frequency noise over BB. For OS, in Fig. 4.9, there was only a slight increase in the high frequency noise similar to that of Fig. 4.8.
4.3.2.2 60° Measurement Location

The 60° measurement location for the single side modified nozzles, Fig. 4.10 have eliminated or reduced screeching for all modifications, as well as decreased the amplitude of the broadband noise component. Fig. 4.11, for the double side modified nozzles also has a reduction in the intensity of the screeching, however there are still strong screech tones appearing in all of the modifications, with shifts in the radiation frequency as those noted in the 90° measurement location. The broadband shock associated noise component for Fig. 4.11 was only reduced for the OS modification, with noticeable amplification to the high frequency noise occurring for the other three modifications. For both Figs. 4.10 and 4.11, a peak was noticed at 4000 Hz, which can be explained as the beginning effects of the turbulent mixing noise. For both the single and the double side modified nozzles, decreases from BB in the turbulent mixing noise can be seen to varying degrees. Fig. 4.10 has reductions from the baseline noise through 30 kHz for all spectra, and Fig. 4.11 has reductions from BB through 30 kHz for OS, through 10 kHz for RS and RC, and through 5 kHz for OC.

4.3.2.3 30° Measurement Location

The turbulent mixing noise peak has now become the dominant feature at the 30° measurement location. Figs. 4.12 for single side modified nozzles shows smooth spectral curves as compared to BB. The modification curves are smooth for OS, RC and OC, but still retain some resemblance of a peak for the RS spectra, due to continued screeching. Fig. 4.13 still shows increased screeching for RC and OC, and reduced screeching for RS
and OS as compared to BB. The screech tones are also shifted in the same manner as discussed before. The Turbulent mixing noise peak, which appeared at the 60° location has also increased in amplitude, but remains at the same frequency. The peak of the turbulent mixing noise corresponds to that of the peak in the ideally expanded spectra in Fig. 4.7, both in frequency value and magnitude. The turbulent mixing noise was reduced for all modifications up to 6 kHz for those in Fig. 4.12 and up to 5 kHz for those in Fig. 4.13. There also still appears to be a slight broadband amplification in the high frequency noise for RC and OC in Fig. 4.13.

4.3.2.4 Comparisons of the Spectra for the Overexpanded Flow Regime

For Figs. 4.8, 4.10 and 4.12, the first obvious similarity is the reduction or elimination of the screech tones. This reduction most likely occurs due to the broken symmetry in the nozzle, possible causing a weakened shock cell structure due to a modification being applied to only one side of the nozzle. Conversely, when a modification was applied to the opposite side of the nozzle as well, in Figs. 4.9, 4.11 and 4.13, the screech tones remained or were amplified for most modifications. Reintroducing the symmetry in the nozzle caused the return of the screeching. One possible explanation for the increase in the amount of screeching, could be from the larger scale structures being formed closer to the nozzle exit, where they interact with the shock cells for a longer period of time.

Screech tone frequency has been seen to depend on the spacing of the cells, as explained by Seiner (1984). In this study, it may be possible to say that the double side modified nozzles in Figs. 4.9, 4.11 and 4.13, have altered shock cell structures, which
would account for the shifts in frequency. Applying a formula, obtained by Harper-Bourne and Fisher (1974), and solving for the shock cell length gives

$$L_{\text{Screech\_Frequency}} = \frac{cM_c}{f_{\text{Screeching}}(1 + M_c)}$$ (13)

where $L_{\text{Screech\_Frequency}}$ is the shock cell length at a specified primary harmonic of screech, $c$ is the speed of sound, being 340 m/s, $M_c$ is the convective Mach number for the flow, 0.83, and $f_{\text{Screeching}}$ is the value of the frequency at the primary harmonic. For the BB nozzle, $L_{7680} = 20.3$ mm, for RS, $L_{8100} = 19.0$ mm, for RC and OC $L_{11000} = 14.0$ mm and for OS $L_{7100} = 21.7$ mm. From these findings, the shock cells where modified for these cases, being reduced in size for the RS, RC and OC double side modified nozzles, causing a higher frequency of radiation than the BB nozzle, and elongated by the OS single and double sided nozzle, giving a lower frequency of radiation. Raman (1997) point out that in the far field, the screech becomes omnidirectional due to the intensity of the tones, accounting for the sustained screeching in the $30^\circ$ case at approximately similar amplitudes as that of the $90^\circ$ case. This is true even though the effects of the turbulent mixing noise tend to overcome the screech tones in the downstream directions.

Overall, the nozzles that expel fluid into the ambient from the jet, RC and OC tend to have the more severe deviations from BB than RS and OS nozzles, which entrain ambient air into the jet. The OS nozzle appears to have the least amount of variation in behavior as compared to the other nozzle modifications used at this flow condition. It has reduced or eliminated screeching throughout the spectra, with insignificant increases in high frequency amplitude and limited increases in the turbulent mixing noise and high frequency noise due to broadband amplification.
4.3.3 Underexpanded Spectra

For the underexpanded flow condition, Figs. 4.14-4.20 give a representative sample for the changes in the spectra from the BB nozzle due to the trailing edge modifications. As in the last section, only microphone 1 will be discussed here, because of its location directly above the modification side, for single side modified nozzles, and over both modifications for double side modified nozzles. However, the other two microphone positions are presented in Figs. A.28-A.38. Just to note, microphone 2 was found to be identical to microphone 3 for the single side modified nozzles, showing reductions in the broadband shock associated noise as in microphone 1. For the Double side modified cases, microphone 2 does not exhibit the large high frequency decreases in noise evident for microphone 1 and 3. Due to the volume of information, features of the spectra will first be pointed out for each measurement location, followed by a comparison relating the features and possible explanations of why they occur.

