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UNSTEADY FLOW CHARACTERISTICS OF A NORMAL SHOCK WAVE AND ASSOCIATED LAMBDA FOOT

Michael D. Sorrell

A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical and Aerospace Engineering to The Graduate School of The University of Alabama in Huntsville May 2024

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Abstract

UNSTEADY FLOW CHARACTERISTICS OF A NORMAL SHOCK WAVE AND ASSOCIATED LAMBDA FOOT

Michael Sorrell

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

Mechanical and Aerospace Engineering

The University of Alabama in Huntsville
May 2024

Shock wave interactions are important in a variety of engineering applications, ranging from gas turbines to rocket nozzles. There is much discussion regarding the sources of unsteadiness related to unsteady shock wave structure. This thesis investigates related interactions through spectral analysis of shock wave tracked positions, and instantaneous surface static pressure, temperature, and heat flux. A shadowgraph system for implementing shock wave tracking analysis is employed within a supersonic test section with an inlet freestream Mach number of 1.54. Unsteady surface static pressure and temperature variations are measured at streamwise locations along the bottom wall. Unsteady temperature data are used to determine surface heat flux variations. Pressure, temperature, and heat flux variations are correlated to the position of the normal shock wave through magnitude squared coherence and time lag. Data show complex physical variations that change as frequency, inlet turbulence intensity, and location relative to the shock wave are altered.
Acknowledgements

I would like to sincerely thank my advisor, Dr. Ligrani, for all his support and guidance throughout my time as a graduate student. I also would like to thank my other committee members, Dr. Zhang and Dr. Hu. Thank you to the following individuals who assisted with laboratory operations, safety considerations, and/or data analysis: Tony Hall, Dr. David Lineberry, Dr. Robert Frederick, Ward Manneschmidt, Chase Herrin, and AnthonyMichael Ciccarelli. I would finally like to thank my family and friends for all the support they have given me while I was working on this thesis.
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<th>Meaning</th>
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<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>HT</td>
<td>High Inlet Turbulence Intensity</td>
</tr>
<tr>
<td>K1</td>
<td>Kulite Pressure Transducer at Location 1</td>
</tr>
<tr>
<td>K2</td>
<td>Kulite Pressure Transducer at Location 2</td>
</tr>
<tr>
<td>K3</td>
<td>Kulite Pressure Transducer at Location 3</td>
</tr>
<tr>
<td>LT</td>
<td>Low Inlet Turbulence Intensity</td>
</tr>
<tr>
<td>NI</td>
<td>National Instruments</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
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<td>Honeywell Pressure Transducer at Location 1</td>
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# List of Symbols

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<th>Symbol</th>
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<tbody>
<tr>
<td>$c$</td>
<td>Speed of sound, m/s</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat, J/(kg*K)</td>
</tr>
<tr>
<td>$C_{xy}$</td>
<td>Magnitude squared coherence</td>
</tr>
<tr>
<td>$F_n$</td>
<td>Frequency, Hz</td>
</tr>
<tr>
<td>$f_s$</td>
<td>Sampling frequency, Hz</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>Frequency resolution, Hz</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity, W/(m*K)</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure, Pa</td>
</tr>
<tr>
<td>$P_o$</td>
<td>Stagnation pressure, Pa</td>
</tr>
<tr>
<td>$P_{xx}$</td>
<td>Power spectral density</td>
</tr>
<tr>
<td>$P_{xy}$</td>
<td>Cross power spectral density</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature, °C</td>
</tr>
<tr>
<td>$T_o$</td>
<td>Stagnation temperature, °C</td>
</tr>
<tr>
<td>$V$</td>
<td>Velocity, m/s</td>
</tr>
<tr>
<td>$\overline{x^2}$</td>
<td>Mean-squared value</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density, kg/m$^3$</td>
</tr>
<tr>
<td>$\tau_{xy}$</td>
<td>Time lag, sec</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Phase angle, rad</td>
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Chapter 1. Introduction

This chapter includes an overview of and motivations behind the present study, a summary of relevant literature, and the organization of the thesis.

