The Pennsylvania State University

The Graduate School

Department of Aerospace Engineering

THE MAPPING OF SUPERSONIC FLOW AND
CALIBRATION OF A FOUR ELEMENT HOT-FILM PROBE

A Thesis in
Aerospace Engineering

by

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ABSTRACT

The major goal of this study was to perform preliminary velocity and flow angulation calibration of a new four element hot-film probe designed by Tao Systems. In order to perform these calibrations over a range of Mach numbers (subsonic and supersonic) the calibration flow fields needed to be established and quantified. Thus a secondary objective, to be undertaken in advance of the hot-film calibration was to map given flow fields with Pitot pressure and static pressure probe measurements. These measurements were undertaken in the jets emanating from converging diverging nozzles of design Mach number $M_d = 1.5$ and 1.65. Additionally, a predominance of the measurements were performed in a purely converging nozzle referred to as $M_d = 1.0$, the exit Mach number for all nozzle pressure ratios exceeding 2.1. These nozzles were also operated over a variety of pressure ratios, including those corresponding to flow average Mach numbers of $M_j = 1.5$, 1.65 and 1.75. Pitot probe measurements were made for the following jet nozzle and flow conditions: $M_d$ of 1.0, $M_j$ of 1.5; $M_d$ of 1.5, $M_j$ of 1.5; $M_d$ of 1.65, $M_j$ of 1.65; $M_d$ of 1.65, $M_j$ of 1.75. Profiles of Pitot pressure and upstream stagnation pressure probes form the basis for evaluating Mach number and mass velocity at various downstream locations. Experimental contour plots are produced for further analysis. These profiles and contour plots form the basis for comparison with the four element hot-film probe. The four element hot-film probe was run at an overheat of 25% and 50% and through the same range of downstream locations as the Pitot probe to allow direct comparison. Angulation sensitivity measurements were also performed using the four element hot-film probe in a fully expanded jet. Preliminary calibration of the four element hot-film probe demonstrated issues with sensor alignment relative to each other or probe alignment with the flow, and the probes sensitivity to ambient conditions which can vary between measurements.
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NOMENCLATURE

\(a\)  
Acoustic velocity.

\(A_w\)  
Overheat ratio.

\(D_p\)  
Diameter of static pressure probe.

\(I_w\)  
Current in wire/film.

\(M\)  
Mach number.

\(M_d\)  
Mach number derived from design.

\(M_j\)  
Mach number derived from \((P_j/P_a)\)

\(P_a\)  
Ambient pressure.

\(P_1\)  
Local static pressure.

\(P\)  
Local pressure.

\(P_p\)  
Local Pitot pressure.

\(P_{t1}\)  
Local total pressure.

\(P_{t2}\)  
Pitot probe pressure.

\(P_w\)  
Power dissipated.

\(PDR\)  
Power dissipation ratio.

\(R\)  
Ideal gas constant.

\(R_a\)  
Measured cold resistance of sensor.

\(R_w\)  
Calculated resistance of wire/film.

\(T\)  
Local temperature.

\(T_a\)  
Ambient temperature.

\(T_{oj}\)  
Exit stagnation temperature.

\(V_s\)  
Sensor output voltage that represents the change in current.

\(V_w\)  
Calculated voltage of wire/film.

\(V_{wm}\)  
Measured wire (or film) voltage.

\(x\)  
Downstream direction, coordinate.

\(x_h\)  
Location of static pressure ports.

\(y\)  
Cross-stream direction, coordinate.

\(u\)  
Flow velocity.
\sqrt{\text{Re}_0} \quad \text{Square root of Reynolds number.}

\rho u \quad \text{Mass Velocity.}

\gamma \quad \text{Ratio of specific heats.}

\mu \quad \text{Dynamic fluid viscosity.}

\rho \quad \text{Density.}

\theta \quad \text{Pitch angle.}

\varphi \quad \text{Yaw angle.}
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Chapter 1

Introduction

1.1 Background

Hot-films and hot-wire sensors have been used for many years as a research tool in the field of fluid mechanics. Many years of research have been performed to help improve the hot-film/wire anemometry techniques and probes. In this study the main focus is on a new design of a multi-element hot-film probe to be used to measure both velocity and flow angulation in supersonic flows.

A hot-film probe is a conducting film on a ceramic substrate. Gold plating is used to isolate the sensitive regions of the probe and provide excellent contact points for the sensors. The metal film is usually less the 1000 Angstrom units in thickness which results in the thermal conductivity of the film to be influenced by the ceramic substrate. Platinum is the preferred material for the metal film as it is stable and resistant to oxidation. The advantage of hot-films over hot-wires is that they have been developed on cylindrical shapes, cones, wedges, parabolas, hemispheres, and flat surfaces depending on the application they are intended for. Supporting electronics used with the hot-films can be constant temperature or constant current systems or in the case of the present study, a Tao Systems constant voltage anemometer system.

1.2 Tao Systems

Tao Systems is an experienced company with an international client base in the field of hot-film probes and constant voltage anemometers. The company developed their own constant voltage anemometers to accompany their product line of probes. The company also provides products and services to the aeronautics/marine engineering
industry. They have contracts from NASA to fund further research into the field of hot-film probes that can be used in place of pitot probes in high speed flow.

Tao Systems does not have the capability to test hot-film probes at supersonic speeds due to the lack of facilities and therefore has contracted this project to The Pennsylvania State University, Aerospace Engineering Department. The finished hot-film probes and associated equipment are provided by Tao Systems along with the knowledge of which flow fields the probe should be calibrated with. It is anticipated that the hot-film probe is sensitive to four variables during calibration; these variables are $\rho U$ (density x flow velocity), Mach number, angles $\theta$ and $\varphi$.

### 1.3 Research Objectives

The primary goal of this study is to develop a calibration technique for a 4 element hot-film probe. This section will discuss the tasks and goals that were set to meet the requirements of Tao Systems.

Tao Systems provided specifications on the probe; in order to calibrate the probe a support arm and calibration system is required. The first goal of the present study was to develop a jet flow condition with the appropriate physical flow fields in which to ultimately calibrate the Tao Systems four element hot-film probe. Several objectives were undertaken to meet this goal. The first objective (of this goal) was to choose jet nozzles and pressure ratio conditions that would provide an adequate range of Mach number and velocity conditions for the ultimate calibrations. In Table 1.1 the choice of nozzle sizes, Mach design and conditions that are chosen to be run can be seen.
The second objective of the first goal was to design a calibration system and establish the properties of the flow fields in which the probe is calibrated. The system needed a probe support and associated traverse system. The support arm has to be aerodynamic to reduce its effects of the flow and to create minimal bending forces so that the probe location does not change. The traverse system must have the ability to traverse in to and out of the flow, traverse downstream of the nozzle exit and the ability to rotate about two axes. The probe system also required the fabrication of a Macor probe body which then has the gold leads and platinum sensors positioned and “fused” to it. Other fabrication goals are for the probe support arm and calibration system.

Calibration can not be performed without the appropriate system to acquire the data and later analyze it. Therefore the final objective of the first goal was to create LabView software for an analog to digital data acquisition system to acquire the probe signals into the personal computer. Such a system needed multi-channel acquisition capability in addition to MatLab and Excel codes to process and analyze the collected data.

The second goal of the study was to perform independent Pitot pressure and static pressure measurements in the jet flow fields in order to establish the local flow conditions in the jets at the locations to be used in the hot-film probe calibrations. The local conditions in a quasi-one dimensional flow field can be established with any appropriate combination of three measurements. The three measurements chosen for most of this work were Pitot pressure, static pressure (being two different probes) and upstream stagnation temperature ($T_o$). Invoking the condition of isoenergetic flow enables the local

<table>
<thead>
<tr>
<th>Nozzle Size (in)</th>
<th>Mach design ($M_d$)</th>
<th>Run condition ($M_j$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>1.0</td>
<td>1.5</td>
<td>1.5</td>
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<tr>
<td>0.7</td>
<td>1.65</td>
<td>1.65</td>
</tr>
<tr>
<td>0.7</td>
<td>1.65</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Table 1.1: Choice of jet nozzles.
stagnation temperature to be assumed to be constant everywhere and equal to the upstream $T_o$. Thus the three conditions are met for these “pre-calibration” measurements.

The third goal of this study was to perform preliminary calibrations of the four element hot-film probe within chosen flow fields. Calibration of the four element hot-film probe involves integration of the probe electronics with the data acquisition system and then using the probe calibration system in pre-mapped flow fields in either velocity calibration measurements along the centerline or angulation measurements to determine flow angle.
Chapter 2

Facility

2.1 Facility Overview

The high speed jet noise facility at The Pennsylvania State University has recently been updated and refurbished and now consists of a high pressure compressed air supply which exhausts through a newly built plenum and nozzle into an anechoic chamber (Figure 2.1). For simulation of hot jets, in acoustic experiments, helium (from compressed gas bottles) is mixed with the air.

Figure 2.1: Schematic of the high speed jet noise facility
The facility can operate with jets ranging of up to 2.54 cm (1 inch) in diameter at \( M = 1.5 \). With these nozzles the facility can reach a maximum of \( M = 1.7 \) for several minutes of steady flow and for sustained periods of time with smaller nozzles (typically) with exit diameters of about 2.0 cm. The facility is designed to allow acoustic measurements to be also made and for various fluid dynamic measurements.

The facility is still undergoing a major upgrade with the installation of duct work leading to an open jet wind tunnel surrounding the jet. This co-flow capability is being installed to facilitate acoustic measurements of model engine exhaust jets in simulated forward flight. In order to have minimal down time from planned experiments the majority of the construction revolves has been scheduled in “break time” between experiments. Co-flow and the eduction fan system are not part of these experiments and therefore will not be mentioned in the full description of the components of the facility.

2.2 Compressed High Pressure Air Supply System

Two 18.9 m\(^3\) (6,700 ft\(^3\)) reservoir tanks pressurized to 2.1 MPa (195 psig) provide the compressed air supply to the facility. When the pressure drops to \( \frac{1}{4} \) of the full capacity a Kaeser air compressor turns on to refill the tanks to capacity. The air supply leaving the tanks is filtered for particulates and dried. The supply is capable of sustaining experimental time ranging from a few minutes to indefinitely dependent on the nozzle diameter and operating conditions. Upon entering the facility the air passes through a 2.54 cm (1 inch) Leslie pneumatic pressure regulator. This regulator is controlled via a line of shop compressed air connected to diaphragm control valve. Following the pneumatic pressure regulator the air passes through a pressure relief valve to avoid overpressurization and damage to the supply system. The relief valve is set at 0.86 MPa (125 psig). A picture of the incoming air supply piping can be seen in Figure 2.2.
The air then travels through pipe work across the ceiling of the room and down into the control cabinet. The helium (not used in the present experiments) also connects into the control cabinet where it is mixed with the air when appropriate. The layout of the control cabinet is shown in Figure 4.1. As can be seen, both air and helium lines are kept separate and have pressure regulators and solenoid valves to control the flow. The lines connect just prior to leaving the cabinet where adequate mixing occurs before
entering the plenum. The cabinet allows the pressure and mass flow rate of the flow to be
controlled whether it is just air or an air and helium mixture.

2.3 The Anechoic Chamber

The chamber is approximately 5 x 6 x 2.8 m (16.5 x 19.8 x 9.1 ft) from wedge-to-
 wedge. Each wall is covered in fiberglass wedges except the opening through which the
plenum enters the chamber. Inside the chamber the plenum sits on a steel stand from
which support platforms extend to allow for experimental setups. The chamber also
contains a barometer, thermometer and hygrometer so that readings of pressure,
temperature and humidity can be recorded for any given experiment. The chamber itself
is a product of Eckel Industries Inc. and was installed in 1968 for use as a jet noise
research chamber. The chamber was decommissioned from 1997 to 1999 when it
underwent its first refurbishment. In 2007, the second refurbishment began for the
chamber and the whole facility, and is due to be completed by the end of 2008.

2.4 Plenum

The facility uses an aluminum tube (Figure 2.3) approximately 1.83 m (6 ft) in
length and a diameter of 12.7 cm (5 in). To reduce noise and turbulence in the plenum a
honey comb section preceded by a perforated plate has been installed at the inlet of the
plenum.
2.5 Nozzles

Three different axisymmetric jet nozzles are used in this study. The first two nozzles each have 1.0 inch exit diameters; the first is a purely convergent nozzle ($M_d = 1.0$) and the second is a contoured CD nozzle designed to produce shock free flow at $M_d = 1.5$. Figure 2.4 shows a schematic of the 1.0 inch diameter CD nozzle, and Table 1.1 summarizes the details of the nozzles.