4.3.3.1 90° Measurement Location

The BB for the 90° figures, Fig. 4.14 and 4.15, have two prominent features, both broad spectra peaks at 6.5 kHz and 13 kHz, with amplitudes of 112 dB and 105 dB respectively. The first peak can be considered the primary harmonic of the broadband shock associated noise and the next the secondary harmonic. Screech does not occur in this situation. For Fig. 4.14, there was a reduction in amplitude of the first harmonic broadband shock associated noise for RS, OS, RC and OC, and a peak frequency up-shift of 2000 Hz for RS, OS and OC, with an up-shift 1000 Hz for RC. The second harmonic
was eliminated for all nozzle modifications in this single side case. Fig. 4.15 had a
greater reduction in amplitude than the single side modified cases, for RS, OS, and RC,
with a similar up-shift in the peak frequency. One major difference though was that the
second harmonic was not eliminated, only reduced, and up-shifted to a higher peak
frequency for all modifications except OC, where it was eliminated. The OC
modification did not notice any reductions in amplitude. However, it was up-shifted in
the frequency, as before. There were negligible changes from BB for the low and high
frequency regimes for both Figs. 4.14 and 4.15.

4.3.3.2 60° Measurement Location

The BB for the next two figures, Figs. 4.16 and 4.17 have one prominent
broadband peak, measured to be at the same location as the secondary harmonic in the
above spectra, at 13 kHz, but at a higher amplitude. For both Figs. 4.16 and 4.17, the
peak was eliminated, and the spectra take the shape and peak frequencies of the ideally
expanded spectra in Fig. 4.6, but with increased amplitude. The broadband amplification,
which occurs for the BB nozzle was also eliminated for all of the nozzle modifications in
both figures, leaving large reductions in the high frequency noise.

4.3.3.3 30° Measurement Location

The BB spectra for the last two figures, Fig. 4.18 and 4.19, display similarities to
the ideally expanded spectra in Fig. 4.7, sharing the same broadband peak frequency at
~3000 Hz, however the amplitude for the underexpanded spectra has increased. In the
two figures, the broadband peaks have vanished into the turbulent mixing noise, however,
the reductions noticed in the figures have a greater significance. Fig. 4.18 for the single side modified nozzle has reductions up to 12 dB starting from 1200 Hz, and continuing till the end of the measurement spectrum for all modifications. Fig. 4.19 has similar results, with a slight decrease in the amplitude of the reductions, to 10 dB, but with the reductions starting at 500 Hz for all modifications.

4.3.3.4 Comparisons of the Spectra for the Underexpanded Flow Regime

The underexpanded flow regime shows a reduction or elimination in amplitude from BB of the primary and secondary peak frequencies for the 90° locations, and elimination of the primary peak at 60° locations. The shift in the peak frequency at the 60° location is due to the Doppler effect in the flow (Seiner 1984 and 1991). The spectra for the modified nozzles at the 60° location appear to take the shape of the turbulent mixing noise, like in Fig. 4.6, losing all of the broadband shock associated noise influence. At the 30° degree location, however, the broadband peaks no longer appear in the BB spectra, and there is a strong turbulent mixing noise peak, nearly identical in shape to that of Fig. 4.7. This reduction in amplitude can be explained when looking at the mixing results in Kim (1998). In the study, the underexpanded flow regime was found to have a considerable spanwise pressure gradient in the nozzle, thus generating strong streamwise vortices when the modifications were applied. This increased the mixing of the jet many jet diameters downstream of the nozzle exit.

The action of the RS and OS modifications entraining ambient air into the jet fluid, or of RC and OC expelling jet fluid into the ambient, formed by a strong pressure
gradient may inhibit the formation of strong shock cells in the flow. At the 90° location, this could account for the reduction in the broadband shock associated noise from the BB nozzle. At the 60° location, the weakening of the shock cell structure by the modifications could also account for the shape of the spectra appearing as ideally expanded. The question then arises for the 30° location, where there was an almost quartering of the acoustical power, how was it that the turbulent mixing noise could be reduced over the entire BB spectrum for all modifications for both the single and double sided nozzles? One probable explanation would be that the creation of the streamwise vortices by the nozzle modifications caused a reduction in the velocity of the large scale structures in the shear layer due to enhanced mixing, thereby decreasing the noise at which they radiate. Looking at Fig. 4.20 may prove this, because this was the microphone on the unmodified side of the nozzle for Fig. 4.18, which shows that there was negligible change to the from the BB case. One other thought would be that the streamwise vortices change the directivity of the turbulent mixing noise, diverting it to radiate in other directions. In either case it appears that the modifications successfully reduce the speed of the flow, reducing the SPL by ¼ in the process.

4.4 OASPL

After a detailed look into the spectral components of the noise radiated from the jet flow, a much cleaner, and in some ways, more qualitative approach to analyzing sound data, would be to calculate the OASPL (overall sound pressure level) for each spectrum. The amplitudes measured at each frequency value were logarithmically added and displayed against the BB nozzle at the 90°, 60° and 30° measurement locations, and
divided into six separate plots for each location depending on flow conditions and either single or double side modified nozzles.

4.4.1 90° Measurement Location

The OE spectra show that the screech, as discussed in section 4.3.3 for the spectra, was reduced in amplitude for the single side modified nozzles, and increased in amplitude over BB for the double-side modified nozzles. For the 90° OE cases single and double side modified nozzles, Figs. 4.21 (a) and (d), mic1 and mic3 show the reductions and increases discussed in the spectra. Fig. 4.21(a) has reductions for mic1 and mic3 on the order of 3 dB for RC case, with the OS and OC cases close behind. The RS nozzle, still screeching, Fig. 4.8, shows less of a decrease in amplitude. Fig. 4.21(d) has increases in amplitude over the BB nozzle for all modifications, except OS, which was not screeching when compared to Fig. 4.9. For Fig. 4.21 (b) and (e), the ideally expanded nozzles, there are no differences in the OASPL, as in the spectra. All measurements are within 1 dB of the BB. Fig. 4.21 (c) and (f) for the underexpanded nozzles also do not show any considerable decrease, all decreases in amplitude are within 2.5 dB, representative of those noticed in Figs. 4.14 and 4.15 for the broadband shock associated noise peaks.