1.1 Overview

Shock wave interactions are important in a variety of engineering applications, ranging from gas turbines and rocket nozzles to high-speed aircraft. Even with decades of research on this topic, there are still many open questions regarding the physical processes creating these interactions. This thesis studies the unsteady characteristics of a normal shock wave and associated lambda foot in a flow with a Mach number of 1.54. The lambda foot is created when the normal shock wave interacts with the boundary layer, terminating at the slip line. When flow passes through the first leg of the lambda foot, the pressure drop across the shock wave creates a region of flow separation and reversal within the boundary layer near the wall. There is much discussion on the physics behind these phenomena and the source of unsteadiness in the shock wave structure. The present thesis investigates such unsteadiness through spectral analysis of shock wave position and correlations between shock wave position and unsteady pressure, temperature, and heat flux along the bottom surface of the wind tunnel test section. Correlations are presented through magnitude squared coherence and time lag. The experimental setup includes a Phantom V711 high-speed camera used for shadowgraph imagery, Kulite pressure transducers measuring unsteady surface static pressure variations, and Medtherm thin film gauges measuring unsteady surface temperature.
variations. Surface heat flux variations are determined from temperature variations using an impulse response filtering method.

Figure 1.1, from Babinsky and Harvey (2011), shows a schematic of a normal shock wave and associated lambda foot, which are the physical structure investigated in this thesis. A strong enough normal shock wave above the triple point will separate the boundary layer from the wall and cause the structure shown in the figure. The upward displacement of the flow initiates a series of oblique compression waves near the separation point that combine to form an oblique shock wave. The rear oblique shock wave forms to equalize the static pressure downstream of the normal shock wave (above the triple point) with the static pressure downstream of the first oblique shock wave (below the triple point). All three shock waves meet at the triple point, and a slip surface develops. Local static pressure and flow direction above and below the slip surface are equal. All other flow properties (Mach number, stagnation pressure, static temperature, etc.) can vary between the sides of the slip surface.

Figure 1.1 Schematic of a normal shock wave with a lambda foot from Babinsky and Harvey (2011).
1.2 Literature Review

Several ideas are proposed for the underlying physics causing low frequency unsteadiness of a normal shock wave and associated lambda foot in a supersonic flow environment. McClure (1992) and Humble et al. (2009) show that upstream turbulent boundary layer fluctuations create shock wave unsteadiness. Bruce and Babinsky (2008) and Galli et al. (2005) demonstrate that variations in pressure downstream of the shock wave are the source of unsteadiness. Piponniau et al. (2009), Pirozzoli et al. (2010), and Grilli et al. (2012) suggest that the unsteadiness is caused by a pulsing motion of the separation bubble beneath the lambda foot. Hu et al. (2021) correlate shock wave unsteadiness with the presence of Görtler vortices in the flow reattachment region. Some sources claim that both upstream and downstream flow variations cause the unsteadiness seen in the normal shock wave structure. Clemens and Narayanaswamy (2014) conclude that upstream boundary layer fluctuations are a source of unsteadiness for weakly separated flows, and that downstream fluctuations are the more prominent source as separation strength increases.

1.2.1 Review of Shock Wave Interactions

The variation of static pressure throughout the separation region is shown in Figure 1.2, from Babinsky and Harvey (2011), where S denotes the separation point and R denotes the reattachment point. As seen in the figure, the static pressure begins to rise prior to separation, plateaus inside the separation region, and increases again before the flow reattaches.
Clemens and Narayanaswamy (2014) review literature from recent decades related to the low-frequency unsteadiness of shock wave interactions. They conclude that the pulsating motion of the separation bubble is partially due to a shear layer entrainment-recharge mechanism. According to their research, upstream turbulent boundary layer fluctuations have a large influence on shock wave unsteadiness for weakly separated flows. As separation strength increases, the influence of downstream fluctuations dominates the interaction. Finally, they highlight the need for further shock wave interaction research into more complex flow arrangements.

1.2.2 Dynamics between the Shock Wave and the Upstream Boundary Layer

McClure (1992) studies the driving mechanism behind an unsteady shock wave in a Mach 5 compression corner flow. Shock wave position is tracked through wall pressure measurements, and pitot pressure measurements give a baseline for pressure measurements. Motion of the front leg of the lambda foot, or the first separation shock, is associated with a breathing motion observed in the separation bubble. McClure (1992) concludes that fluctuations in the outer two-thirds of the upstream turbulent boundary layer have the greatest effect on shock wave movement. Humble et
al. (2009) study a shock wave interaction at Mach 2.1 using particle image velocimetry (PIV). Upstream structures in the turbulent boundary layer creating low- and high-speed fluid are found to affect the shock wave pattern in the region of interest.

1.2.3 Dynamics between the Shock Wave and the Downstream Boundary Layer

Bruce and Babinsky (2008) study an unsteady shock wave using schlieren video and pressure measurements. Back pressure variations are controlled by the rotation of an elliptical cam mounted in the diffuser downstream of the test section. Shock wave position is determined by using a line scanning technique in collected high-speed images. They find that cyclic variations in back pressure cause a predictable shock wave movement and present a model for amplitude and frequency of shock wave motion. Galli et al. (2005) also employ a rotating elliptical cam in the downstream section of their wind tunnel and evaluate the resulting shock wave unsteadiness.