Figure 2.3: Photo of Jet Noise Facility plenum.
The third nozzle is a CD nozzle with a 0.7 inch exit diameter and an area ratio designed for $M_d = 1.65$. This nozzle is made using rapid prototyping with a convergent/divergent (CD) with constant angle conical surfaces. The interior of the nozzle is composed of a facetted surface; this nozzle was fabricated for another study and also in ownership by The Pennsylvania State University. Figure 2.5 shows a schematic of the 0.7 inch diameter nozzle.
2.6 Probe Traverse Systems

Two probe traverse systems have been designed for this study. The first system allows x-y travel only and the second system is for use in the probe angulation experiments.

The first system has been designed and assembled. The system comprises of two linear traverse stages (see Figure 2.6 & Figure 2.7), a horizontal traverse stage and a vertical traverse stage. These components are used to move the pressure probes vertically and horizontally in the plane of the jet centerline. The first traverse stage used to give horizontal travel is the Velmex MB6000 which connects to the Velmex VXM motion controller. The traverse has a minimum increment of travel of 0.002 inches and a maximum length of travel of 6 inches. The second traverse stage used is a Superior Electrics traverse which provides the vertical motion. This is connected to the Velmex MB6000 via a 90 degree mounting plate. The Superior Electrics traverse is also connected to the Velmex VXM motion controller. The range of travel is similar to the Velmex MB6000, differing only in the maximum length of travel, where the Superior Electrics traverse has a maximum of 4 inches of travel. The Velmex VXM motion controller is connected to the computer through the serial port and a LabView code is programmed to communicate with the controller and acquisition card.
Figure 2.6: Single sensor probe drive traverse stage set up.

Figure 2.7: Photo of single sensor probe drive traverse stage set up in Jet Noise Facility.
2.7 Probe Angulation Systems

An angulation and traverse system has also been assembled. This system is comprised of two linear traverse stages and two rotation stages (see Figure 2.8, Figure 2.9); one horizontal motorized stage, one horizontal manual stage and two motorized rotation stages. The two horizontal traverses are aligned to move the probe in the axial and cross stream directions (vertical) of the jet nozzle. The horizontal motorized traverse stage used is the Velmex MB6000 which connects to the Velmex VXM controller. The MB6000 has a minimum increment of travel of 0.002 inches and a maximum length of travel of 6 inches. The horizontal manual traverse stage used is the Velmex A40 series UniSlide with Graduated Knob. The A40 has a minimum increment of 0.001 inches and a maximum length of travel of up to 4 inches.

As mentioned two rotation stages are also used that allow the probe to be rotated about two orthogonal axes for calibration experiments. The first rotation stage is the Velmex B4836TS with limit switches. The Velmex B4836TS rotates at 0.05 degrees per step and a maximum rotation speed of 100 degrees per second. The second rotation stage used is the Velmex B5990TS with limit switches. The Velmex B5990TS rotates at 0.010 degrees per step and a maximum rotation speed of 40.2 degrees per second. The major differences between the two rotation stages include the size, maximum torque, maximum horizontal and vertical loading (see Appendix A.1 & A.2 for detailed specifications). Both rotation stages connect to the Velmex VXM motion controller which is connected to the computer via the serial port. A LabView code is programmed to communicate with the motion controller and the data acquisition card (described later).
The probe angulation system can be used in two different setups. The first setup can be seen in Figure 2.8 & Figure 2.9; this setup employs the motorized MB6000 traverse in the y-direction and the A40 in the x-direction. This setup allows the probe to
start outside the flow and then computer controlled via the user to move into the flow. The second setup can be seen in Figure 2.10; this setup employs the motorized MB6000 in the x-direction and the A40 in the y-direction. This setup allows the probe to be moved downstream of the nozzle and manually pre-centered or inserted into the flow.

Figure 2.9: Photo of Velmex MB6000 and A40 setup with rotation stages.
Figure 2.10: Velmex MB6000 and A40 setup for moving probe downstream of nozzle.
Chapter 3
Instrumentation

3.1 Facility Sensors

The Jet Noise Facility contains three permanent sensors which are used to collect data during all experiments. The first sensor is the thermocouple temperature probe located inside the plenum. It is located approximately half way down the plenum and allows the upstream temperature, $T_o$, to be recorded via a small digital readout voltmeter.

The second permanent instrument in the facility is a combined barometer and humidity gage. These are located on the side of the plenum support stand and allow ambient pressure to be monitored during experiments.

The third permanent sensor is a single hole Pitot probe as previously mentioned. The probe is installed inside the plenum to provide a reading of the jet upstream stagnation pressure. This probe is located approximately half way down the length of the plenum to allow for turbulent flow to smooth out before reaching the probe; this also allows for the turbulence caused by the interaction of the probe with the flow to decay before reaching the nozzle. The probe is connected to a Validyne pressure transducer and demodulator. The demodulator is connected to the data acquisition system and a voltmeter; this allows the user to monitor the voltage output without having to activate the data acquisition system.

3.2 Calibration Sensors

Two types of probes were used to survey the flow; a Pitot pressure probe and a static pressure probe. The single hole Pitot probe used for surveying the jet is much smaller than that found in the plenum. The single hole Pitot probe is mounted on an
aerodynamic fin (see Figure 3.1) that is in turn mounted on the X-Y traverse system (Figure 2.6). This Pitot probe is connected to a Setra model 205-2 pressure transducer whose output in turn is fed to the A/D convertor.

![Diagram of single hole Pitot probe used for nozzle survey.](image)

Figure 3.1: Diagram of single hole Pitot probe used for nozzle survey.

The other probe used in single sensor probe measurements is the static pressure probe. The static pressure probe has a larger diameter then the single hole stagnation Pitot probe (the single hole Pitot probe has an outer diameter of 0.02 inches, whereas the static pressure probe has an outer diameter of 0.038 inches); it is mounted on an aerodynamic fin in a similar fashion (see Figure 3.2). This fin is mounted on the X-Y traverse system again in the same manner as the single hole stagnation Pitot probe. The static pressure probe is connected to a Validyne 20 PSI pressure transducer which is connected to a demodulator. The demodulator outputs a voltage to the A/D convertor.
3.3 Four Element Hot Film Probe

The main goal of this research was to provide reliable calibrations of the Tao Systems four element hot-film probe. The probe is composed of a solid CNC machined Macor piece; a schematic can be seen in Figure 3.3 below upon which four hot-film sensors are mounted (or laid upon) the surface of the hemispherical tip in a pattern depicted in Figure 3.4. Gold leads connect the four hot-film elements to the probe leads that are routed to an 8 pin connector. These eight leads are then connected to the Tao Systems constant voltage anemometer (CVA) that supplies the current to the hot-films and provides output voltages that are proportional to the cooling rates subjected to the hot-films.

Figure 3.2: Photo of static pressure probe used for nozzle survey
The resistance per unit length is orders of magnitude higher than that of the copper wires (or gold leads) in the circuit so that the voltage drop and particularly the ohmic heating in the hot-films is also orders of magnitude larger than in the leads.

The body of the sensor is mounted on a probe support system that facilitates angulation in two axes. The probe support arm is securely attached to the angulation system that has the capability to traverse in 2 axes (see Figure 2.8). The hot films are connected to the Tao Systems CVA via gold leads protected by varnish and plastic shrink wrap. The Tao Systems CVA outputs a varying voltage from each of the four sensors that depends on flow velocity and direction.

Figure 3.3: Macor Tao Systems probe specimen schematic
3.4 Data Acquisition System (DAS)

3.4.1 NI-6110 PCI DAQ Card

One of the acquisition cards installed and used for these experiments is a National Instruments 6110 PCI acquisition card. This card possesses multiple channel simultaneous analog to digital (A/D) conversion and is used in conjunction with the National Instruments BNC 2110 shielded connector block. The acquisition card has 12 bit analog to digital conversion capabilities with a voltage input range of ± 0.1 V to ± 10 V
V. The acquisition card is also able to sample simultaneously 4 channels at a maximum of 1.25 MHz per channel or 5 MHz for one channel. The sampling rate being used for the single sensor pitot probe experiments is 30 Hz which is well within the capabilities of the acquisition card. The final important feature of the data acquisition card is that it is LabView compatible and can be controlled via a LabView code.

3.4.2 NI-6123 PCI DAQ Card

Because of the need to acquire more than 4 channels of data, a second acquisition card was installed and used for these calibration experiments. This National Instruments 6123 PCI acquisition card possesses simultaneous multiple channel A/D conversion also and is used in conjunction with another National Instruments BNC 2110 shielded connector block. This acquisition card has 16 bit analog to digital conversion capabilities, 16 M samples of storage, with a voltage input range of ±1.25 V to ± 10 V. The acquisition card is able to sample simultaneously over 8 channels at an acquisition rate of 500 kS/s per channel. This acquisition card is primarily used for the four element hot-film probe measurements as it has the ability to simultaneously sample two output signals from each of the four hot-film sensors as well as the facility stagnation pressure and temperature. This acquisition card is also compatible with LabView and can be controlled via a LabView code.

3.4.3 Plenum Probe Data Acquisition System

All the experiments use the Pitot probe located in the plenum to give an accurate reading of the upstream stagnation pressure. The stagnation pressure Pitot probe inside the plenum is connected to a transducer which in turn connects to a demodulator; this is connected to the data acquisition system via BNC cables. The data acquisition system then converts the analog signal to a digital signal which can be read by a digital voltmeter or recorded by LabView in an ASCII file in a second computer in the lab.
Single sensor probe and four element hot-film probe experiments have different setups for their respective acquisition systems. These two different setups are described in the following sections.

### 3.4.4 Single Sensor Data Acquisition System

As noted earlier the flow field for each jet nozzle and operating pressure ratio was established by a combination of a traversing Pitot probe and/or a static pressure probe (simultaneously with the plenum Pitot probe). The traversing probes were mounted on the two linear direction probe traverse, described earlier. The signal from either traversing probe is routed from their respective pressure transducers to the data acquisition analog to digital convertors. A general block diagram for these experiments can be seen in Figure 3.5. In this diagram we can see the connections made by the plenum Pitot probe and the single sensor probe to their respective pressure transducers; which all connect to the data acquisition system. The data acquisition system converts all analog signals to digital signals which the computer can understand. LabView records this data to an ASCII file which can be viewed with any computer.
3.4.5 Four Element Hot-Film Data Acquisition System

The general experimental setup is very similar to that used for single sensor probe measurements. The Pitot probe inside the plenum is also employed in the four element hot film data acquisition system. The plenum Pitot probe is connected to the A/D system via BNC cables through the demodulator and pressure transducer as previously mentioned. A four element hot film probe in the jet nozzle exit flow connects to a Tao
Systems constant voltage anemometer (CVA); the CVA connects to the A/D system via BNC cables also.

The data acquisition system converts all analog signals to digital signals which the computer can understand. LabView records this data to an ASCII file which can be viewed with any computer. A block diagram showing the connections to the data acquisition system can be seen in Figure 3.6 below.

Figure 3.6: Block diagram of connections to the DAQ system used four element hot film probe experimental setup (Arrows indicate BNC cable connections).
3.4.5.1 Tao Systems Constant Voltage Anemometer

The Tao Systems constant voltage anemometer (CVA) model HF-CVA is designed for applications such as “measuring shear stress, mass flow rate, and flow diagnostics...” [12]. The CVA has a high sensitivity, a large bandwidth (30 KHz), virtually immune to EMI/RFI and requires no critical adjustments at each flow condition. Table 3.1 shows detailed information with regards to the specifications of the CVA.

Table 3.1: Constant Voltage Anemometer – Specifications.[12]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum probe current</td>
<td>200 mA</td>
</tr>
<tr>
<td>Maximum probe voltage, Vw</td>
<td>2 V</td>
</tr>
<tr>
<td>Range of output voltage, Vs</td>
<td>0-20 V</td>
</tr>
<tr>
<td>Frequency response</td>
<td>DC - 470 kHz</td>
</tr>
<tr>
<td>Equivalent input noise</td>
<td>2.6 nV/Hz</td>
</tr>
<tr>
<td>Operating resistance</td>
<td>2-20 Ω</td>
</tr>
<tr>
<td>Probe cable</td>
<td>0-100 m</td>
</tr>
<tr>
<td>Probe connection</td>
<td>BNC connector</td>
</tr>
<tr>
<td>Output impedance</td>
<td>100 Ω</td>
</tr>
<tr>
<td>Output connection</td>
<td>BNC connector</td>
</tr>
<tr>
<td>Power supply</td>
<td>110V/220V</td>
</tr>
<tr>
<td>Dimensions</td>
<td>180 x 255 x 90 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>1.8 kg</td>
</tr>
</tbody>
</table>

3.5 Schlieren Imaging System

Schlieren visualization is used in these experiments as it allows for a clear image of the flow to be seen including all shocks. An advantage to using Schlieren over other flow visualization methods is that no seeding of the flow is required.