4.4.2 60° Measurement Location

Fig. 4.22(a to f) displays the intermediate measurement location of 60°, where the effects of screech are still noticed, but the effects of turbulent mixing noise must also be weighted. Fig. 4.22 (a) and (d) show that OS, because it has reduced screeching, and
perhaps reduced broadband shock associated noise, performs the best over all modifications from BB in the overexpanded flow regime, also seen in Figs. 4.10 and 4.11. For the Fig. 21(d), OS reduced the OASPL from the BB nozzle by 3.5 dB. Fig. 4.22 (b) and (c) display the ideally expanded flow condition for the 60° location, and again, the OASPL shows that there was less than 1 dB difference between the BB and the modifications. Fig. 4.22 (c) and (f) for the underexpanded flow regime show increased activity from the 90° location. Decreases in the amplitude from BB up to 4 dB are noticed for OC, Fig. 4.22(c) at mic1, and for both mic1 and mic3, Fig. 4.22(f), where OC sees a 5 dB reduction in noise from BB nozzle. All other modifications for Fig. 4.22(f) show less reduction in noise.

4.4.3 30° Measurement Location

At the 30° location, the turbulent mixing noise and Mach wave radiation are considered the dominant noise source, with the general shape of the spectral curves mimicking that of the ideally expanded flow regime in Fig. 4.7. Figs. 4.23 (a) and (d) display the OASPL for the single and double side modified nozzles for the overexpanded flow condition. Notice that there were large reductions in Fig. 4.23(a), up to 4.5 dB for all nozzle modifications on both mic1 and mic3. The double side modified nozzle in Fig. 4.23(d), had reductions in the overall noise up to 5.5 dB for mic1 and mic3. Fig. 4.23 (b) and (e) for the ideally expanded condition show up to a 1.5 dB reduction but these are still negligible in comparison to the other decreases seen. Fig. 4.23 (c) and (f) for the underexpanded flow condition, referring to the spectra plots in Figs. 4.18 and 4.19, show large reductions in the OASPL from the BB nozzle. Fig. 4.23(c) shows the reduction
from BB up to 10 dB, but only for the modified side as expected, and Fig. 4.23(f) show a reduction in the noise up to 8 dB for both mic1 and mic3, the modified sides of the nozzle.

4.4.4 OASPL Comparisons

The OASPL figures give a good representation of the data, much cleaner and more condensed than the spectra plots. The same trends are noticed between the spectra and the OASPL in the overexpanded data, where the screech was reduced in the single side modified nozzles, a reduction in the noise from BB can qualitatively be seen for the 90° location. The underexpanded flow regime also contained similarities between the spectra and the OASPL plots for the 30° location, where the noise was considerably reduced for the modified sides of the nozzle from the BB.

Over and above the results obtained through the spectra, the OASPL figures give clues as to the “ideal” nozzles for reduction of the various noise sources. For the overexpanded flow regime, Figs. 4.21, 4.22 and 4.23, (a) and (d), the OS nozzle modification appears to be the best nozzle for reducing shock associated noise. The underexpanded flow regime does not have an ideal nozzle per say, but the greatest effect of the modifications in that flow regime was the reduction of the turbulent mixing noise in the 30° direction, Fig. 4.23(c) and (f). Figs. 4.21 and 4.22, (c) and (i), show that the decreases in the noise from the BB nozzle become greater with decreasing measurement angle. The sideline microphone, mic2, does not seem to experience any reductions or increases in noise greater than 3 dB from the BB nozzle. The first obvious reason for this would be that there was no modification applied to that side of the nozzle.
4.5 Perceived Noise Level

The Perceived Noise Level (PNL) as discussed in Smith (1989), is a method of weighting the subjective effects of airplane noise on humans between the center frequencies of 50 to 10000 Hz on the third octave band scale. This technique was developed, so airplane designers and manufactures could produce and alter airplanes to radiate noise at frequencies outside those that are most annoying to humans. The first step in this process was to convert the data to perceived noisiness, which are in units of noys. The noys values were gathered from human test responses to the annoyance they felt when subjected to the noise radiating at the center frequencies of the third octave band for varying decibel levels. Then calculating a new value for the PNL in units of noys decibels, and adding a tone correction factor and duration, or measurement time correction factor, the effective PNL is found. For the current experiments, only the PNL was calculated, because the fly over and time scales needed for the effective PNL values cannot be simulated at this time.

4.5.1 Scaling of Jet Noise Data

The frequency range of the presented spectra are as measured for the 18.6 mm equivalent diameter jet nozzle, but the reader should note that the measured noise decreases from the BB spectra may not be similar to that of an actual sized nozzle with modifications applied. The mixing noise decreases and increases, when scaled may or may not be of importance for the larger nozzles. In order to apply the PNL method to this data and to obtain meaningful results, several steps were taken to use the entire
measured spectra. The first, and most important step was to scale the data to a larger nozzle by equating the Strouhal Number for the test nozzle to that of an actual sized nozzle, where $f$ is the frequency, $D$ is the exit diameter, and $V$ is the velocity at the jet exit.

$$\frac{f_{\text{test}} D_{\text{test}}}{V_{\text{test}}} = \frac{f_{\text{actual}} D_{\text{actual}}}{V_{\text{actual}}} \quad (14)$$

Using the relation, $c = (\gamma RT)^{0.5}$, where $c$ is the speed of sound, $\gamma$ is the ratio of specific heats, $R$ is the universal gas constant, and $T$ is the temperature, and $M = V/c$, where $M$ is the Mach number and $V$ is the velocity, both of the jet, then

$$f_{\text{actual}} \approx f_{\text{test}} \frac{D_{\text{test}}}{D_{\text{actual}}} \sqrt{\frac{T_{\text{actual}}}{T_{\text{test}}}} \quad (15)$$

Substituting into Eqn. 15, the values of $T_{\text{actual}} = 800$ K, $D_{\text{actual}} = 0.3$ m, $T_{\text{test}} = 288$ K, and $D_{\text{test}} = 0.0186$ m.

$$f_{\text{actual}} \approx (0.1033) f_{\text{test}} \quad (16)$$

Applying Eqn. 16 to the data, and converting it to the third octave band, gives the original spectra from 0 to 80000 Hz in a compressed form from 0 to 8000 Hz, for a larger sized nozzle.