1.2.4 Dynamics between the Shock Wave and the Separation Bubble

Piponniau et al. (2009) study a Mach 2.3 flow using a PIV system. Experimental observations agree with a model relating low-frequency shock wave motions to pulsations of the separation bubble. Pirozzoli et al. (2010) analyze shock wave motion through turbulent simulation data for various shock wave strengths. Their analysis finds that high-frequency shock wave motion is associated with turbulence structures in the upstream boundary layer, while low-frequency movement is associated with a breathing motion of the separation bubble. Grilli et al. (2012) analyze the shock wave interaction using a large eddy simulation (LES) of a compression-expansion ramp. Using Fourier analysis and dynamic mode decomposition, they conclude that the pulsating of the separation bubble is associated with low-frequency oscillations of the shock wave. Hu et al. (2021) simulate a backward-facing step in a Mach 1.7 flow using LES. Their analysis shows a connection between shock wave motion, the separation bubble, and the reattachment
region. Hu et al. (2021) state that Görtler vortices in the reattachment region are highly correlated with low-frequency unsteadiness.

1.2.5 Background on Unsteady Pressure Measurements

Three types of diaphragms are commonly employed within pressure transducers which are utilized in high-speed flow environments: flat metal, corrugated metal, and semiconductors. The main problem with flat metal diaphragms is maintaining a linear signal response, which is generally present only when diaphragms deflect less than 30 percent of their thickness. Whereas one issue with corrugated metal diaphragms is large sensor diameter, which means that such devices are only useful within applications where sensor size is not important. With semiconductor diaphragms, the diaphragms are micro-machined directly onto a silicon chip, which is generally shielded from the measuring environment using a steel diaphragm. Due to the size of the associated sensors, the frequency response of such devices usually exceeds 100 kHz (Beckwith et al. 2007).

Kulite pressure transducers generally use semiconductor diaphragms comprised of p-type silicon with sensor areas less than 0.3 mm². A four-arm Wheatstone bridge circuit is also often included with these diaphragms, which are molecularly bonded to each other but electrically isolated from each other (Kulite 2023). For each Kulite pressure transducer, the diaphragm is protected by either a M or B screen, which consists of numerous 0.1524 mm (0.006 in) diameter holes on the measuring surface. These screens have no effect on the static calibration of the sensor, and no effect on the dynamic response at frequencies from 20 Hz to 20 kHz (Kulite 2018). For each diaphragm design, Kulite employs shock tubes to determine the dynamic characteristics of their sensors. Such an approach is capable of characterizing Kulite pressure transducer performance up to frequencies greater than 100 kHz (Kulite 2018).
Bershader (1988) investigates the dynamic characteristics of Kulite pressure transducers using a high-pressure shock tube. The diaphragms of the Kulite pressure transducers are located in the presence of a fully developed shock wave. For the flush mounted Kulite pressure transducers, the change in pressure, rise time, and ringing frequency are determined to be in agreement with the dynamic characteristics that are provided for the Kulite 093 series transducers.

1.2.6 Background on Unsteady Temperature Measurements

Collection of temperature data in high-speed environments presents an interesting challenge when trying to present minimal disruptions to the flow. Several measurement techniques are commonly employed: temperature probes, optical measurement systems, and thin film gauges. Temperature probes are not preferred due to limited time response and a potential for flow disturbance (Domenico et al. 2019). Optical measurements systems include the use of particle image velocimetry (PIV) lasers and spectroscopy, and provide more accurate resolution of high-frequency temperature variations. Such systems are employed in a variety of supersonic flow environments (Panda and Seasholtz 2004, Domenico et al. 2019, Wernet et. al 2020). Thin-film gauges are used in multiple environments with high-frequency temperature variations due to their fast response to transient temperature events. Such environments include turbine blades (Oldfield 2008) and supersonic jets (Alam and Kumar 2019). The present study employs thin film gauges to record transient temperature fluctuations in a supersonic flow environment with a normal shock wave and associated lambda foot. Transient temperature data are converted to surface heat flux data using an impulse filtering response method described in Chapter 3.