The Schlieren setup used is a Z-type Schlieren system, shown schematically in Figure 3.7 below. In this Schlieren system the light source used is a Spectrum Dynamics
Spectralite Model 900 xenon lamp, which is a short duration spark light. This is transformed into a virtual source after passing through a focusing lens and a slit (0.02 in). When the slit is positioned at the focal length of the first parabolic mirror a parallel beam of light is created; the first parabolic mirror is 15 cm in diameter with a focal length of 1.2 m. A second identical spherical mirror focuses the light onto a knife edge after it has passed through the jet, the knife edge is used to stop part of the light beam. Variations in air density within the field of view (caused by the jet) will cause more or less light to be blocked by the knife edge; which results in lighter or darker areas to appear on the image plane (of the camera). Having the capability to see the flow as the probe is profiling means we can see shocks caused by the probe as well as regions of the flow that we may want to concentrate on refining measurements.

Figure 3.7: Z-type Schlieren system schematic.
Chapter 4
Experimental Procedures

4.1 Operational Procedure for the Facility

The operation of the facility requires two phases of control to achieve the desired pressure. The first phase of operation requires the activation of the compressor system and opening the air supply line into the facility. The second phase involves controlling the pressure and flow rate of the air being supplied to the plenum.

Activation of the compressor and air dryer are the first and most important steps to operating the facility. If the compressor is not activated then the air supply would run out very quickly and experiments could not be maintained. To activate the compressor, the ball valve to the air supply tanks must first be opened. Then the compressor is turned on using the ignition key. The compressor will automatically pressurize the tanks to 195 psi if they are not already at maximum pressure. Once the compressor is active, the solenoid valve in the air control cabinet must be activated to avoid a shock tube effect from taking place inside the air cabinet piping system which can potentially cause damage to components. The ball valve at the main inlet control is closed, and the gate valve to the shop air supply is slowly opened to once again avoid over pressurization in the main line. The shop air activates the main pneumatic control valve allowing it to open fully and let the pressurized air into the facility. Once the main pneumatic control valve is open, the air supply line becomes pressurized to 195 psi.

The second phase of facility operation is primarily focused around the control of air pressure in the plenum and the flow rate. Figure 4.1 shows a diagram of the control cabinet front panel; the control cabinet is used to accomplish this second phase. Following only the air line; the solenoid valve (S1) must be active to allow air flow through as it will remain closed when not powered. Following this the first branch is
reached, the ball valve directly after the first branch (B1) is shut and the ball valve on the first branch is opened (B2), this forces the air to flow through the first branch. The reason for using this first branch is that the air pressure can be controlled precisely via the use of the pressure regulator. If more air flow is required then B2 is shut and B1 is opened. The main gate valve (G1) is opened fully to allow the air to flow through to the plenum.

![Diagram of control cabinet front panel.](image)

**Figure 4.1:** Diagram of control cabinet front panel.

To shut down the facility, the main gate valve and the smaller fine adjustment gate valve are both fully closed thus stopping the air supply to the plenum. The main pneumatic control valve is then shut by closing off the shop air supply via the gate valve. Remaining shop air in the pipes must be vented to atmosphere via the ball valve; the ball valve is left open to avoid any leaking air from building up pressure in the line. The main gate valve on the control cabinet is then opened to vent remaining air from the main air supply line and the solenoid valve is deactivated to close it. The final step is turning off
the compressor and closing the ball valve leading to the pressure tanks to avoid the tanks emptying.

4.2 LabView System

The LabView software is directly setup with the data acquisition card and therefore part of the data acquisition system. A versatile LabView code has been written for this study, this LabView code was written so that it is able to perform the single sensor pressure probe experiments mentioned above, “Probe_acquisition_v6.vi”, a simplified block diagram of the LabView acquisition code can be seen below in Figure 4.2, the full LabView code can be seen in Appendix B.1.

![Simplified block diagram of LabView acquisition code](image-url)

Figure 4.2: Simplified block diagram of LabView acquisition code “Probe_acquisition_v6.vi”.
As we can see from the simplified block diagram the code outputs the voltages read by the DAQ card to an ASCII format file. The LabView code also outputs the motor movements as mentioned. A real-time graph of analog inputs is provided so that the user may view the data being recorded and stop the experiment if a problem is observed.

Another feature that can be seen from the block diagram is that the code gives the user 3 main options on how to run the software with basic setup and runtime instructions. The first option is called acquire only, the second option is motor movement only, and the third option is acquire data then move motor.

The first option allows for only acquisition of the analog channels without any motor movement involved.

The second option allows the user to only activate the stepper motors without the ability to acquire any data. This option is useful for when an experiment is prematurely stopped so that the probe can be reset to the starting position. The second option contains the ability to choose between a novice user and an intermediate user. The intermediate user has multi-axis control such as ‘Move axis 1 then move axis 2’. Another multi-axis control option is the ability to move two axes simultaneously; an example of this is as follows, ‘Move axis 3 and axis 1’.

The third option is used to run the experiments as it allows for a looping to be set up if desired. This lets the user set the amount of distance to be moved between each acquisition and the number of times to loop through this process. This option also contains the same level of motor control as the second option, motor movement only.

4.3 Pressure Transducer Calibration

A standard procedure that is always followed is to calibrate all pressure transducers prior to any experiments. To achieve this each pressure transducer is connected to a hand held calibration device. The device displays the pressure in the line to the transducer and a voltmeter connected to the transducer gives the voltage equivalent of that pressure. The information is recorded; this is performed at 6-8 different pressures that are approximately uniformly distributed. A plot is then produced from the recorded
data; the slope of the curve gives the calibration of the transducer (see Figure 4.3). As can be seen in the figure a linear relationship is observed between the voltage and the pressure.

![Graph showing calibration curve for Setra model 205-2 pressure transducer.](image)

Figure 4.3: Calibration curve for Setra model 205-2 pressure transducer.

### 4.4 Data Acquisition Procedure (DAP)

Instructions for operating the LabView code to perform the following procedures can be found in Appendix C.1.
4.4.1 Single Sensor Probe Measurements DAP

A pressure probe survey is performed using either a 0.7 inch or a 1.0 inch exit diameter jet nozzle. A jet pressure ratio and the corresponding voltage of the stagnation pressure probe transducer output are determined in advance. In some cases the pressure can be evaluated from a FORTRAN code designed for this purpose. The code requires several inputs to calculate the pressure required to achieve the desired speed. The inputs required are temperature, atmospheric pressure, humidity, desired pressure ratio and the diameter of the nozzle.

The motor movement is precisely controlled through LabView and tied in with acquisition through a looping method. This means that LabView takes a specified amount of data and then moves the probe a specified amount of distance. Since the distance being moved is user specified we have a precise knowledge of the probe’s location with respect to its start position. Motor voltage would be fed into LabView and used as a trigger but this is not possible as the Velmex motion controller works on a closed loop system and communicates with the computer via the serial port. The LabView code “Probe_acquisition_v6.vi” used for this specific acquisition can be found in Appendix B.1.

Radial profiles of the jet are taken by starting the probe on the centerline of the jet and moving it out of the flow until it is one diameter away from the nozzle. A sampling rate of 20 Hz is used collecting a maximum of 20 scans per Δy/D = 0.01. The motor step size is chosen based upon the total length of travel and the required resolution of the flow field, thus resulting in 40 points in the profile with 20 scans per point (see Figure 4.4) for the following flow conditions: $M_d$ of 1.0, $M_j$ of 1.5; $M_d$ of 1.5, $M_j$ of 1.5. A finer resolution of 56 points in a profile with 20 scans per point is used for the following flow conditions: $M_d$ of 1.65, $M_j$ of 1.65; $M_d$ of 1.65, $M_j$ of 1.75. Radial jet profiles are taken at different x/D locations between x/D = 0.0 to x/D = 2.0 or greater.
4.4.2 Four Element Hot-Film Probe DAP

Due to the size of the four element hot-film probe a 1.0 inch exit diameter jet nozzle is required for calibration purposes. As with the single pressure probe measurements a jet pressure ratio and the corresponding voltage of the plenum stagnation pressure probe transducer output are determined in advance. The transducer “set points” are calculated from the atmospheric temperature and pressure, the desired pressure ratio and the calibration constant of the transducer.

The LabView code “Probe_acquisition_v6.vi” facilitates data collected with the probe via two different methods, static and dynamic acquisition. For the purposes of calibration, the static acquisition method should be used when the probe is not moving during acquisition of data. Another important feature of the code will be used in the four element hot-film measurements; this feature allows the monitoring of all available channels in real-time and calculates information required to set the overheat.

Prior to the start of the four element hot-film probe measurements the resistance of each sensor is checked with previously recorded resistances to ensure continuity and reduce error. This is done by first measuring the resistance of each sensor before they attach to the leads and by measuring the resistance at the connector of the sensors and

---

Figure 4.4: Example map of mean flow measurement traverse locations.
leads. Table 4.1 shows the cold resistances of the four element hot-film probe after manufacturing and before experimentation.

Table 4.1: Cold resistance of four element hot-film probe.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>After Manufacture (Ω)</th>
<th>Pre-Experiment (sensors) (Ω)</th>
<th>Pre-Experiment (sensors &amp; leads) (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>21.35</td>
<td>19.9</td>
<td>21.5</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>21.92</td>
<td>20.2</td>
<td>22.0</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>22.5</td>
<td>21.9</td>
<td>22.6</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>24.24</td>
<td>22.7</td>
<td>24.4</td>
</tr>
</tbody>
</table>

After determining the resistance of each sensor the overheat ratio ratios must be calculated. The overheat ratio is defined as the following:

\[
\alpha = (R_{oper} - R_{sensor}) / R_{sensor}
\]  

The operating temperature is calculated as:

\[
R_{oper} = (\alpha + 1) * R_{sensor}
\]

Before beginning the calibration process, the cold resistance without any overheat applied is recorded. Then, the overheat of the probe is set using the hyper-terminal interface with the CVA via a RS-232 (Serial) cable (see Appendix H.1 for detailed instructions to set overheat). No flow data are collected at this time which later will be used in the data processing. After the no flow data are collected the overheat is switched off and after 30 seconds the “cold resistance (Ra)” is collected again. The overheat is reapplied and calibration can begin. The first calibration was performed along the centerline of the jet where Mach number and mass velocity varies and has been established by the pre-calibration flow field surveys. This pre-calibration was performed in the single sensor measurements in preparation for the four element hot-film probe measurements in these same jets. The four element hot-film probe started at x/D = 0.0 and was moved downstream in the jet nozzle until x/D = 2.0. The probe was moved in x/D = 0.1 increments, collecting 4000 data points at each location using a sampling rate of 10 kHz. The “cold resistance in the flow (adiabatic wall resistance) Ra” was collected
at regular intervals between $x/D = 0.0$ to $2.0$, and the flow remains on for these. These centerline traverses were performed with an overheat ratio of 25% and 50%. This type of calibration was first performed in the $M_d$ of 1.0, $M_j$ of 1.5 jet nozzle as the mass velocity and Mach number vary with $x/D$ over a wide range. The measurements were then repeated for the jet condition of $M_d$ of 1.65, $M_j$ of 1.75 as specified in Table 1.1.

The second calibration was for angulation so that sensitivity flow direction can be determined. The probe was positioned at $x/D = 1.0$ from the jet nozzle and was not traversed from this location (with the exception of moving the probe into and out of the flow at the start and end of the experiment). The starting pitch angle of the probe was $\theta = -30^\circ$ and the probe was swept through the yaw angle $\varphi = 30^\circ$ to $-30^\circ$ in $5^\circ$ increments. Then $\theta$ was incremented $+2^\circ$ and the $\varphi$ sweep was performed again; this was repeated until $\theta = 30^\circ$, resulting in a total of 225 sweep points. At each sweep point 3900 samples were collected using a sampling rate of 10 kHz. As with the centerline calibration, an overheat ratio (50%) was applied to the four element hot-film probe for these measurements. This calibration was performed in the $M_d$ of 1.0, $M_j$ of 0.4 jet nozzle first. The measurements were then repeated for $M_d$ of 1.0, $M_j$ of 0.8. At the end of all calibrations the overheat was turned off and the probes were powered down.