4.5.2 Converting Decibels to Noys

The third octave and SPL data was then converted to the third octave band with a total of 23 center frequencies. The sound pressure level values were then compared to the weighted perceived noisiness table in Smith (1989), substituting the SPL values for
the appropriate noys values, depending on their decibel levels. From there, Eqns. 17 and 18 were used to calculate the PNL.

\[
N = 0.85n_{\text{max}} + 0.15 \sum_{i=1}^{23} n \quad (17)
\]

\[
PNLdB = 40 + \frac{10}{\log_{10} 2} \log_{10} N \quad (18)
\]

\(N\) is the total perceived noise, \(n\) represents the perceived noise, which are all of the values from the created "noys" table based on the data, and \(n_{\text{max}}\) is the maximum value of \(n\). The calculated PNL values are displayed in the same manner as the OASPL data, in Figs. 4.24, 4.25 and 4.26 for 90°, 60° and 30° respectively.

### 4.5.3 PNL Measurement Locations

Fig. 4.24 displays the results for the PNL at the 90° location, which do not show the reductions in screech and turbulent mixing noise that were present in the spectra and the OASPL data. From the BB nozzle, modifications for the curves in Fig. 4.24 (a), (b), (c), (e) and (f) show negligible differences from the BB nozzle. Fig. 4.24(d) gives increases in the perceived noise for the modifications less than those seen in Fig. 4.21(d). The calculated PNL values at the 60° location for Fig. 4.25(a) shows that the perceived noisiness was reduced for the modifications for mic1 and mic2, with mic3 having a negligible reduction. Fig. 4.25(d) however shows increases, consistent with those in Fig. 4.22(d). The ideally expanded flow regime, Fig. 4.25 (b) and (e), again are negligible, and Fig. 4.25 (c) and (f), show the decreases consistent with those in Fig. 4.22 (c) and (f).

For Fig. 4.26 (a), (b), (d) and (e), the 30° measurement location, the data has, again,
similar increases or decreases from the BB nozzle, as in the OASPL discussion. Fig. 4.26 (c) and (f), do follow the results obtained for the OASPL measurements in Fig. 4.23 (c) and (f), with reductions in mic1 for the single side modified nozzle and reducing in the noise for mic1 and mic3 for the double side modified nozzle.

4.5.4 PNL Comparisons

The PNL uses the scaled data to calculate the annoyance of the sound coming from the nozzle for this experiment. Because it was scaled, the increases in the high frequency noise over the BB nozzle for most modification seen in the spectra was used in the calculation, which from the PNL table, the higher the dB at a specific frequency, the higher the weighting this value receives. This can be seen in the overall data, as there were fewer reductions in the noise from the BB nozzle, when compared to the OASPL. Overall in Figs. 4.24-4.26, the PNL level in noys, which is comparable to the SPL level in decibels is 10 to 15 dB's or noys' above the OASPL results, for example, in Fig. 4.21, the maximum decibel level is 136 dB, and in Fig. 4.24, the maximum noys level is 148 noys. This could signify that a larger jet nozzle could be noisier than the test nozzle. The results do show that the major mixing noise reductions seen in Fig. 4.23 (c) and (f), for the OASPL, are present for the PNL in Fig. 4.26 (c) and (f), but the increases and decreases in screech tones for the overexpanded flow regime are not present.

4.6 Mixing and Acoustic Measurement Comparisons

In section 4.1, it was discussed that the farther the downstream mixing area measurements were taken, depending on the type of vortices generated by the cutouts and
their interaction, mixing levels could increase or decrease, whether constructive, RS and OS, or destructive, RC and OC, vortices are produced. The streamwise vortices were generated due to the induced spanwise wall pressure gradient on or in the vicinity of the cutouts. This pressure gradient was diminished in the fully expanded flow regime and in the overexpanded flow regime, due to flow separation within the nozzle. Therefore, the effects of cutouts on mixing and noise can be only relatively easily understood in the underexpanded flow regime. The streamwise vortices are considered the reason for this mixing increase, Figs. 4.1 through 4.4, and thus the cause of the significant decreases in downstream noise noticed at the 30° measurement location, Fig. 4.19.

For the mixing comparisons in the underexpanded flow condition, Fig. 4.27 shows the normalized mixing area. At this flow condition, OC and RC are seen to have low to upper moderate mixing areas at $x/D_{eq} = 1$, with OS and RS having lower-mid to high mixing areas. As the measurement area moves farther downstream, the RC and OC nozzle modifications slowly increase in their amount of mixing, where the two other nozzle modifications either rapidly increase and then decrease in the amount of mixing, OS, or have an overall decrease in mixing, RS. The side cutout nozzles have vortices that initially grow quickly, but by interacting with each other in the downstream directions, decrease in size and mixing, accounting for the decreases. The center cutout nozzles have a gradual increase in the amount of mixing as the vortices grow in the downstream direction.

It may be possible to predict the behavior of a nozzle by examining the mixing, but due to the limited study, these are only generalizations. The nozzles, OS and RS,
which entrain the ambient air into the jet have the largest mixing areas early on, but decrease in size as the streamwise vortices interact with each other, possibly creating cascading large scale noise. These modifications tend to increase the high frequency noise as compared to RC and OC against the BB nozzle, Fig. 4.19. The OC and RC nozzle expel the jet air into the ambient, gradually increasing in the amount of mixing at farther downstream locations. These nozzles tend to decrease the high frequency noise more efficiently, due to the continued growth of the streamwise vortices.