1.3 Thesis Organization

In this thesis, Chapter 2 describes the experimental apparatus and procedures, with instrumentation details. Chapter 3 presents the instrumentation and methods used for collecting
transient temperature and heat flux data. Chapter 4 describes the data analysis procedures implemented in Chapters 5 through 9. Chapter 5 compares data collected at different sampling frequencies, Chapter 6 presents shadowgraph flow visualization results, Chapter 7 presents unsteady pressure results, Chapter 8 presents unsteady temperature results, and Chapter 9 presents unsteady heat flux results. Chapter 10 then gives a final summary and conclusions of the present study.
Chapter 2. Experimental Apparatus, Setup, and Procedure

Presented in this chapter are discussions regarding the visualization system, including instrumentation and the Phantom V711 camera and software, pressure instrumentation for steady measurements, pressure instrumentation for unsteady measurements, pressure and temperature measurements to quantify flow conditions, and the data acquisition system.

2.1 Test Section Instrumentation

Figure 2.1 shows a labeled cross-section view of the test section during supersonic flow. Several sensors are installed in the bottom wall of the test section, and measurement locations are labeled with respect to the normal shock wave, lambda foot, separation region, upstream boundary layer, and downstream boundary layer. T1, T2, and T3 indicate Medtherm thin film gauges used to measure unsteady temperature variations. K1, K2, and K3 denote Kulite pressure transducers used to measure unsteady pressure variations. PT1, PT2, and PT3 indicate Honeywell pressure transducers used to measure steady-state pressure. Sensors in location 1 are beneath the upstream boundary layer, sensors in location 2 are beneath the separation region under the lambda foot, and sensors in location 3 are beneath the downstream boundary layer.
2.2 Flow Visualization System Instrumentation

Experimental techniques employed to visualize supersonic flows are shadowgraph and schlieren. Both of these techniques depend on the refractive index of the medium, which, for gases, is linearly related to density variations. According to Settles (2001), illuminance levels for schlieren and shadowgraph correspond to the first and second spatial derivatives of density, respectively. As a consequence of this distinction, schlieren systems are more sensitive than shadowgraph systems in detecting density variations within supersonic flows. However, Settles (2001) also indicates that shadowgraph visualization systems are more suited to visualize flows with turbulence or shock waves. Because of this advantage, a shadowgraph visualization system is implemented to visualize shock waves, flow separation regions, and boundary layer development within the present investigation.

A schematic diagram of the shadowgraph visualization system is presented in Figure 2.2, and a photograph of the shadowgraph flow visualization system, along with the wind tunnel leg
and test section employed for the present investigation, is shown in Figure 2.3. With this arrangement, light is generated using a SugarCUBE LED Illuminator that is located one focal length away, 152.40 cm (60 in), from the first 15.24 cm (6 in) diameter focusing mirror. Produced from the first focusing mirror is a constant and two-dimensional 15.24 cm (6 in) diameter beam of light, which travels through the test section, until it is reflected by a second 15.24 cm (6 in) diameter focusing mirror. After the light reflects off of this second focusing mirror, which is positioned on the opposite side of the test section, the light contracts down to a point at a distance of 152.40 cm (60 in) from the mirror. At distances beyond this point, the light image begins to expand. The image from this second mirror is then viewed and captured by a Phantom V711 camera as it is located at a distance of 10.16 cm (4 in) beyond the light point. Note that minor adjustments are often required to the locations of the two mirrors, which are Edmund Optics focusing mirrors, in order to produce an appropriate image at the camera, as well as a constant diameter, two-dimensional beam of light between the two mirrors. The entire system is from Edmund Optics Inc., part number 71-013. Appropriate positioning of the camera is also required, along with adjustment of the lens aperture so that the light image is fully captured by the camera.

The high-speed Phantom V711 camera captures a time sequence of digitized flow visualization images during each wind tunnel test at rates as high as 1400 kHz. Phantom Camera Control Application 2.7 software processes the images which are captured by the camera. Spatial resolution of each image is 20 μm per pixel location. The exposure time is 1.0 μs at all sampling rates which are employed in the present investigation.
2.3 Phantom V711 Camera, Associated Software, Data Acquisition, and Data Analysis

A Phantom V711 camera, manufactured by the AMETEK Materials Analysis Division of Vision Research Company, is used to capture time sequences of digitized flow visualization images in grayscale format. The serial number of the Phantom V711 camera is 13968. A Nikon Nikkor
180 mm 1:2.8 ED lens is employed with the camera. The default exposure time for the camera is 1 μs, with a capability to set exposure times as small as 300 ns. The camera has a minimum acquisition speed of 7 gigapixels per second, which results in a minimum frame rate of 10 Hz. The maximum frame rate is 680 kHz, which is provided with a spatial resolution of 128 by 8 pixels (Vision Research). For the present study, images with a spatial resolution of 1024 by 512 pixels are obtained with a sampling frequency ranging from 100 Hz to 12.5 kHz. Because the camera has a limited amount of internal memory, the period for which data are acquired decreases as the sampling frequency increases. With an image sampling frequency of 100 Hz, more than 10 seconds of data are acquired. With an image sampling frequency of 12.5 kHz, a total of 32,434 images and 2.595 seconds of data are acquired.