### 4.5 Data Processing

#### 4.5.1 Data Processing for Single Sensor Probe Measurements

Two MatLab codes were written for converting the voltages gathered into pressures. One code processes data gathered using the static method of acquisition (“Static_Survey_Processing_code_v2.m”) and the other code processes data gathered using the dynamic method of acquisition (“Dynamic_Survey_Processing_code_v1.m”). Both codes apply the relevant calibration curves to that data. Once converted the pressures are averaged for each point in the profile resulting in an averaged data point per
profile point. The resulting pressures are then non-dimensionalized with $P_o$, and further processed as detailed below. The following assumption is made about the flow:

$$T_{oj} = T_a$$

Where $T_{oj}$ is the exit stagnation temperature and $T_a$ is the ambient temperature. Other assumptions made are that the local stagnation pressure is equal to the upstream stagnation pressure, except in the shear layer or outside the flow when this no longer holds true. Also, the local pressure is approximately equal to the ambient pressure when within the shear layer.

The Mach number is related to the Pitot pressure $P_{i2}$ and the static pressure $P_1$ via the Rayleigh-Pitot formula when the flow is supersonic ([2], [9], [10], [11]).

$$\frac{P_{i2}}{P_1} = \left( \frac{\gamma+1}{2M_1^2} \right)^{\frac{\gamma}{\gamma-1}}$$

4.4

In the shear layer, when the Mach number falls below unity, the isentropic formula should be used.

$$\frac{P_p}{P_1} = \left( 1 + \frac{\gamma-1}{2} M_1^2 \right)^{\frac{\gamma}{\gamma-1}}$$

4.5

In order to obtain a good representation of the value of the static pressure in the flow without the presence of the static probe, it has been shown that the distance between the holes and the tip of the probe, $x_h - x$, should be at least 10 times the diameter $D_p$ of the static probe. Then, the static pressure $P_1$ measured by the probe is a good representation of the static pressure in the flow at location $x_h$ in the absence of any probe (provided the probe is aligned with the local oncoming flow). The use of any smaller
value of $x_h - x$ leads to a measured static pressure lower than the actual value. In the present experiments, $x_h - x$ is 12.7 mm and $D_p$ is 1 mm [2].

Knowledge of three appropriate gasdynamic properties in a compressible flow is sufficient to uniquely specify all properties of the flow. In an adiabatic flow of this type the isoenergetic approximation of constant jet stagnation temperature, $T_o$, is very accurate [2]. An important problem occurs with the use of the static pressure probe; the static pressure probe resolution sensing volume is larger than required for accurate definition of the flow field (particularly in shock containing plumes). Therefore a second (alternate) method was developed for the isentropic flow region inside of the surrounding shear layer (annulus) and upstream of the first oblique shock waves. In this region the normal shock relation for $P_{t2} / P_{t1}$ is [2]:

$$\frac{P_{t2}}{P_{t1}} = \left( \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2 + 2} \right)^{\frac{\gamma}{2(\gamma-1)}} \left( \frac{\gamma + 1}{2\gamma M_1^2 - (\gamma-1)} \right)^{-\frac{1}{\gamma-1}} \tag{4.6}$$

Eq. 4.5 can continue to be used in the shear layer for regions below $M_{local} = 1$. The appropriate assumption here is that local pressure $P_I$ is equal to the external ambient pressure $P_a$. As it can be seen the Rayleigh-Pitot formula and normal shock relation (alternate method) are implicit methods for solving for Mach number, therefore have to
be solved using an iterative method which is written as part of the MatLab code(s) and
can be seen in Appendix E, “Static_Survey_Processing_code_v2.m” &
“Dynamic_Survey_Processing_code_v1.m”. Once all information has been converted
and calculated the code outputs each quantity to an ASCII format file respectively. The
data are formatted so that they can be easily plotted via the use of an external program
such as Excel or TecPlot. The schematic in Figure 4.5 shows the nomenclature used in
the Rayleigh-Pitot and Isentropic formulas.

Further processing is required to determine the mass velocity ($\rho u$) of the flow
field. A MatLab code, “Mass_Velocity_Processing_code_v3.m”, is used to post-process
the data after it has been processed using either “Static_Survey_Processing_code_v2.m”
or “Dynamic_Survey_Processing_code_v1.m”. To determine the mass velocity the
MatLab code uses the calculated Mach flow field and the assumption of:

$$P_{\text{it}} = \text{constant (collected data is averaged to determine value)}, \quad T_{\text{oj}} = \text{constant}$$

Isentropic flow relations are used in the following order to determine the mass
velocity:

**Step 1** – Calculate $P_1$

$$\frac{P_{\text{it}}}{P_1} = \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}}, \quad \text{or} \quad P_1 = P_a \text{ in the shear layer below } M_1 = 1 \quad 4.7$$

**Step 2** – Calculate $T_1$

$$\frac{T_{\text{oj}}}{T_1} = \left(1 + \frac{\gamma - 1}{2} M^2 \right) \quad 4.8$$

**Step 3** – Calculate $\rho_1$

$$\rho_1 = \frac{P_1}{RT_1} \quad 4.9$$
Step 4 – Calculate speed of sound

\[ a = \sqrt{\gamma RT_1} \]  \hspace{1cm} 4.10

Step 5 – Calculate velocity of flow

\[ u = Ma \]  \hspace{1cm} 4.11

Step 6 – Calculate mass velocity

\[ \rho u \]  \hspace{1cm} 4.12

As with the other MatLab codes, the mass velocity is output to an ASCII format file where the data is formatted so that it can easily be plotted via the use of an external program such as Excel or TecPlot. In order to validate the MatLab code, a set of hand calculations were made which can be seen in Appendix F.1.

After all processing is complete contours to compliment the profile plots can be easily produced using MatLab. The contours can be used to make a comparison with the Schlieren if available.

4.5.2 Data Processing for Four Element Hot-Film Measurements

Two MatLab codes have been developed to process the collected data for the four element hot-film measurements. The MatLab codes require an input file containing data from 8 channels and an input file in the specified format containing information such as cold resistance, number of samples per channel and scan rate. The first MatLab code is “FASS_Processing_code_v1b.m” which is used for processing the data collected in the angulation calibrations. The second MatLab code that was developed is “FASS_velocity_calibration_Processing_code_v1.m” which is used to process the data collected during the centerline calibration. Copies of both of these codes are given in Appendix E.

The same set of equations is used in the MatLab codes, the difference between the codes being the way the input data file is formatted. The input data should be 8 channels
where the first 4 channels represent $V_{wm}$ and the last 4 channels represent $V_s$ (where $V_{wm}$ is the measured wire (or film) voltage and $V_s$ is the sensor output voltage that represents the change in current). If this is not the case then the outputted data by the MatLab codes will be incorrect. First the code(s) determines the current:

$$I_w = \frac{(V_s - V_{wm})}{(COA \text{ calibration})} \quad 4.13$$

Where the COA calibration is given in Table 4.2 below and is specific to this probe.

**Table 4.2: COA calibration coefficients**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>COA Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>17.97</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>18.07</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>18.01</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>18.02</td>
</tr>
</tbody>
</table>

The resistance, $R_w$, is calculated from $I_w$ and $V_{wm}$ using the following equation:

$$R_w = \left( \frac{V_{wm}}{I_w} \right) - R_{\text{lead}} \quad 4.14$$

Where $R_{\text{lead}}$ can be calculated from Table 4.1, by subtracting the resistance of the sensors from the resistance of the sensors and leads together, i.e.

$$R_{\text{lead}} = R_{\text{sensors and leads}} - R_{\text{sensors}} \quad 4.15$$

The next step in the data processing code(s) is to calculate the voltage, $V_w$ using Ohm’s Law:

$$V_w = R_w \times I_w \quad 4.16$$

Next, the overheat is calculated from $R_w$ and the cold resistance $R_a$:

$$A_w = \frac{R_w - R_a}{R_a} \quad 4.17$$
The power dissipated by each sensor is calculated:

\[ P_w = V_w \times I_w \]  \hspace{1cm} (4.18)

Finally the code(s) calculates the power dissipation ratio for each sensor:

\[ PDR = \frac{P_w}{(R_w - R_a)} \]  \hspace{1cm} (4.19)

All calculated values are outputted to separate ASCII files so that they can be stored and later referenced if necessary. The final portion of the data processing is performed in Excel where the values of PDR for each calibration case are imported into a spreadsheet. This is done so that \( PDR_{\text{net}} \) can be calculated using the following equation:

\[ PDR_{\text{net}} = PDR_{\text{flow}} - PDR_{\text{no flow}} \]  \hspace{1cm} (4.20)

For analysis purposes \( PDR_{\text{net}} \) is plotted against \( \sqrt{Re_v} \), where \( \sqrt{Re_v} \) is:

\[ \sqrt{Re_v} = \frac{(\rho u)D}{\mu} \]  \hspace{1cm} (4.21)

(D is the probe diameter)

After all processing is completed, plots can be made using Excel or TecPlot.
Chapter 5

Experimental Results

5.1 Single Sensor Pressure Measurements Experimental Results

In chapter 4 the methods used to obtain mean flow field measurements along with data reduction techniques are described. The main purpose of these experiments was to map the flow fields so that calibrations could be performed using a four element hot-film probe over a broad range of velocity, density and Mach numbers. This chapter will focus on discussing the results found from these experiments.

The single sensor pressure probe measurements were performed primarily using a single hole Pitot probe and a static pressure probe (as described in Chapter 4.4.1) in the following cases: $M_d$ of 1.0 and $M_j$ of 1.5. The main region of interest in these experiments is near the nozzle exit, region of $x/D \leq 1.0$, but other regions of the flow are also mapped to help build a full understanding of the flow.

As mentioned previously in Chapter 4 the following setup is used for mapping the flow field; 40 points for each profile with 20 samples per point (see Figure 4.4) for the following flow conditions: $M_d$ of 1.0, $M_j$ of 1.5; $M_d$ of 1.5, $M_j$ of 1.5. A finer resolution of 56 points in a profile with 20 scans per point was used for the following flow conditions: $M_d$ of 1.65, $M_j$ of 1.65; $M_d$ of 1.65, $M_j$ of 1.75.

The results for the following pre-calibration flow conditions are included in Appendix G: $M_d$ of 1.5, $M_j$ of 1.5; $M_d$ of 1.65, $M_j$ of 1.65; $M_d$ of 1.65, $M_j$ of 1.75.

5.1.1 $M_d$ of 1.0, $M_j$ of 1.5

Data processing of the raw data produces one main input and two main outputs ($P_{t2}/P_o$, Mach number and mass velocity) which are subsequently plotted. $P_{t2}/P_o$ data are
computed initially from a direct ratio of those two independently measured quantities. \( P_{t2}/P_o \) profiles are plotted and used as a quick analysis tool to determine any anomalous points in the flow. Figure 5.1 shows the profile plot for this given jet nozzle and flow condition. The data from the profile plot is mirrored about the centerline and a contour plot is produced using MatLab which can be seen in Figure 5.2. The shape of the flow can be seen in the contour plot and further detail can be seen more clearly in the profile plots.

Figure 5.1: Profile plot for \( M_d \) of 1.0, \( M_j \) of 1.5.
Next is presented Mach number profiles computed with the most accurate method (using equation Eq. 4.6 for flow inside of the shear layer, and Eq. 4.5 for flow within the viscous shear layer and outside the $M = 1$ locus (Figure 5.3)). Figure 5.4 shows a contour plot of local Mach number computed from the Mach number profiles in Figure 5.3. The second methodology is only able to solve for Mach number in the regions where the assumption of known stagnation pressure ahead of the probe shock wave made hold true. When the Mach number is very close to $M = 1.0$ near the nozzle exit a solution can not be found because of the iterative method used to converge to a solution; this can be seen in the region of $x/D \leq 0.2$ in Figure 5.3. The Mach number contour plot of the second method matches well with the contour plot of $P_{t2}/P_o$ seen in Figure 5.2. If we refer to the Schlieren (Figure 5.5) with the static pressure probe in the supersonic flow we can observe that a shock forms at the tip of the static pressure probe which is then reflected back into the probe. This reflected shock causes the difference in the Mach gradients and
accounts for why the first methodology is producing incorrect results and therefore will not be used further in this study.

Figure 5.3: Mach number profile for second methodology \((P_{t2}/P_o)\) for \(M_d\) of 1.0, \(M_j\) of 1.5.
Figure 5.4: Mach number contour plot for second methodology ($P_{t2}/P_o$) for $M_d$ of 1.0, $M_j$ of 1.5.