4.7 Coherence between the Microphones

The coherence indicates how well the acoustic intensity at each frequency measured from two separate microphone locations were correlated, where 1 indicates perfect correlation and 0, no correlation. In most cases, if a field had coherency above 50% for one group of microphones, usually mic1 and mic3, then the other two groups also had strong coherence. Table 4.1 displays the results of such an analysis, disseminated from Figs. 4.28 through 4.33 and B.1 through B.38, where higher than 50% coherency was taken to indicate strong correlation. The coherency results for the ideally expanded cases are not present on the table, due to the similarity between all of the cases, however some sample coherence plots are in Appendix B.

For the overexpanded flow regime, Tab. 4.1, the coherence at 90° between the microphones could be related to the strong screeching, Fig. 4.28, such as in RS for the single side modified nozzle, Fig. 4.8, and for all of the modifications for the double side modified nozzles, Fig. 4.9. Remember that in the far field, screech radiates.
Coherence as rated for each modification for the specific conditions.

<table>
<thead>
<tr>
<th>90°</th>
<th>60°</th>
<th>30°</th>
</tr>
</thead>
<tbody>
<tr>
<td>OE</td>
<td>SS</td>
<td>DS</td>
</tr>
<tr>
<td></td>
<td>BB</td>
<td>BB</td>
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<tr>
<td>RC</td>
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<td>OC</td>
<td>OC</td>
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<td>RS</td>
<td>RS</td>
<td>RS</td>
</tr>
<tr>
<td>OS</td>
<td>OS</td>
<td>OS</td>
</tr>
</tbody>
</table>

Table 4.1: Nozzle modifications with coherency above 0.5 or 50% for mic1 and mic3, at the 90°, 60° and 30° measurement locations, taken at both overexpanded (OE) and underexpanded (UE) flow conditions for single (SS) and double (DS) sided nozzle modifications.

omnidirectionally. As the measurement angle decreases, all modifications, both single and double sided are coherent to some degree. At the 60° location, screech was still present, but the turbulent mixing noise, which radiates in the downstream directions and causes low frequency noise, under 10 kHz, was coherent between all of the microphones groups, Fig. 4.29 being an example. The 30° measurement location had the turbulent mixing noise very coherent for all microphone groups, Fig. 4.30, and for most nozzle modifications. One of the causes for such high coherency for the turbulent mixing noise would be that the screech tones are so strongly related to the flow structure through the feedback loop. Since the screech was seen to be omnidirectional, it could be assumed that the turbulent mixing noise would be fairly.
The underexpanded flow condition, Tab. 4.1, had insignificant values, less than 10%, for the coherence for all modifications and the BB nozzle at the 90° measurement location. However, just as in the overexpanded regime, the coherence between the microphones improved at decreasing measurement angles. The 60° location did have some coherence, around 50%, for most microphone groups, in the turbulent mixing noise range of less than 10 kHz, Fig. 4.16. The 30° location did have an increased coherence in the turbulent mixing region for all nozzles tested, Fig. 4.32. Comparing Fig. 4.32 to the ideally expanded case, Fig. 4.33, both for the 30° case, the turbulent mixing noise coherency can be seen to be much reduced for the underexpanded case, signifying that the streamwise vorticity has affected the flow.

4.8 Microphone Comparisons

It has been thought that asymmetric jets achieve symmetry in the acoustic far field after a long distance from the nozzle, as Tam (1998) has demonstrated. However, for the asymmetric nozzle with trailing edge modifications in this study, the acoustic far field was found only to be axisymmetric in the upstream directions, where in the downstream directions there were differences between the microphones. In Figs. 4.34-4.39, the spectra of each microphone are plotted on the same curve, dividing each figure up into the three measurement locations, single or double side modified, and flow condition. First notice in all of the figures, the differences between the microphones beginning at the 60° measurement location, with increasing differences as the measurement angle is decreased. In Figs. 4.34 and 4.35, the overexpanded flow condition, and in Figs. 4.36 and 4.37, the ideally expanded flow condition, and Fig. 4.39, the underexpanded flow
condition, the deviations on the lower measurement angles occurs just for microphone 2. The other two microphones appear to be identical for their readings. Fig. 4.38 has differing readings for all microphones.

In the overexpanded flow regime, Fig. 4.35 seems to have an increasing amount of difference between microphones 1 and 3, and 2, than Fig. 4.34, most likely due to the increased screeching. Figs. 4.36 and 4.37, for the perfectly expanded cases, show no difference between the single or double side modified cases, and does show some asymmetry in the noise field in the downstream measurement locations, for all modifications, including the BB case. In the underexpanded flow condition, for Fig. 4.38, the single side modified nozzle, there is asymmetry in the downstream locations in the noise field at all of the microphones for each of the modifications, with microphone 2 remaining above the other two microphone in amplitude. This may be caused by the creation of streamwise vortices altering the flow field in differing ways for the modified side than the unmodified side, where microphone 2 could be expected to deviate as demonstrated above. For Fig. 4.39, microphone 1 and 3 are similar, but microphone 2 is not, signifying that the streamwise vortices alter the flow in similar ways on the modification sides of the nozzle, but not on the sideline.
Figure 4.1: Flow visualizations displaying average cross sectional images at the $x/D_{eq}=1$ for the three flow conditions. Taken from Kim (1998).
Figure 4.2: Flow visualizations displaying average cross sectional images at the $x/D_{eq} = 2$ for the three flow conditions. Taken from Kim (1998).
Figure 4.3: Flow visualizations displaying average cross sectional images at the $x_D_{eq}=4$ for the three flow conditions. Taken from Kim (1998).
**Figure 4.4:** Flow visualizations displaying average cross sectional images at the $x D_{eq}=8$ for the three flow conditions. Taken from Kim (1998).
Figure 4.5: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for an SS case measured by microphone 1.
Figure 4.6: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for a DS case measured by microphone 2.
Figure 4.7: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for an SS case measured by microphone 3.
Figure 4.8: Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for an SS case measured by microphone 1.
Figure 4.9: Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for a DS case measured by microphone 1.
OE SS 60Deg mic1, with a 25dB shift up for each spectra from BB