The Phantom Camera Control Application software is employed to operate the Phantom V711 camera. For the present study, a Windows 7 Dell desktop computer, which is a Dell Precision T1700 workstation with an Intel Core i7-4790 CPU Processor, is used to operate version 2.7 of this software. The image acquisition rate is set within this software, along with camera exposure time and resolution, which are set to 35 μs and 1024 x 512 pixels, respectively. Table 2.1 summarizes the data collected with the Phantom V711 camera and various sensors.

Table 2.1 Data Acquisition Summary.

<table>
<thead>
<tr>
<th>Run</th>
<th>Data Acquisition Rate</th>
<th>Wind Tunnel Run Time</th>
<th>Data Collection Time</th>
<th>Number of Data Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 kHz</td>
<td>11.0 sec</td>
<td>3.243 sec</td>
<td>32,434</td>
</tr>
<tr>
<td>2</td>
<td>10 kHz</td>
<td>11.0 sec</td>
<td>3.243 sec</td>
<td>32,434</td>
</tr>
<tr>
<td>3</td>
<td>12.5 kHz</td>
<td>11.0 sec</td>
<td>2.595 sec</td>
<td>32,434</td>
</tr>
<tr>
<td>4</td>
<td>6.25 kHz</td>
<td>20.0 sec</td>
<td>5.189 sec</td>
<td>32,434</td>
</tr>
</tbody>
</table>
The computer is connected to the Phantom V711 camera with an Ethernet cable. In order to correlate time-varying flow visualization data with digitized data from other sources (such as Kulite pressure transducers or thin film heat flux gages), the ready signal from the Phantom V711 camera is acquired with a National Instruments USB-6341 data acquisition card. Once the Phantom V711 camera starts acquiring images, the USB-6341 notifies the LabVIEW 2020 version 20.0.1 software to start acquiring measurements from the other National Instruments equipment.

2.4 Pressure and Temperature Measurements

A United Sensor Corporation KCC-8 Kiel probe, several Honeywell 060-C54985172080 pressure transducers, and two Omega 5TC-TT-T20-36 copper-constantan Type T thermocouples are used to determine the flow conditions at the entrance of the test section. The Honeywell pressure transducers are calibrated using the apparatus and procedures given in Section 2.5. The Kiel probe is located at the test section inlet. As supersonic flow approaches the probe, a normal shock wave is present just upstream of the Kiel probe, such that the Kiel probe measures the stagnation pressure downstream of the shock wave. Multiple static pressures are also measured along the bottom wall of the test section, at locations which are upstream of the shock wave. From these measurements, the ratio of total pressure downstream of the normal shock wave, denoted by $p_{02}$, relative to the static pressure upstream of the shock wave, which is denoted by $p_1$, is determined. Using the Rayleigh equation, the test section inlet Mach number $M_1$ is determined to be approximately 1.54, for conditions when flow within the test section is fully established and steady. The ratio of specific heats is denoted by $\gamma$. The Rayleigh equation is given by

$$\frac{p_{02}}{p_1} = \left( \frac{(\gamma + 1)^2 M_1^2}{4\gamma M_1^2 - 2(\gamma - 1)} \right)^{\gamma/(\gamma-1)} \frac{1 - \gamma + 2\gamma M_1^2}{\gamma + 1}. \quad (1)$$
Because of the flow disturbances which result from the presence of the Kiel probe and thermocouples at the inlet of the test section, these items are removed as subsequent flow visualization and surface sensor data are acquired. This approach is validated by test section inlet conditions which are highly repeatable as data are acquired at different times and days.

Thermocouple recovery temperature at the test section inlet is measured using two Omega 5TC-TT-T20-36 copper-constantan Type T thermocouples. These thermocouples are mounted on the Kiel probe, with wire tips arranged to be parallel to the flow direction. With this configuration, the recovery factor of the thermocouples is 0.86. With measured magnitudes of recovery temperature downstream of the probe-generated normal shock wave, the recovery factor, and the Mach number, the freestream static temperature and the freestream total temperature are determined for a flow location, which is upstream of the probe shock wave. Freestream velocity magnitude upstream of the probe shock wave is then also determined.