Figure 5.5: Schlieren of static pressure probe in the flow creating a shock that is reflected.
The second output produced during data processing is the mass velocity. The mass velocity is calculated from the Mach number using the method described in Section 4.5.1 and the profile can be seen in Figure 5.6. In the profile plots we can see that in the regions where the Mach number is changing slowly we see a fairly constant mass velocity. Upon examination of the centerline profile plot which can be seen in Figure 5.7, we can see that the variation is much greater as the Mach number is changing very rapidly.

Figure 5.6: Mass velocity profile plot for $M_d$ of 1.0, $M_i$ of 1.5.
Chapter 4 described the techniques used to calibrate the four element hot-film probe and the associated data reduction methods. The main purpose of these experiments is to perform velocity calibrations along the centerline of the jet and angulation calibrations to determine flow direction sensitivity. This section will focus on discussing the results found from the experiments.

The four element hot-film probe measurements were performed in the following cases for centerline velocity calibration: $M_d$ of 1.0 and $M_j$ of 1.5; $M_d$ of 1.65 and $M_j$ of 1.75. The flow angulation sensitivity calibrations were performed in the following cases: $M_d$ of 1.0 and $M_j$ of 0.4 and 0.8.

![Graph](image)

Figure 5.7: Centerline plot of mass velocity for $M_d$ of 1.0, $M_j$ of 1.5.

5.2 Four Element Hot-Film Probe Measurements Experimental Results

Chapter 4 described the techniques used to calibrate the four element hot-film probe and the associated data reduction methods. The main purpose of these experiments is to perform velocity calibrations along the centerline of the jet and angulation calibrations to determine flow direction sensitivity. This section will focus on discussing the results found from the experiments.

The four element hot-film probe measurements were performed in the following cases for centerline velocity calibration: $M_d$ of 1.0 and $M_j$ of 1.5; $M_d$ of 1.65 and $M_j$ of 1.75. The flow angulation sensitivity calibrations were performed in the following cases: $M_d$ of 1.0 and $M_j$ of 0.4 and 0.8.
The results for $M_d$ of 1.65 and $M_j$ of 1.75 are not included in this thesis as the results were very preliminary and would need to be repeated before the results could be analyzed.

5.2.1 $M_d$ of 1.0, $M_j$ of 1.5

The first set of centerline velocity calibrations was performed with an overheat ratio of 25%. An average of the power dissipation ratio ($PDR$) of all four sensors is plotted in Figure 5.8. From prior work with hot-film sensors in supersonic flows [14][15] it is anticipated that the best calibration “collapse” will occur with the plots of the power dissipation ratio to each hot film ($PDR_{net}$) as a function of the square root of the probe Reynolds number, based on the air viscosity at the flow stagnation temperature ($\sqrt{Re_o}$). Different symbols are used correspondingly to three ranges of Mach number used in these experiments. These experimental data were recorded on our first day of operation of the probe when our procedures were uncertain and the subsonic and supersonic measurements were separated in time by several hours.
The same jet condition was maintained and an overheat ratio of 50% is used. In this case subsonic data were taken on the same day prior to obtaining supersonic data. In Figure 5.9, it can be noted that the subsonic data follows the expected trend with the supersonic data and is also linear. If the supersonic data are compared between the two overheat ratios (Figure 5.8 and Figure 5.9) we can see that they show very similar trends and all thus consistent in that respect.

Figure 5.8: Average sensor output for the condition of $M_d$ of 1.0 and $M_j$ of 1.5 ($A_w = 0.25$).
Figure 5.9: Average sensor output for the condition of $M_d$ of 1.0 and $M_j$ of 1.5 ($Aw = 0.5$).

Figure 5.10 shows a comparison of the two different overheat ratios being applied to the same flow condition as the probe is traversed along the jet axis, through the varying flow field documented in Figure 5.1 to Figure 5.7. From this comparison plot we can see that the experiment is repeatable and that the shape of both curves is very similar.
5.2.2 Flow Angle Sensitivity Calibration (M = 0.4 and 0.8)

Figure 5.11 shows the calibration for the four element hot-film probe in a subsonic flow of Mach 0.4. In this figure the difference between the top and bottom sensors is plotted against the difference between the left and right sensor. Where each data point represents a specific pitch and yaw angle. Each curved line running from left to right represents the locus of constant pitch. The dashed curved line represents the locus of constant yaw. A large skewness can be observed in this plot at positive pitch angles of the probe which could be caused by one of two factors. The first possibility is that the sensors are not all at 90° to each other and therefore creating cross-talk in signals. The second possibility is that the probe axis is not aligned correctly with the flow.

Figure 5.10: Net PDR comparison for different overheats when $M_d$ of 1.0 and $M_j$ of 1.5.
The same flow angle calibration was performed at a higher Mach number of 0.8. The calibration plot produced from these results can be seen in Figure 5.12. We can see the same skewness that was seen in Figure 5.11, thus this is a systematic error.

Figure 5.11: Calibration plot when \( M_d \) of 1.0, \( M_j \) of 0.4 (\( A_w = 0.5 \))
Figure 5.12: Calibration plot when $M_d$ of 1.0, $M_j$ of 0.8 (Aw = 0.5)
Chapter 6

Conclusions

6.1 Single Sensor Measurement Conclusions

From the single sensor measurements we can conclude that in each case we see that a detailed picture of the flow field has been developed using refined Pitot probe measurements. It was shown that the flow properties, Mach number and mass velocity ($\rho u$) could be calculated by two methods, one using static pressure probe measurements and the other using upstream stagnation pressure (the latter measurement is made for all measurements as the method of setting repeatable nozzle flow conditions). The method using the static pressure probe measurement produces errors in regions of substantial flow angulation (to the probe) and in regions where the inadequate probe resolution is a problem. The possibility of the shock from the tip of the probe can reflect from the shear layer to produce a measurable disturbance in the flow. This disturbance was barely seen when measurements were made in the 1 inch diameter jets (instead of the ½ inch diameter jets).

The second method of computing the flow properties required the use of the upstream stagnation pressure together with the assumption that this property is constant, which is good (to engineering accuracy) in the inviscid regions away from the shear layer (annulus) of the jet. It was also possible to account for small decrease in the stagnation pressure property through straight shock waves of known angle and entering flow Mach number.

The majority of the hot-film probe calibrations were performed in the $M_d = 1.0$, operating at a pressure ratio of 3.67, corresponding to a perfectly expanded jet at $M_j = 1.5$. In this case the flow Mach number along the jet centerline beginning at the nozzle exit monotonically increases in Mach number until it reaches a maximum of about 2.6 at
which point the flow enters an oblique shock wave. Behind this first shock wave the flow Mach number is below 1.5 until it encounters the next group of expansion waves. This region can be calculated reasonably accurately using the reduced local stagnation pressure (ahead of the Pitot probe bow shock) as noted earlier.

In the region of flow from the nozzle exit to the first oblique shock wave the Mach number steadily increases. This produces a region of steadily decreasing mass velocity ($\rho u$) that is very useful for calibration of the hot-film probe. In this region of increasing Mach number (and velocity) the mass velocity decreases because the density decreases at a faster rate due to the strong expansion of the flow.

Appendix G shows profile plots of the Mach number for each jet nozzle and condition used in these measurements. If we refer to the Mach profiles in Appendix G.3 we can notice that the use of the isentropic flow relations when entering the viscous layer is also a good assumption. In Appendix G.4, the mass velocity profiles can be seen; in each profile plot a peak in mass velocity can be seen at the interchange between the supersonic region and the viscous region. This peak can be attributed to a slight total temperature decrement since the Prandtl number is less than 1, and the thermal diffusivity is slightly higher than the momentum diffusivity, a slight decrease in total temperature leads to a slight increase in density (and thus $\rho u$).

Further detailed mapping of the flow field should be performed in the future using an increment of $x/D = 0.05$ and double the amount of points is collected in each profile also the iterative scheme used to solve for the Mach number should either be improved or replaced with a reliable scheme when $M \approx 1.0$.

6.2 Four Element Hot-Film Probe Measurement Conclusions

The results of centerline velocity calibrations in the four element hot-film probe measurements demonstrate that the resistance of the films is dependent on atmospheric conditions at the time of measurement. The measurements also tell us that the experiments are repeatable as the same trends can be seen, Figure 5.10, with different overheats. Another important conclusion that can be drawn from this calibration is that a
3/8 inch probe may be too large in the 0.7 inch diameter jet nozzle to provide reliable calibration results.

The results of the flow angle sensitivity calibrations demonstrate that either the sensors at not 90° to each other or the probe was not aligned precisely with the flow. This is not to say that the data collected is incorrect, rather that cross-talk is occurring between sensors in much larger magnitudes than expected.

If it is possible to run the measurements with constant atmospheric conditions then this should be done to reduce changes in sensor resistance. A minimum of 1.0 inch jet nozzle should be used ideally so that a larger potential core is produced. The sensor orientation to each other should be checked and the sensor alignment with the flow to reduce the asymmetric flow angulation sensitivity results.
Bibliography


Appendix A

Motorized Rotary Stages Detailed Specifications

A.1 B4836TS

B4836 is one in a series of three rotary tables that use a worm and gear drive with a central rotating ball bearing. The gear ratio is 36:1. This gear ratio requires holding torque to maintain position. The table can be driven by a frame size 23 stepper motor, Bodine Type K or a Pittman PM DC motor. The table has a hollow spindle, a $360^\circ$ scale and an adjustment to minimize gear backlash.

There are two options to securing the base of the table. First, there are two clearance holes for 10-32 UNF cap screws for attachment from above through the top access hole. Second, attach with screws from below using four threaded holes. The holes are 1/4-20 x 7/16” UNC on a 4” diameter bolt circle. Table A1.1 shows other specifications about this rotary stage. Figure A1.1 shows a schematic of the B4836TS rotary stage including all holes that can be used for mounting.
Table A1.1: Further Detailed Specifications for B4836TS [13]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal load capacity</td>
<td>200 lbs</td>
</tr>
<tr>
<td>Vertical load capacity</td>
<td>25 lbs</td>
</tr>
<tr>
<td>Cantilever load (Horizontal)</td>
<td>500 in-lbs</td>
</tr>
<tr>
<td>Table top axial runout</td>
<td>0.00025” TIR</td>
</tr>
<tr>
<td>Table top radial runout</td>
<td>0.0005” TIR</td>
</tr>
<tr>
<td>Accuracy</td>
<td>100 arc-seconds</td>
</tr>
<tr>
<td>Repeatability</td>
<td>1 arc-seconds</td>
</tr>
<tr>
<td>Table weight</td>
<td>5.5 lbs/2.5 kg</td>
</tr>
<tr>
<td>Maximum input shaft torque</td>
<td>150 oz-in</td>
</tr>
<tr>
<td>Maximum input shaft speed</td>
<td>600 RPM</td>
</tr>
</tbody>
</table>
Figure A1.1: Schematic of B4836TS rotary stage [13].
A.2 B5990TS

The B5990TS has a gear ratio of 90:1 and a 1.7” diameter table. This rotary stage is pre-fitted with a NEMA 17 stepper motor. Table Table A1.2 shows other specifications about this rotary stage. Figure A1.2 shows a schematic of the B4836TS rotary stage including all holes that can be used for mounting.

Table A1.2: Further Detailed Specifications for B5990TS [13]

<table>
<thead>
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<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Vertical load capacity</td>
<td>5 lbs</td>
</tr>
<tr>
<td>Cantilever load (Horizontal)</td>
<td>20 in-lbs</td>
</tr>
<tr>
<td>Table top axial runout</td>
<td>0.00011” TIR</td>
</tr>
<tr>
<td>Table top radial runout</td>
<td>0.00008” TIR</td>
</tr>
<tr>
<td>Accuracy</td>
<td>100 arc-seconds</td>
</tr>
<tr>
<td>Repeatability</td>
<td>1 arc-seconds</td>
</tr>
<tr>
<td>Table weight</td>
<td>2.7 lbs w/ motor</td>
</tr>
<tr>
<td>Maximum input shaft torque</td>
<td>50 oz-in</td>
</tr>
<tr>
<td>Maximum input shaft speed</td>
<td>600 RPM</td>
</tr>
</tbody>
</table>
Figure A1.2: Schematic of B4836TS rotary stage [13].
Appendix B

LabView Codes

B.1 Probe_acquisition_v6.vi

The main code block diagram is shown below. The events in the code allow the user to acquire only, move the motors only, acquire and move. For further detail of this LabView please contact the Aerospace Engineering Department to obtain full documentation.
B.2 Acquire_in_ASCII.vi
Appendix C

LabView Code Instructions

C.1 Probe_acquisition_v3.vi Instruction Set

This instruction set will give you a step-by-step guide on how to run this specific piece of LabView code. Please note the instruction set is written for running a generic experiment relevant to this code. (Even though version 6 of this code was used during measurement this instruction set is still relevant).