Figure 4.10: Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for an SS case measured by microphone 1.
Figure 4.11: Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for a DS case measured by microphone 1.
Figure 4.12: Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for an SS case measured by microphone 1.
Figure 4.13: Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for a DS case measured by microphone 1.
Figure 4.14: Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for an SS case measured by microphone 1.
Figure 4.15: Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for a DS case measured by microphone 1.
Figure 4.16: Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for an SS case measured by microphone 1.
Figure 4.17: Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for a DS case measured by microphone 1.
Figure 4.18: Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for an SS case measured by microphone 1.
Figure 4.19: Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for a DS case measured by microphone 1.
Figure 4.20: Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for an SS case measured by microphone 3.
Figure 4.21: Overall sound pressure level plots for the 90° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.
Figure 4.22: Overall sound pressure level plots for the 60° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.
Figure 4.23: Overall sound pressure level plots for the 30° measurement location. The legend was placed in the lower right.  (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.
Figure 4.24: Perceived noise level plots for the 90° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.
Figure 4.25: Perceived noise level plots for the 60° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.
Figure 4.26: Perceived noise level plots for the 30° measurement location. The legend was placed in the lower right. (a) Single side modified, overexpanded. (b) Single side modified, ideally expanded. (c) Single side modified, underexpanded. (d) Double side modified, overexpanded. (e) Double side modified, ideally expanded. (f) Double side modified, underexpanded.
Figure 4.27: Normalized-mixing area curves for the underexpanded flow condition. Taken from the flow visualization images of Kim (1998) for several double side modified nozzle configurations, at several downstream locations. Displays the mixing increase or decrease due to the nozzle modification.
Figure 4.28: Coherence curves for a double sided RC nozzle at 90°, running in the overexpanded flow condition.
Figure 4.29: Coherence curves for a double sided OC nozzle at 60°, running in the overexpanded flow condition.
Figure 4.30: Coherence curves for a double sided OC nozzle at 30°, running in the overexpanded flow condition.
Figure 4.31: Coherence curves for a single sided OC nozzle at 60°, running in the underexpanded flow condition.
Figure 4.32: Coherence curves for a single sided RC nozzle at 30°, running in the underexpanded flow condition.
Figure 4.33: Coherence curves for a single sided OC nozzle at 30°, running in the ideally expanded flow condition.
Figure 4.34: Differences between the three microphones for the single side modified cases taken and 90°, 60° and 30° for the overexpanded flow condition.
Figure 4.35: Differences between the three microphones for the double side modified cases taken at 90°, 60° and 30° for the overexpanded flow condition.
Figure 4.36: Differences between the three microphones for the single side modified cases taken and 90°, 60° and 30° for the ideally expanded flow condition.
Figure 4.37: Differences between the three microphones for the double side modified cases taken and 90°, 60° and 30° for the ideally expanded flow condition.
Figure 4.38: Differences between the three microphones for the single side modified cases taken and $90^\circ$, $60^\circ$ and $30^\circ$ for the underexpanded flow condition.
Figure 4.39: Differences between the three microphones for the double side modified cases taken at 90°, 60° and 30° for the underexpanded flow condition.
CHAPTER 5

CONCLUSIONS

A modular anechoic chamber, designed to be used in cold and heated supersonic jet studies, was constructed to the specifications outlined. It can be used for acoustic measurements, laser based flow measurements or both, with little modification to the structure. The chamber is a fully anechoic room, for in-flight testing of the acoustic radiation of jet flows, but if the effects of reflections from a runway would be desired, the floor sections of the chamber may be removed, converting the chamber to a hemi-anechoic room. The chamber has been proven to follow the inverse radius squared law for acoustic pressure decay in an anechoic room in eight radial directions from the center as required by the ANSI (1990) Standard. The measurement directions towards the bellmouth and towards the ventilation opening have some deviation in the lowest frequencies, but are outside of the usable measurement sphere, therefore are neglected. All other areas have free field characteristics up to a \( \frac{1}{4} \) wavelength from the wedge tips, based on the cutoff frequency of 250 Hz.
The acoustic experiments for a Mach 2 rectangular jet with trailing edge modifications, which was initially completed in an open room, has been reexamined in the newly designed anechoic chamber to identify the effects of the modifications on the flow field. Measurements were conducted in the 90°, 60° and 30° degree directions from the jet axis, in order to capture the screech and broadband shock associated noise in their dominant radiation direction, upstream, and to measure the effects of the turbulent mixing noise and possible Mach wave radiation effects in their dominantly downstream radiation direction. Three microphones, two placed perpendicular to the flow on the minor axis of the nozzle and one on the major axis, were used to measure the effects that the single and double side modifications had on the flow field. As concluded from the work of Kim (1998), the modifications, when applied to a nozzle, have been shown to alter the screech tones in the overexpanded flow regime, not affect the noise field in the ideally expanded flow regime, and significantly reduce the noise in the under expanded flow regime.