The Omega 5TC-TT-T20-36 copper-constantan Type T thermocouples are calibrated using an Omega Thermoregulator HCTB-3030 Constant Temperature Liquid Circulating bath, and a Fluke Hart Scientific Division 1523 thermometer for reference temperature measurements. As the calibration is undertaken, the thermocouples are secured so that measuring junctions are placed inside the bath, which is filled with distilled water. The temperature of the bath is set from ambient temperature to 45°C in 5°C increments. A National Instruments NI 9213 thermocouple input card is employed to acquire each voltage signal from the thermocouples. Signals from this card are acquired and saved using LabVIEW 2020 version 20.0.1 software. The data for each temperature measurement is subsequently exported to Microsoft Office Excel version 2013, where calibration equations are determined to provide correlation relationships between thermocouple voltage and temperature. During calibration and measurement, signals from the thermocouple measurements
are averaged by taking approximately 50 measurements, which provides an average value over a
time duration of approximately 1 second.

2.5 Steady-state Pressure Measurements

Three Honeywell FPA 060-C54985172080 pressure transducers are used to record steady-
state static pressures at three different locations along the bottom wall of the test section. These
transducers are connected to the pressure tap locations shown in Figure 2.4 with metal tubing,
rubber tubing and hose clamps.

![Figure 2.4](image)

**Figure 2.4** Locations of the pressure taps along the bottom wall of the test section for steady pressure measurements using Honeywell FPA 060-C54985172080 pressure transducers. Units are cm.

For calibration of the Honeywell pressure transducers, a compressed air deadweight tester
with a pressure manifold is used, which allows each transducer to be calibrated simultaneously.
The digital signals are acquired inside the LabVIEW 2020 version 20.0.1 software for pressures
ranging from ambient to 310.3 kPa (45 psi) above ambient pressure, in 20.7 kPa (3 psi) increments.
As the calibration is undertaken, the ambient pressure is monitored and measured with a barometer.
For each pressure value, one sample, consisting of approximately 1 second of data or 5000
measurements, is recorded, saved, and exported from LabVIEW to Microsoft Office Excel version
Using Excel, a calibration equation is determined for each Honeywell pressure transducer to provide a correlation relationship between voltage values and measured pressures.

### 2.6 Unsteady Pressure Measurements

![Image of a Kulite XCQ-062 Pressure Transducer](image)

**Figure 2.5** Kulite XCQ-062 Pressure Transducer.

Figure 2.5 shows a photograph of a XCQ-062 Kulite pressure transducer (Kulite 2023). For the unsteady pressure measurements, three Kulite XCQ-062-5BarA pressure transducers with in-line amplifiers are used. These sensors have a maximum diameter of 1.7 mm (0.066 in) and a length of 9.5 mm (0.375 in). These pressure transducers use silicon diaphragms with a fully active four arm Wheatstone bridge to sense fluctuations in pressure and process the associated electronic signals. The response time and rise time for these transducers are not provided; however, Kulite notes that “the rise time of the transducer is much faster than the period to which it will respond accurately” (Kulite 2018). For the selected model, the natural frequency of each sensor without a Kulite screen is between 300 kHz and 380 kHz. However, there are Kulite B-screens installed above each sensor location to protect the pressure diaphragm. According to Kulite, the B-screen has no effect on the dynamic response of transducers for sampling frequencies from 20 Hz to 20 kHz (Kulite 2018). Attached to each Kulite is an in-line auxiliary amplifier. Each KEA-B-1B amplifier magnifies the output voltage from the Wheatstone bridge circuit inside the transducer to a voltage between 0.5 VDC and 4.5 VDC. For the selected model of amplifier, KEA-B-1B, the
noise levels are low and stable between a frequency bandwidth of 0 to 40 kHz. The present Kulite XCQ-062-5BarA pressure transducers, with Kulite B-screens, operate most effectively for sampling frequencies up to 20 kHz. Therefore, a sampling frequency below 20 kHz is employed for the majority of the present wind tunnel tests.

Figure 2.6 shows the sensor locations along the bottom wall of the test section for unsteady pressure measurements using the Kulite XCQ-062-5BarA pressure transducers. According to this figure, all three Kulite transducers are located 1.905 cm (0.750 in) away from the centerline of the test plate.

![Figure 2.6 Sensor locations along the bottom wall of the test section for unsteady pressure measurements using Kulite XCQ-062-5BarA pressure transducers. Units are cm.](image)

These sensors are calibrated by Kulite with a CPC6000 Modular Precision Pressure Controller, with apparatus and procedures which are verified and validated by the National Institute of Standards and Technology (NIST). Calibration information for each Kulite transducer unit is given in Table 2.2. Associated calibration certificates are provided within Appendix D.