1. Click on Start\Program Files\National Instruments\LabView 7.1\LabView or click on the desktop icon if it exists.
2. The LabView splash screen will appear offering you the choice of starting a new file or opening an old one. Click on open.
3. Locate and open “Probe_acquisition_v3.vi”.
4. Set up experiment/double check set up.
5. Click on the run button  
6. Under the heading “Method selection” is 4 options of control. Click on the appropriate method.

(Skip to instruction section referencing selected control method).
C.1.1 Acquire Only:

1. Enter the number of channels you wish to acquire on. (Note: channel numbers start at 0 not 1). Example of entering multiple channels:

0:2

This is the format that should be used to select multiple channels. This is channels 0 thru 2.

2. Enter the maximum number of scans you want to collect and enter that value under “Max. # of scans to write to file” & “# of scans to acquire at a time”.

3. Adjust the scan rate to be at least twice the value of the maximum frequency of the input you are recording.
4. Adjust buffer size to meet the needs of the maximum amount of data you wish to collect.
5. The default voltage range is -5V to +5V, but this can be adjusted to a maximum of -10V to +10V and a minimum of -0.1V to +0.1V.
6. Once all settings have to changed to meet the needs of the acquisition and been double checked, click on the acquisition toggle switch to begin acquiring.
7. Click “Exit Program” when you have completed acquisition.

Note: As the buffer is emptied to file LabView will automatically plot the raw data to the front panel.

C.1.2 Motor Only:
1. Start Menu\Program Files\COSMOS
2. Use the COSMOS setup wizard to setup your motion controller. (You can adjust the speed using the help files).

   **WARNING: DO NOT USE HIGH POWER OR INCREASE SPEED BEYOND DEFAULT!**

3. Activate the LabView Code following earlier steps.
4. Select Motor Only.
   - Novice: allows control of only one motor.
   - Intermediate: allows control of one motor, one motor then another motor or two motors simultaneously.
6. Select the motor you want to control & then enter the number of steps you want to move it. Then press the confirm button.
7. Then click “Motor Move Only” button.
8. Commands sent to the motion controller are echoed to the front panel.
9. If an error occurs then click on “Purge Controller Buffer” button to clear any previous commands that may remain in memory.
10. Click “Exit Program” to end session.
C.1.3 Acquire & Move - Static:

1. Follow steps 1-5 from Acquire Only section.
2. Then follow steps 1-6 from Motor Only section. (Number of steps being moved is no longer the total length of travel for Acquire & Move).
3. Determine the length of travel you want between acquisition points. Enter this value in “# of steps”.
4. Divide total length of travel (in steps) you wish to cover by the number of steps between acquisitions. Then add one to this number. See example below:

\[ \frac{3000}{100} = 30 \implies 30 + 1 = 31 \]
5. Time Lag between the end of motor movement and acquisition occurring can be adjusted from the front panel.

   **Note:** The steps 6-7 are for use with a pitot probe and allow for the quick look graph to be utilized.

6. If your experiment uses a single/or more hole pitot probe then you can enter the desired plenum pressure in the appropriately labeled box.
7. Enter the calibration of the transducer for the probe including any offset.

8. Double check all settings.
9. Click Move & Acquire.
10. Click “continue” in the window that pops up once you have tripled checked all settings.
11. If an error occurs then click on “Purge Controller Buffer” button to clear any previous commands that may remain in memory.
12. At end of movement and acquisition you’ll be prompted to enter a file name for the data to be saved to. (All data is ASCII)
13. Click “Exit Program” when experiment is complete.
C.1.4 Acquire & Move - Dynamic:

1. Upon selecting this button a new window will appear restricting access to the previous window.
2. Follow steps 1-5 from Acquire Only section.
3. Then follow steps 1-6 from Motor Only section. (Number of steps being moved is the total length of travel).
4. Once you have followed steps 2 & 3 of this section, you will notice that timings may not correspond in the following box.
5. Ensure that the correct motor speed is entered in the “motor speed” box.

6. If timings are still not the same, adjust acquisition “scan rate” and “# of scans to acquire at a time” until a match occurs. (Try to match “scan rate” such that a minimum of 10 scans per step is recorded).

7. Click “Move w/ Acquire” button.

8. If an error occurs then click on “Purge Controller Buffer” button to clear any previous commands that may remain in memory.

9. Click “Exit Program” button to close dynamic acquisition window.

10. Click “Exit Program” button again to stop code.
Appendix D

Macor Stress Analysis and Testing

D.1 Macor Stress Analysis and Testing

Due to Macor being a glass ceramic and having little available information with regards to its maximum bending stress an analysis was performed. The analysis determines the approximate forces that would be acting on the hemi-spherical probe head and the resultant moments acting on the shaft of the probe. The force acting on a ½ inch diameter hemi-spherical probe in a Mach 1.5 jet is theoretically estimated to be 4.95 lbf. The resulting moment acting on the shaft of the probe at point of attachment is estimated to be 4.95 lb-in (assuming 1 inch from point of attachment to load point).

A simple experiment is then used to determine whether the material can withstand the bending moments. A piece of Macor is attached in a clamp (1 inch from point of attachment to load point) so that a load can be applied at the other end. The loading applied is increased linearly and until a loading of 6 lbs is reached which is beyond predicted forces to allow of an engineering safety margin. The results can be seen in Figure D4.1 below. From this analysis and testing we learn that the material is capable of withstanding the forces that will be applied to it.
Figure D4.1: Bending stress vs. force applied to a ¼ inch diameter Macor cylindrical rod.
Appendix E

MatLab Codes

E.1 Static_Survey_Processing_code_v2.m

clear all;

disp(' ');
disp(' ');
disp('For every input, be aware to type capital letters where you have to...');
% Get User Inputs

% Ask user to input file name
disp('Please enter file name of data file containing static acquisition method
data.');
filename = input('File name: ','s');

% Ask user for misc info file name
disp('Please enter file name of misc info file.');
filename1 = input('File name: ','s');
filename1 = 'misc.txt';

% Load misc info needed to run code successfully
misc = load(filename1);

% Perform data sorting and averaging

% assign misc info to variables
N = misc(1,1);
pinf = misc(2,1);
dpp = misc(3,1);
stepsMoved = misc(4,1);
transCal = misc(5,1);
calOffset = misc(6,1);
probetransCal = misc(7,1);
probecalOffset = misc(8,1);

% Import data from files
[ch, chdata] = parseDataFile(filename);

% Organise data scanned from file
if (N >= 1)
    ch0data = chdata{1,1};
end;

if (N >= 2)
    ch1data = chdata{1,2};
if (N >= 3)
  ch2data = chdata(1,3);
end;

if (N >= 4)
  ch3data = chdata(1,4);
end;

% This channel is the plenum voltage
if (N >= 5)
  ch4data = chdata(1,5);
end;

% Average data for more accurate data point at each location

sum = 0;

if (N >= 1)
  for i = 1:pinf;
    for j = 1:dpp;
      sum = ch0data(j,i) + sum;
    end
    temp = sum/dpp;
    avgch0data(i,1) = temp;
    sum = 0;
  end
end;

if (N >= 2)
  for i = 1:pinf;
    for j = 1:dpp;
      sum = ch1data(j,i) + sum;
    end
    temp = sum/dpp;
    avgch1data(i,1) = temp;
    sum = 0;
  end
end;

if (N >= 3)
  for i = 1:pinf;
for j = 1:dpp;
    sum = ch2data(j,i) + sum;
end
temp = sum/dpp;
avgch2data(i,1) = temp;
sum = 0;
end
end;
if (N >= 4)
    for i = 1:pinf;
        for j = 1:dpp;
            sum = ch3data(j,i) + sum;
        end
        temp = sum/dpp;
        avgch3data(i,1) = temp;
        sum = 0;
    end
end;
if (N >= 5)
    for i = 1:pinf;
        for j = 1:dpp;
            sum = ch4data(j,i) + sum;
        end
        temp = sum/dpp;
        avgch4data(i,1) = temp;
        sum = 0;
    end
end;

% Plenum voltage conversion & Probe voltage conversion

% Convert Plenum voltage to gage pressure
for i = 1:pinf;
    avgplenumvolt(i,1) = avgch0data(i,1)*(transCal + calOffset);
end;

% Convert the Probe Voltage to gage pressure
for i = 1:pinf;
    avgprobevolt(i,1) = (avgch1data(i,1)*(probetransCal + probecalOffset));
end;
% Non-dimensionalize Pressure
for i = 1:pinf;
    avgNDimPressure(i,1) = avgprobevolt(i,1)/avgplenumvolt(i,1);
end;
% for i = 1:pinf;
%    avgNDimPressure(i,1) = avgprobevolt(i,1)/53.100488;
% end;
%-------------------------------------------------------------------------
% Solve for Mach #

% Initial values
for j = 1:1;
    for i = 1:pinf;
        Mach(i,j) = 2.0;
    end
end
gam = 1.4;

% Iterate to solution
for j = 1:1;
    for i = 1:pinf;
        for k = 1:dpp;
            rel = relation(avgNDimPressure(i,j), Mach(i,j));
            drel = drelationdx(avgNDimPressure(i,j), Mach(i,j));
            Mach(i,j) = Mach(i,j) - rel/drel;
        end
    end
end

%-------------------------------------------------------------------------
% Output Mach Number & Non-dimensional Pressure to file
output = 'Mach.txt';
output2 = 'Non-Dim Pressure.txt';
output3 = 'Avgch1data.txt';

%Open output file & write
fid = fopen(output,'wt');
fprintf(fid,'%12.8f \n', Mach);
fclose(fid);
fid = fopen(output2, 'wt');
fprintf(fid, '%12.8f \n', avgNDimPressure);
fclose(fid);

fid = fopen(output3, 'wt');
fprintf(fid, '%12.8f \n', avgch1data);
fclose(fid);

%--------------------------------------------------------------------------

E.2 relation.m

%--------------------------------------------------------------------------

function [rel] = relation(pr,M)

gam = 1.4;

rel = (((((gam+1)/2)*M^2) / (1+((gam-1)/2)*M^2)) ^ (gam/(gam-1)) *
(1/((2*gam/(gam+1))*M^2-(gam-1)/(gam+1))))^(1/(gam-1)) - pr;

return;

%--------------------------------------------------------------------------

E.3 drelationdx.m

%--------------------------------------------------------------------------

function [drel] = drelationdx(pr, M)

gam = 1.4;
dx = 1e-4;

drel = (relation(pr, M+dx) - relation(pr, M-dx))/(2 * dx);

return;
E.4 parseDataFile.m

function [names, data] = parseDataFile(fileName)
%PARSEDATAFILE This function parses a specific ASCII formatted data
%   file and returns the channel name and corresponding data.
% The file has the following format:
% Channel X: data0 datal ... Channel X+1: data0 datal ... etc...
% where X is a number and dataN is the Nth data point for that channel
%
%INPUT
%  fileName - is the file with the specific format
%
%OUTPUT
%  names    - is a cell array containing the channel names
%  data     - is a cell array containing each channel's data
%
%Created By: Ryan Swanson 2-26-08

%initialize return vars
names = {}; data = {}; %open the file and get the data
fid = fopen(fileName, 'r'); %open says a me
x = fscanf(fid, '%c'); %grab all ASCII characters
fclose(fid); %don't be an ass, close the file
%determine the number of channels and where the for each is
[startI endI] = regexpi(x, '\w+\s\d+:'); %find 'Channel X:' labels
numChan = length(startI); %oh the magic that is regexpi!
%loop through and parse the data
for iCh=1:numChan
    names{iCh} = x(startI(iCh):endI(iCh))); %grab the channel name
    if( iCh==numChan ) %last channel?
        readTo=length(x); %read to end of file
    else
        readTo=startI(iCh+1)-1; %read to next channel start
    end
end
E.5 Dynamic_Survey_Processing_code_v1.m

clear all;

disp(' ');

disp('-------------------------------------------------------------------');
disp('Dynamic Pitot Survey Data Processing Code - V1.0');
disp('-------------------------------------------------------------');
disp('For every input, be aware to type capital letters where you have to...');

% Get User Inputs

% Ask user to input file name
disp('Please enter file name of data file containing static acquisition method data.');
filename = input('File name: ','s');

filename1 = input('File name: ','s');
filename1 = 'dmisc.txt';