In the 90°, 60° and 30° directions for the overexpanded flow regime, the modifications have been found to only effect the shock associated noise, as there was no increase in the mixing noticed in the flow visualizations due to the lack of a spanwise pressure gradient in the nozzle to generate streamwise vorticity. For the single side modified nozzles, it has been found that the modifications, which expel fluid into the ambient, eliminate the screech tones on the minor axis and reduce the broadband shock associated noise on the major axis. For the same for conditions, the modifications, which tend to entrain the ambient air into the jet, reduce the screeching on the minor axis, but tend to increase the broadband shock associated noise over the baseline case on the major
axis. For the double sided cases, the screech tones were amplified for the modifications which expel jet fluid into the ambient as well as for the rectangular cutout nozzle which entrains the air into the jet. These nozzles also had an increase in the broadband shock associated noise component, most likely due to screech induced amplification, which increased the high frequency noise, above that of the baseline case. The oblique cutout nozzle which tends to entrain air did not see any increase in screeching over the single sided measurements for the same modification, and did not show significant increase in the broadband shock associated noise, nor the high frequency noise from the baseline.

For all measurement angles, in the ideally expanded flow regime, the microphone readings measured negligible deviations from the baseline case due to the modifications. This was expected, as found by Kim (1998), where at this flow condition a spanwise pressure gradient did not form in the nozzle.

For all measurement directions and microphone locations in the underexpanded flow regime, it was found that the noise was significantly reduced by the modifications. This was caused by the generation of streamwise vortices, which significantly enhanced the mixing of the flow. The broadband shock associated noise was reduced from the baseline case by all modifications in the 90° direction, with further reduction in the 60° direction, as well as high frequency noise reductions for all modifications. In the 30° direction, the streamwise vortices reduced the turbulent mixing noise from approximately 1500 Hz by up to 10 dB in the single side modified case, and up to 8 dB in the double side modified cases. Note however that in downstream measurement directions, only the microphones located above the cutouts noticed the reductions in noise. Other
microphones, such as the one on the major axis or the minor axis without a cutout, did not have reductions from the baseline case, but in some instances slight increase were seen.

The overall sound pressure levels (OASPL) and perceived noise levels (PNL) were calculated for non-scaled and scaled nozzles respectively. The PNL was on the order of 10 dB greater than the OASPL measured for the experiment, possibly signifying that the noise radiated by a full size aspect ratio three nozzle would be much more intense than that of the test nozzle. This difference is due to the weighting of specific frequencies and decibel levels, which exaggerates some of the acoustic qualities of the jet. The PNL of the scaled nozzle did not notice the reductions in the screeching as in the 90° overexpanded case for the OASPL, but did have similar reductions to the OASPL in the turbulent mixing noise for the underexpanded flow regime at the 30° measurement location.

In the overexpanded flow regime, there was strong coherency for the microphones, due to the omnidirectionality of the screech. In the downstream direction, 30°, the turbulent mixing noise was also seen to be highly coherent, which was most likely caused by the screech tones being tied to the flow by the feedback mechanisms which generate it. For the ideally expanded flow regime, the microphones were very coherent in the downstream directions, with no coherency in the upstream directions. The underexpanded case had increasing coherency between the microphones as the measurement angle was reduced, but was less coherent in comparison to that of the over and ideally expanded cases.
The significance of the reduction of the screech tones was pointed out in the overexpanded cases, especially for the single and double oblique side cutout nozzles, where there was significant reduction due to the altering of the symmetry in the nozzle, but not from the creation of streamwise vortices. In the downstream direction, the mixing areas, measured by Kim (1998) were shown to be linked to the noise results for double side modified nozzle at the 30° measurement location. The exact mechanism that occurs for the reduction has not been determined; however, diffusing of the noise into other directions through the induced streamwise vortices, and or the slowing of the structures that generate the noise may cause the reductions in the sound. The creation of the streamwise vortices in the underexpanded flow condition did prove to significantly reduce the noise for all trailing edge modifications, both single and double sided, and has been shown to only be significant in the underexpanded flow regime and at when downstream noise elimination is of interest.
APPENDIX A

Additional Spectra Plots

Please Note: The spectra plots presented here are in the same format as those presented in the text.
Figure A.1: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for an SS case measured by microphone 2.
Figure A.2: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for an SS case measured by microphone 3.
Figure A.3: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for a DS case measured by microphone 1.
Figure A.4: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for a DS case measured by microphone 2.
Figure A.5: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 90° for a DS case measured by microphone 3.
Figure A.6: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for an SS case measured by microphone 1.
Figure A.7: Each nozzle modification as compared to the BB for the ideally expanded flow condition at $60^\circ$ for an SS case measured by microphone 2.
Figure A.8: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for an SS case measured by microphone 3.
Figure A.9: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for a DS case measured by microphone 1.
Figure A.10: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 60° for a DS case measured by microphone 3.
Figure A.11: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for an SS case measured by microphone 1.
Figure A.12: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for an SS case measured by microphone 2.
Figure A.13: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for a DS case measured by microphone 1.
Figure A.14: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for a DS case measured by microphone 2.
Figure A.15: Each nozzle modification as compared to the BB for the ideally expanded flow condition at 30° for a DS case measured by microphone 3.
Figure A.16: Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for an SS case measured by microphone 2.
OE SS 90Deg mic3, with a 25dB shift up for each spectra from BB

Figure A.17: Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for an SS case measured by microphone 3.
Figure A.18: Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for a DS case measured by microphone 2.
OE DS 90Deg mic3, with a 25dB shift up for each spectra from BB

**Figure A.19:** Each nozzle modification as compared to the BB for the overexpanded flow condition at 90° for a DS case measured by microphone 3.

153
Figure A.20: Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for an SS case measured by microphone 2.
OE SS 60Deg mic3, with a 25dB shift up for each spectra from BB

Figure A.21: Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for an SS case measured by microphone 3.

155
OE DS 60Deg mic2, with a 25dB shift up for each spectra from BB

Figure A.22: Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for a DS case measured by microphone 2.
OE DS 60Deg mic3, with a 25dB shift up for each spectra from BB

Figure A.23: Each nozzle modification as compared to the BB for the overexpanded flow condition at 60° for a DS case measured by microphone 3.
OE SS 30Deg mic2, with a 25dB shift up for each spectra from BB

Figure A.24: Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for an SS case measured by microphone 2.
Figure A.25: Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for an SS case measured by microphone 3.
Figure A.26: Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for a DS case measured by microphone 2.