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity (mV/BAR)</th>
<th>Zero Balance Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>796.072</td>
<td>N/A</td>
</tr>
<tr>
<td>K2</td>
<td>806.214</td>
<td>N/A</td>
</tr>
<tr>
<td>K3</td>
<td>808.196</td>
<td>N/A</td>
</tr>
</tbody>
</table>
2.7 Data Acquisition System

Figure 2.7 shows a schematic diagram of the data acquisitions system, which includes a number of National Instruments data acquisition cards and devices. Connected to the computer with an Ethernet cable is the Phantom V711 camera. Also, connected to the computer with USB cables are a National Instruments cDAQ-9178 chassis and a National Instruments USB-6341 data acquisition card. The National Instruments USB-6341 card is connected to the Phantom V711 camera and to the computer with separate cables. The cDAQ-9178 is an eight-slot USB chassis, which interfaces with an NI 9237 data acquisition card, an NI 9239 data acquisition card, and the National Instruments USB-6341 data acquisition card. The NI 9237 data acquisition card is a National Instruments simultaneous bridge module that has the capability of sampling four bridge-based sensors up to 50 kHz simultaneously. Within the present study, the NI 9237 data acquisition card is used to measure the bridge output voltages from the Honeywell FPA 060-C54985172080 pressure transducers. The digital signals, which are provided by the NI 9237 data acquisition card and the cDAQ-9178 chassis, are acquired and recorded using LabVIEW 2020 version 20.0.1 software.

In order to operate each Honeywell pressure transducer, each transducer is wired into a NI 9923 terminal block that transmits the differential analog voltage signals from the transducers to a NI 9237 data acquisition card, which is a National Instruments simultaneous bridge module. The NI 9237 data acquisition card is also connected to a National Instruments cDAQ-9178 chassis, which converts the analog signals into digital signals that are viewable in the LabVIEW 2020 version 20.0.1 software.

Analog signals from the Kulite XCQ-062-5BarA pressure transducers are acquired using an NI 9239 data acquisition card. The NI 9239 data acquisition card is a National Instruments Voltage Input C Series Module, which has the capability of acquiring 4 different sensors up to 50
kHz and measures the amplified voltage provided by the KEA-B-1B in-line amplifier. The digital signals, which are provided by the NI 9238 data acquisition card and the cDAQ-9178 chassis, are acquired and recorded using LabVIEW 2020 version 20.0.1 software.

EMI shielding is installed around the Medtherm thin film gauge wires to prevent interference from nearby wall power sources at 60 Hz. The thin film gauge wires connect to the National Instruments (NI) 9238 data acquisition card, which is installed in the NI cDAQ-9178 chassis. Data are sent from this chassis to the computer over USB, and LabVIEW 2020 version 20.0.1 software is used to record the data.

The digitized flow visualization images from the Phantom V711 camera are acquired by the PCC 2.7 software on the computer while the ready signal is acquired by the National Instruments USB-6341 data acquisition card, as mentioned. This card is employed to synchronize the acquisition of the flow visualization images with the data acquired by the Kulite pressure transducers. Once the USB-6341 detects the ready signal, the USB-6341 notifies LabVIEW to start acquiring data for the Kulite and Honeywell pressure transducers and Medtherm thin film gauges through the cDAQ-9178 chassis. The ready signal is detected by LabVIEW once the user starts acquiring data in the Phantom Camera Control Application software. When employed in this manner, the data sampling frequency is identical for each of the Kulite pressure transducers and the acquisition of the Phantom acquired digital camera images.
2.8 Test Section Flow Conditions

The main flow Mach number at the test-section inlet is approximately 1.54. This value is determined from the inlet nozzle design and is confirmed by measurements of local static pressure and local stagnation pressure using Equation 1. The associated test-section mass flow rate is approximately 12.5 kg/s. Test section inlet flow conditions are given in Table 2.3.

<table>
<thead>
<tr>
<th>P [Pa]</th>
<th>88,250.09</th>
<th>P_o [Pa]</th>
<th>232,913.43</th>
</tr>
</thead>
<tbody>
<tr>
<td>T [°C]</td>
<td>21.53</td>
<td>T_o [°C]</td>
<td>31.74</td>
</tr>
<tr>
<td>c [m/s]</td>
<td>344.10</td>
<td>V [m/s]</td>
<td>529.91</td>
</tr>
</tbody>
</table>
Chapter 3. Time-Resolved Surface Temperature and Heat Flux Determination

Presented in this chapter are discussions regarding Medtherm Corporation thin film gauges, temperature data processing, thin film gauge calibration, surface heat flux determination procedures, and surface heat transfer coefficient determination procedures.