% Load misc info needed to run code successfully
misc = load(filename1);

% Perform data sorting and averaging

% assign misc info to variables
N = misc(1,1);
pinf = misc(2,1);
transCal = misc(3,1);
calOffset = misc(4,1);
probetransCal = misc(5,1);
probecalOffset = misc(6,1);
sps = misc(7,1);
motorsp = misc(8,1);
stepmoved = misc(9,1);

% Import data from files
chdata = load(filename);

% Average data for more accurate data point at each location
sum = 0;
dpp = sps/motorsp;
if (sps == stepmoved)
    % Average Data in first Column
    k = 0;
    for l = 1:stepmoved;
        sum = 0;
        for j = 1:dpp
            k = k + 1;
            sum = chdata(k,1) + sum;
        end
        temp = sum/dpp;
        avgch0data(l,1) = temp;
    end

    % Average Data in second Column
    k = 0;
    for l = 1:stepmoved;
        sum = 0;
        for j = 1:dpp
            k = k + 1;
            sum = chdata(k,2) + sum;
        end
        temp = sum/dpp;
        avgch1data(l,1) = temp;
    end
end

if (sps == stepmoved)
    for i = 1:pinf
        avgch0data(i,1) = chdata(i,1);
        avgch1data(i,1) = chdata(i,2);
    end
end

% %------------------------------------------------------------------------
% % Plenum voltage conversion & Probe voltage conversion
% %
% % Convert Plenum voltage to gage pressure
% for i = 1:stepmoved;
%     avgplenumpress(i,1) = avgch0data(i,1)*(transCal + calOffset);
% end;
% % Convert the Probe Voltage to gage pressure
for i = 1:stepmoved;
    avgprobepress(i,1) = (avgch1data(i,1)*(probetransCal + probecalOffset));
end;

% % Non-dimensionalize Pressure
for i = 1:stepmoved;
    avgNDimPressure(i,1) = avgprobepress(i,1)/avgplenumpress(i,1);
end;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% % Solve for Mach #
% % Initial values
for j = 1:1;
    for i = 1:stepmoved;
        Mach(i,j) = 2.0;
    end
end
gam = 1.4;

% % Iterate to solution
iter = dpp*10;

for j = 1:1;
    for i = 1:stepmoved;
        for k = 1:iter;
            rel = relation(avgNDimPressure(i,j), Mach(i,j));
            drel = drelationdx(avgNDimPressure(i,j), Mach(i,j));
            Mach(i,j) = Mach(i,j) - rel/drel;
        end
    end
end

% Output Mach Number & Non-dimensional Pressure to file
output = 'Mach.txt';
output2 = 'Non-Dim Pressure.txt';
output3 = 'Avgch1data.txt';
%Open output file & write
fid = fopen(output, 'wt');
fprintf(fid, '%12.8f \n', Mach);
fclose(fid);

fid = fopen(output2, 'wt');
fprintf(fid, '%12.8f \n', avgNDimPressure);
fclose(fid);

fid = fopen(output3, 'wt');
fprintf(fid, '%12.8f \n', avgch1data);
fclose(fid);

%--------------------------------------------------------------------------

E.6 Mass_Velocity_Processing_code_v3.m

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Mass Velocity Processing Code - V3.0                  %%
%% Written By : Ujas Patel                            %%
%% Created On : 04/22/2008                             %%
%% Updated On : XX/XX/2008                            %%
%%
%% Description : Misc Info file must be in the following order:        %%
%% - Line 1 : Number of points in profile                %%
%% - Line 2 : Number of X/D locations                   %%
%% - Line 3 : Value of Po in PSI                         %%
%% - Line 4 : Value of To in Rankine                    %%
%%
%% This code calculates the mass velocity from the calculated Mach   %%
%% flow field.                                              %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
clc

gam = 1.4;
R = 1716;  %(ft-lb/R-slug)

%--------------------------------------------------------------------------
% Get User Inputs

disp(' ');
disp('----------------------------------------------------------');
disp('Mass Velocity Processing Code - V3.0');
disp('----------------------------------------------------------');
disp(' ');

disp(' ');
disp('----------------------------------------------------------');
disp(' ');
disp('Enter the file name containing Mach Number (n x n matrix)');
disp(' ');
disp('----------------------------------------------------------');
disp(' ');

filename1 = input('File name: ','s');
Mach = load(filename1);

disp(' ');
disp('----------------------------------------------------------');
disp(' ');
disp('Enter the file name containing Misc Info');
disp(' ');
disp('----------------------------------------------------------');
disp(' ');

filename2 = input('File name: ','s');
misc = load(filename2);

%-------------------------------------------------------------
% assign misc info to variables
pinf = misc(1,1);
nXDloc = misc(2,1);
Po = misc(3,1);
To = misc(4,1);

%-------------------------------------------------------------
% Solve
for i = 1:pinf;
    for j = 1:nXDloc;

\[ P(i,j) = \frac{P_0}{(1 + \frac{(\gamma - 1)}{2} \cdot (\text{Mach}(i,j))^2)^{\frac{\gamma}{\gamma - 1}}}; \quad \text{Pressure} \]

\[ T(i,j) = \frac{T_0}{1 + \frac{(\gamma - 1)}{2} \cdot (\text{Mach}(i,j))^2}; \quad \text{Temperature} \]

\[ \rho(i,j) = \frac{P(i,j)}{R \cdot T(i,j)}; \quad \text{Density} \]

\[ a(i,j) = (\gamma R T(i,j))^{\frac{1}{2}}; \quad \text{Speed of Sound} \]

\[ U(i,j) = \text{Mach}(i,j) \cdot a(i,j); \quad \text{Flow Velocity} \]

\[ \text{MV}(i,j) = \rho(i,j) \cdot U(i,j); \quad \text{Mass Velocity} \]

% Output Mass Velocity to file
output = 'MV.txt';

% Open output file & write
fid = fopen(output, 'wt');
fprintf(fid, '%12.8f \n', MV);
fclose(fid);

E.7 FASS_Processing_code_v1b.m

clear all;
disp(' '); disp('-------------------------------------------------------------------');
disp('FASS Measurement Processing Code - V1.0');
disp('-------------------------------------------------------------------');
disp('For every input, be aware to type capital letters where you have to...');
%------------------------------------------------------------------------
% Get User Inputs
% Ask user to input file name
disp('Please enter file name of data file containing Vwm and Vs data.');
filename = input('File name: ','s');
%Ask user for misc info file name
disp('Please enter file name of the information file.');
filename1 = input('File name: ','s');
% Load misc info needed to run code successfully
misc = load(filename1);
%------------------------------------------------------------------------
% Perform data sorting and averaging
% assign misc info to variables
NoChans = misc(1,1);
n = misc(2,1);
m = misc(3,1);
stepsMoved = misc(4,1);
Ra = [misc(5,1); misc(6,1); misc(7,1); misc(8,1)];
COAcalibr = [17.97; 18.07; 18.01; 18.02];
Rlead = [4.6; 4.9; 3.4; 4.7];
% Import data from data file
[ch, chdata] = parseDataFile(filename);
% Organise data scanned from file
ch0data = chdata{1,1};
ch1data = chdata{1,2};
ch2data = chdata{1,3};
ch3data = chdata{1,4};
ch4data = chdata{1,5};
ch5data = chdata{1,6};
ch6data = chdata{1,7};
ch7data = chdata{1,8};
% Average data for more accurate data point at each location
sum = 0;
sum1 = 0;
sum2 = 0;
sum3 = 0;
sum4 = 0;
sum5 = 0;
sum6 = 0;
sum7 = 0;

for i = 1:n;
    for j = 1:m;
        sum = ch0data(j,i) + sum;
        sum1 = ch1data(j,i) + sum1;
        sum2 = ch2data(j,i) + sum2;
        sum3 = ch3data(j,i) + sum3;
    end
end
sum4 = ch4data(j,i) + sum4;
sum5 = ch5data(j,i) + sum5;
sum6 = ch6data(j,i) + sum6;
sum7 = ch7data(j,i) + sum7;
end

temp = sum/m;
avgch0data(i,1) = temp;
temp1 = sum1/m;
avgch1data(i,1) = temp1;
temp2 = sum2/m;
avgch2data(i,1) = temp2;
temp3 = sum3/m;
avgch3data(i,1) = temp3;

% Create Vxm array from average values
Vwm(i,1) = avgch0data(i,1);
Vwm(i,2) = avgch1data(i,1);
Vwm(i,3) = avgch2data(i,1);
Vwm(i,4) = avgch3data(i,1);

temp4 = sum4/m;
avgch4data(i,1) = temp4;
temp5 = sum5/m;
avgch5data(i,1) = temp5;
temp6 = sum6/m;
avgch6data(i,1) = temp6;
temp7 = sum7/m;
avgch7data(i,1) = temp7;

% Create Vs array from average values
Vs(i,1) = avgch4data(i,1);
Vs(i,2) = avgch5data(i,1);
Vs(i,3) = avgch6data(i,1);
Vs(i,4) = avgch7data(i,1);

sum = 0;
suml = 0;
sum2 = 0;
sum3 = 0;
sum4 = 0;
sum5 = 0;
sum6 = 0;
sum7 = 0;
end

% Apply equations to find Iw, Rw, etc
for i = 1:4;
    for j = 1:n;
        Iw(j,i) = (Vs(j,i) - Vwm(j,i))/COAcalibr(i);
        Rw(j,i) = (Vwm(j,i)/Iw(j,i)) - Rlead(i);
        Vw(j,i) = (Rw(j,i)*Iw(j,i));
        Aw(j,i) = (Rw(j,i) - Ra(i))/Ra(i);
        Pw(j,i) = (Vw(j,i)*Iw(j,i));
        PDR(j,i) = Pw(j,i)/(Rw(j,i) - Ra(i));
    end
end
end
end

% Output Vs, Vwm, Iw, ...etc

% Open output file & write

dlmwrite('Vs.txt', Vs, 'delimiter', '	', 'precision', 6)
dlmwrite('Vwm.txt', Vwm, 'delimiter', '	', 'precision', 6)
dlmwrite('Iw.txt', Iw, 'delimiter', '	', 'precision', 6)
dlmwrite('Rw.txt', Rw, 'delimiter', '	', 'precision', 6)
dlmwrite('Vw.txt', Vw, 'delimiter', '	', 'precision', 6)
dlmwrite('Aw.txt', Aw, 'delimiter', '	', 'precision', 6)
dlmwrite('Pw.txt', Pw, 'delimiter', '	', 'precision', 6)
dlmwrite('PDR.txt', PDR, 'delimiter', '	', 'precision', 6)

E.8 FASS_velocity_calibration_Processing_code_v1.m

clear all;

disp(' ');
disp('-------------------------------------------------------------------');
disp('FASS Measurement Processing Code - V1.0');
disp('-------------------------------------------------------------------');
disp('For every input, be aware to type capital letters where you have to...');

%--------------------------------------------------------------------------
% Get User Inputs
% Ask user to input file name
disp('Please enter file name of data file containing Vwm and Vs data.');
filename = input('File name: ','s');

% Ask user for misc info file name
disp('Please enter file name of the information file.');
filename1 = input('File name: ','s');

% Load misc info needed to run code successfully
misc = load(filename1);
chdata = load(filename);

%--------------------------------------------------------------------------
% Perform data sorting and averaging
% assign misc info to variables
NoChans = misc(1,1);
n = misc(2,1);
m = misc(3,1);
stepsMoved = misc(4,1);
Ra = [misc(5,1); misc(6,1); misc(7,1); misc(8,1)];
COAcalibr = [17.97; 18.07; 18.01; 18.02];
Rlead = [4.6; 4.9; 3.4; 4.7];

% Organise data scanned from file
ch0data = chdata(:,1);
ch1data = chdata(:,2);
ch2data = chdata(:,3);
ch3data = chdata(:,4);
ch4data = chdata(:,5);
ch5data = chdata(:,6);
ch6data = chdata(:,7);
ch7data = chdata(:,8);

% Average data for more accurate data point at each location
sum = 0;
sum1 = 0;
sum2 = 0;
sum3 = 0;
sum4 = 0;
sum5 = 0;
sum6 = 0;
sum7 = 0;
for i = 1:1:
    for j = 1:m:
        sum = ch0data(j,i) + sum;
        sum1 = ch1data(j,i) + sum1;
        sum2 = ch2data(j,i) + sum2;
        sum3 = ch3data(j,i) + sum3;
        sum4 = ch4data(j,i) + sum4;
        sum5 = ch5data(j,i) + sum5;
        sum6 = ch6data(j,i) + sum6;
sum7 = ch7data(j,i) + sum7;
end

temp = sum/m;
avgch0data(1,1) = temp;
temp1 = sum1/m;
avgch1data(1,1) = temp1;
temp2 = sum2/m;
avgch2data(1,1) = temp2;
temp3 = sum3/m;
avgch3data(1,1) = temp3;