160
OE DS 30Deg mic3, with a 25dB shift up for each spectra from BB

Figure A.27: Each nozzle modification as compared to the BB for the overexpanded flow condition at 30° for a DS case measured by microphone 3.
Figure A.28: Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for an SS case measured by microphone 2.
Figure A.29: Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for an SS case measured by microphone 3.
Figure A.30: Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for a DS case measured by microphone 2.
Figure A.31: Each nozzle modification as compared to the BB for the underexpanded flow condition at 90° for a DS case measured by microphone 3.
Figure A.32: Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for an SS case measured by microphone 2.
Figure A.33: Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for an SS case measured by microphone 3.
**Figure A.34:** Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for a DS case measured by microphone 2.
UE DS 60Deg mic3, with a 15dB shift up for each spectra from BB

Figure A.35: Each nozzle modification as compared to the BB for the underexpanded flow condition at 60° for a DS case measured by microphone 3.
Figure A.36: Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for an SS case measured by microphone 2.
Figure A.37: Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for a DS case measured by microphone 2.
Figure A.38: Each nozzle modification as compared to the BB for the underexpanded flow condition at 30° for a DS case measured by microphone 3.
APPENDIX B

Additional Coherency Plots

Please Note: The coherency plots presented here are in the same format as those presented in the text.
Figure B.1: Coherence curves for a single sided BB nozzle at 90°, running in the overexpanded flow condition.
Figure B.2: Coherence curves for a single sided RS nozzle at 90°, running in the overexpanded flow condition.
Coherence between Mics 1 & 2 for the oc DS 90 Degree OE case

Coherence between Mics 1 & 3 for the oc DS 90 Degree OE case

Coherence between Mics 2 & 3 for the oc DS 90 Degree OE case

Normalized Similarity

Frequency [Hz]

Figure B.3: Coherence curves for a single sided OC nozzle at 90°, running in the overexpanded flow condition.
Figure B.4: Coherence curves for a double sided OS nozzle at 90°, running in the overexpanded flow condition.
Figure B.5: Coherence curves for a double sided RS nozzle at 90°, running in the overexpanded flow condition.
Figure B.6: Coherence curves for a single sided BB nozzle at 60°, running in the overexpanded flow condition.
Figure B.7: Coherence curves for a single sided RC nozzle at 60°, running in the overexpanded flow condition.
Figure B.8: Coherence curves for a single sided OC nozzle at 60°, running in the overexpanded flow condition.
Figure B.9: Coherence curves for a single sided RS nozzle at 60°, running in the overexpanded flow condition.
Figure B.10: Coherence curves for a single sided OS nozzle at 60°, running in the overexpanded flow condition.
Figure B.11: Coherence curves for a double sided RC nozzle at 60°, running in the overexpanded flow condition.
Figure B.12: Coherence curves for a double sided RS nozzle at 60°, running in the overexpanded flow condition.
Figure B.13: Coherence curves for a double sided OS nozzle at 60°, running in the overexpanded flow condition.
Figure B.14: Coherence curves for a single sided BB nozzle at 30°, running in the overexpanded flow condition.
Figure B.15: Coherence curves for a single sided RC nozzle at 30°, running in the overexpanded flow condition.
Figure B.16: Coherence curves for a single sided OC nozzle at 30°, running in the overexpanded flow condition.
Figure B.17: Coherence curves for a single sided RS nozzle at 30°, running in the overexpanded flow condition.
Figure B.18: Coherence curves for a single sided OS nozzle at 30°, running in the overexpanded flow condition.
Figure B.19: Coherence curves for a double sided RC nozzle at 30°, running in the overexpanded flow condition.
Figure B.20: Coherence curves for a double sided RS nozzle at 30°, running in the overexpanded flow condition.
Figure B.21: Coherence curves for a double sided OS nozzle at 30°, running in the overexpanded flow condition.
Figure B.22: Coherence curves for a single sided BB nozzle at 60°, running in the underexpanded flow condition.
Figure B.23: Coherence curves for a single sided RS nozzle at 60°, running in the underexpanded flow condition.
Figure B.24: Coherence curves for a double sided RC nozzle at 60°, running in the underexpanded flow condition.
Figure B.25: Coherence curves for a double sided OC nozzle at 60°, running in the underexpanded flow condition.
Figure B.26: Coherence curves for a double sided OS nozzle at 60°, running in the underexpanded flow condition.
Figure B.27: Coherence curves for a single sided BB nozzle at 30°, running in the underexpanded flow condition.
Figure B.28: Coherence curves for a single sided OC nozzle at 30°, running in the underexpanded flow condition.
Figure B.29: Coherence curves for a single sided RS nozzle at 30°, running in the underexpanded flow condition.
Figure B.30: Coherence curves for a single sided OS nozzle at 30°, running in the underexpanded flow condition.
Figure B.31: Coherence curves for a double sided RC nozzle at 30°, running in the underexpanded flow condition.
Figure B.32: Coherence curves for a double sided OC nozzle at 30°, running in the underexpanded flow condition.
Figure B.33: Coherence curves for a double sided RS nozzle at 30°, running in the underexpanded flow condition.
Figure B.34: Coherence curves for a double sided OS nozzle at 30°, running in the underexpanded flow condition.
Figure B.35: Coherence curves for a single sided BB nozzle at 60°, running in the ideally expanded flow condition.
Figure B.36: Coherence curves for a single sided RC nozzle at 60°, running in the ideally expanded flow condition.
Figure B.37: Coherence curves for a single sided BB nozzle at 30°, running in the ideally expanded flow condition.
**Figure B.38:** Coherence curves for a single sided OS nozzle at 30°, running in the ideally expanded flow condition.
LIST OF REFERENCES


212


213


215