% Create Vxm array from average values
Vwm(1,1) = avgch0data(1,1);
Vwm(1,2) = avgch1data(1,1);
Vwm(1,3) = avgch2data(1,1);
Vwm(1,4) = avgch3data(1,1);


temp4 = sum4/m;
avgch4data(1,1) = temp4;
temp5 = sum5/m;
avgch5data(1,1) = temp5;
temp6 = sum6/m;
avgch6data(1,1) = temp6;
temp7 = sum7/m;
avgch7data(1,1) = temp7;

% Create Vs array from average values
Vs(1,1) = avgch4data(1,1);
Vs(1,2) = avgch5data(1,1);
Vs(1,3) = avgch6data(1,1);
Vs(1,4) = avgch7data(1,1);

sum = 0;
sum1 = 0;
sum2 = 0;
sum3 = 0;
sum4 = 0;
sum5 = 0;
sum6 = 0;
sum7 = 0;

end

% Apply equations to find Iw, Rw, .... etc
for i = 1:4;
    for j = 1:1;
        Iw(j,i) = (Vs(j,i) - Vwm(j,i))/COAcalibr(i);
        Rw(j,i) = (Vwm(j,i)/Iw(j,i)) - Rlead(i);
        Vw(j,i) = (Rw(j,i)*Iw(j,i));
        Aw(j,i) = (Rw(j,i) - Ra(i))/Ra(i);
        Pw(j,i) = (Vw(j,i)*Iw(j,i));
        PDR(j,i) = Pw(j,i)/(Rw(j,i) - Ra(i));
    end
end
end
% Output Vs, Vwm, Iw, ... etc

% Open output file & write

dlmwrite('Vs.txt', Vs, 'delimiter', '	', 'precision', 6)
dlmwrite('Vwm.txt', Vwm, 'delimiter', '	', 'precision', 6)
dlmwrite('Iw.txt', Iw, 'delimiter', '	', 'precision', 6)
dlmwrite('Rw.txt', Rw, 'delimiter', '	', 'precision', 6)
dlmwrite('Vw.txt', Vw, 'delimiter', '	', 'precision', 6)
dlmwrite('Aw.txt', Aw, 'delimiter', '	', 'precision', 6)
dlmwrite('Pw.txt', Pw, 'delimiter', '	', 'precision', 6)
dlmwrite('PDR.txt', PDR, 'delimiter', '	', 'precision', 6)
Appendix F

Hand Calculations

F.1 Hand Calculations to Validate Mass Velocity Code

To verify the MatLab code written to perform mass velocity calculations the following hand calculations were performed and then compared with the results produced by the code at the same point in the flow.

Jet Nozzle $M_d$ of 1.0, $M_j$ of 1.5
Mach number at the centerline at $x/D$ of 0.0 = 1.008
$P_{atm}$ = 14.46 psi
$P_o$ = 53.07 psi
$\gamma$ = 1.4
$T_o$ = 530 °R

**Calculate $P$:**

$$\frac{P_o}{P} = \left(1 + \frac{(\gamma - 1)}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} \Rightarrow \frac{53.07}{P} = \left(1 + \frac{(1.4 - 1)}{2} 1.008^2 \right)^{\frac{1.4}{1.4 - 1}}$$

$$\Rightarrow P = \frac{53.07}{1.910726} = 27.77478 \text{ psi}$$

**Calculate $T$:**

$$\frac{T_o}{T} = \left(1 + \frac{(\gamma - 1)}{2} M^2 \right) \Rightarrow \frac{530}{T} = \left(1 + \frac{(1.4 - 1)}{2} 1.008^2 \right)$$

$$\Rightarrow T = \frac{530}{1.20321} = 440.48836 \text{ °R}$$
Calculate $p$:

$$\rho = \frac{P}{RT} \Rightarrow \rho = \frac{27.77478}{(1716)(440.48836)} = 3.6745 \times 10^{-5} \frac{lb}{ft^3}$$

Calculate $a$:

$$a = \sqrt{\gamma RT} \Rightarrow a = \sqrt{(1.4)(1716)(440.48836)} \Rightarrow a = 1028.70269 \frac{ft}{s}$$

Calculate $U$:

$$U = Ma \Rightarrow U = (1.008)(1028.70269) = 1036.9323 \frac{ft}{s}$$

Calculate Mass Velocity:

$$\rho u \Rightarrow \rho u = (3.6745 \times 10^{-5})(1036.9323) = 0.0381 \frac{lb}{ft^2 s}$$

From hand calculations a value of 0.0381 lb-ft$^{-2}$-s$^{-1}$ and a value of 0.0381 lb-ft$^{-2}$-s$^{-1}$ was produced by the MatLab code. This verifies that the MatLab code is producing the correct result according to hand calculation.
Appendix G

Pitot Probe Surveys

G.1 Results

The results from the Pitot probe surveys are listed in this appendix with their respective profiles. The following conditions can be found detailed here; $M_d$ of 1.5, $M_j$ of 1.5; $M_d$ of 1.65, $M_j$ of 1.65; $M_d$ of 1.65, $M_j$ of 1.75.

G.1.1 $M_d$ of 1.5, $M_j$ of 1.5

As with the condition of $M_d$ of 1.0, $M_j$ of 1.5 the data processing method produces two main results and a primary input which are analyzed. Figure 7.4 shows the $P_{t2}/P_o$ profile plot for $x/D = 0.0$ to $x/D = 1.0$. From this profile plot we can see a weak shock located near the centerline at $x/D = 0.6$, this is further supported by Figure 7.7 which shows the Mach number profile plot for this jet nozzle and flow condition. From this figure we can note that the Mach number remains at approximately $M = 1.5$ inside the potential core. The weak shock implies that the on-design condition was not precisely met at the time of measurement.

As mentioned previously the mass velocity is calculated from Mach number; the mass velocity profile plot for this nozzle and condition can be seen in Figure 7.10. Even though the flow is not shock free as expected, when we analyze the mass velocity contour plot, Figure 7.17, we can see that generally the flow is uniform and variations occur near the centerline. A profile of the mass velocity along the centerline can be seen in Figure 7.13. Upon further analysis of the centerline profile we can see that largest fluctuations in mass velocity are on the order of $\pm 0.007$ at $x/D = 0.6$. This result further suggests that a very weak shock cell structure is present in the flow.
G.1.2 \(M_d\) of 1.65, \(M_j\) of 1.65

Profiles were made in the region of \(x/D \leq 2.0\) and the corresponding \(P_{i2}/P_o\) profile plots can be seen in Figure 7.5. Figure 7.18 shows a contour plot of \(P_{i2}/P_o\), in this contour plot we can observe that though the nozzle is running on-design the flow contains shocks which can be clearly seen. This is due to the fact that the nozzle is not designed to produce a shock free flow when run at on-design condition.

For this nozzle a much finer resolution is used when profiling the flow. This can be seen in Figure 7.5 which shows the \(P_{i2}/P_o\) profile plot or in Figure 7.8 which shows the Mach number profile plot. If we look at the Mach number contour plot, Figure 7.19, we can see the fairly well defined shape of the shocks and the regions of constant Mach number.

Figure 7.11 shows a profile plot of the mass velocity for this nozzle at the on-design flow condition. If compared with the Mach number profile plot we can see that at approximately \(x/D = 0.8\) where Mach number is at its highest we see a large difference in mass velocity. Other than this area of rapidly increasing Mach number the mass velocity remains very constant throughout the flow. This is further supported by the centerline profile plot which can be seen in Figure 7.14. The centerline profile plot shows this large difference very clearly at \(x/D = 0.8\). If we look at the centerline profile plot in more detail, we can observe the change in mass velocity at \(x/D = 0.8\) is approximately 0.02 ± 0.001.

G.1.3 \(M_d\) of 1.65, \(M_j\) of 1.75

It should be noted that for this nozzle and condition profiles were only taken for \(x/D \leq 1.0\). This is due to a larger flow rate of air being used and therefore exhausting the air supply much quicker then in other measurements.

The profile plot for \(P_{i2}/P_o\) shows us that the shape of the flow is very similar to that of \(M_d\) of 1.65, \(M_j\) of 1.65. This can be seen more clearly in the \(P_{i2}/P_o\) contour plot in Figure 7.1 which is produced from the \(P_{i2}/P_o\) contour plot, Figure 7.6. As expected in
Figure 7.9, we can see a Mach number approximately of 1.75 between $x/D = 0.0$ to $x/D = 0.4$. This is more clearly seen in the Mach contour plot Figure 7.2. We can also notice in Figure 7.1 & Figure 7.2 that the size of the shock cell is much longer in the downstream direction when compared with $M_d$ of 1.65, $M_j$ of 1.65.

![Mach contour plot](image)

Figure 7.1: Contour plot of $P_{t2}/P_o$ for $M_d$ of 1.65, $M_j$ of 1.75.

Also as expected in Figure 7.2 we see that in the regions of rapidly increasing Mach number the mass velocity decreases. This is supported by the centerline profile plot in Figure 7.3. This nozzle and condition also produces the highest values of mass velocity.
Figure 7.2: Contour plots of Mach number (left) and mass velocity (right) for $M_d$ of 1.65, $M_j$ of 1.75.

Figure 7.3: Centerline plot of mass velocity for $M_d$ of 1.65, $M_j$ of 1.75.
G.2 $P_{t2}/P_0$ Profiles

Figure 7.4: Profile plot for $M_d$ of 1.5, $M_j$ of 1.5.
Figure 7.5: Profile plot for $M_d$ of 1.65, $M_j$ of 1.65.

Figure 7.6: Profile plot for $M_d$ of 1.65, $M_j$ of 1.75.
Figure 7.7: Mach number profile for $M_d$ of 1.5, $M_j$ of 1.5.
Figure 7.8: Mach number profile for $M_0$ of 1.65, $M_j$ of 1.65.

Figure 7.9: Mach number profile for $M_0$ of 1.65, $M_j$ of 1.75.
G.4 Mass Velocity Profiles

Figure 7.10: Mass velocity profile for $M_d$ of 1.5, $M_j$ of 1.5.
Figure 7.11: Mass velocity profile for $M_d$ of 1.65, $M_j$ of 1.65.

Figure 7.12: Mass velocity profile for $M_d$ of 1.65, $M_j$ of 1.75.
G.5 Centerline Plots of Mach Number & Non-Dimensional Mass Velocity

Figure 7.13: Mach Number and Non-dimensional mass velocity comparison for $M_d$ of 1.5, $M_j$ of 1.5.
Figure 7.14: Mach Number and Non-dimensional mass velocity comparison for $M_d$ of 1.65, $M_j$ of 1.65.
G.6 Contour Plots – $M_d$ of 1.5, $M_j$ of 1.5

Figure 7.15: Contour plot of $P_{oi}/P_o$ number for $M_d$ of 1.5, $M_j$ of 1.5.
Figure 7.16: Contour plot of Mach number for $M_d$ of 1.5, $M_j$ of 1.5.

Figure 7.17: Contour plot of mass velocity for $M_d$ of 1.5, $M_j$ of 1.5.
G.7 Contour Plots – $M_d$ of 1.65, $M_j$ of 1.65

Figure 7.18: Contour plot of $P_{12}/P_o$ for $M_d$ of 1.65, $M_j$ of 1.65.
Figure 7.19: Contour plot of Mach number for $M_d$ of 1.65, $M_j$ of 1.65.
Appendix H
Tao Systems CVA Instructions

H.1 Setting Overheat

1. Activate the HyperTerminal window to connect to the COA.
2. In the HyperTerminal window type ‘o’ to set the overheat ratio.
3. To set the overheat to 25%, type 0.25 and press enter.
4. To apply the overheat to the sensors type ‘A’, this will bring up information about the sensors and ask if you want to continue to the overheat loop.
5. Type ‘c’ to continue or follow instructions to cancel.
6. The overheat loop can be cancelled at any time by typing ‘x’.
7. To adjust the overheat for channel 1 use ‘<’ key to lower the overheat and ‘>’ key to increase the overheat, for channel 2 ‘<Shift> + “<”’ to lower and ‘<Shift> + “>”’ to increase the overheat.
8. For sensor safety the maximum current should be set to 120mA. Whilst in the overheat loop, type ‘a’ to lower the maximum current on channel 1 and ‘A’ to lower the maximum current on channel 2.