3.1 Medtherm Corporation Thin Film Gauges

Three Medtherm Corporation thin film gauges (part number TCS-061-JU-.125-240-11251) are installed along the bottom plate of the wind tunnel to measure unsteady surface temperature variations. Their streamwise locations are shown in Figure 3.1 and are the same as the Honeywell pressure transducers.

![Sensor Locations Inside the Test Section.](image)

Sensor T1 is located beneath the upstream boundary layer, sensor T2 is located beneath the separation region under the lambda foot, and sensor T3 is located beneath the downstream
boundary layer. These thin film gauges are Type J Coaxial Surface (TCS) thermocouples with a thermocouple grade iron sheath. Associated sheath properties are given in Table 3.1 (Incropera and DeWitt, 1996). Time-varying temperature measurements from these sensors (along with other information) are used to determine heat flux variations using an impulse response filter (Oldfield, 2008). Figure 3.2 shows a schematic diagram from Medtherm Corporation of a thin film gauge.

Table 3.1 Thin Film Gauge Substrate Properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($\rho$)</td>
<td>$7870 \text{ kg/m}^3$</td>
</tr>
<tr>
<td>Specific Heat ($c$)</td>
<td>$447 \text{ J/kgK}$</td>
</tr>
<tr>
<td>Thermal Conductivity ($k$)</td>
<td>$72.7 \text{ W/mK}$</td>
</tr>
</tbody>
</table>

Figure 3.2 Medtherm Thin Film Gauge (Medtherm Corporation, 2021).
3.2 Signal Acquisition and Processing

EMI shielding is installed around the Medtherm thin film gauge wires to prevent interference from nearby wall power sources at 60 Hz. The thin film gauge wires connect to the National Instruments (NI) 9238 data acquisition card, which is installed in the NI cDAQ-9178 chassis. Data are sent from this chassis to the computer using a USB connection. LabVIEW 2020 version 20.0.1 software is used to record the data. Figure 2.7 shows system details.

3.3 Thin Film Gauge Voltage to Temperature Conversion

Instantaneous time-varying voltage (µV) values are converted to temperature (°C) values using inverse polynomials developed by the National Institute of Standards and Technology (NIST). The form of the conversion equation is given by

\[ T = \sum_{i=0}^{n} c_n E^n, \]  

where \( c_n \) are constants and \( E \) is the voltage (µV). Tabulated values of \( c_n \) given by NIST are different for each thermocouple type (ITS-90 Thermocouple Direct and Inverse Polynomials). The thermocouple calibration curves are applied to the collected data using the built-in LabVIEW calibration tools by selecting ‘Type J’ for the thermocouple type. Table 3.2 shows numerical values of the constants used for type J thermocouples. A type J thermocouple has an iron positive junction leg and a constantan negative junction leg. Constantan is a copper-nickel alloy.
Table 3.2 Type J Thermocouple Inverse Polynomial Constants (Omega 2023).

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>0 to 760°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Range</td>
<td>0 to 42,919 µV</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
    c_0 &= 0.000000... \\
    c_1 &= 1.978425 \times 10^{-2} \\
    c_2 &= -2.001204 \times 10^{-7} \\
    c_3 &= 1.036969 \times 10^{-11} \\
    c_4 &= -2.549687 \times 10^{-16} \\
    c_5 &= 3.585153 \times 10^{-21} \\
    c_6 &= -5.344285 \times 10^{-26} \\
    c_7 &= 5.099890 \times 10^{-31} \\
    \text{Error Range} &= 0.04 \text{ to } -0.04°C
\end{align*}
\]

Because of several degrees of temperature variation between thin film gauges when subject to ambient temperature, small correction voltage offsets are applied to signals from two of the gauges. With this modification, gauge voltage output values closely match when gauge sensors are subject to the same temperature.

3.4 Time-Varying Surface Heat Flux Determination

Unsteady temperature measurements recorded with the thin film gauges are converted to heat flux variations in MATLAB version R2023a using an impulse response filtering method
developed by Oldfield (2008). This involves using the filter() and fftfilt() functions in MATLAB. A “discrete deconvolution” is used to find the impulse response $h(t)$ (Oldfield, 2008) from given basis functions for temperature and heat flux. The properties given in Table 4 are also employed for this analysis. Surface heat flux is determined using the convolution integral, as expressed using

$$ q(t) = h(t) * T(t) = \int_{-\infty}^{\infty} h(\tau)T(t - \tau) d\tau, \quad (3) $$

where $h(t)$ is the impulse response function, $T(t)$ is the thin-film gauge surface temperature, and $q(t)$ is the surface heat flux. Since the convolution integral “can be difficult to evaluate” (Oldfield, 2008), this integral is replaced by a “discrete convolution sum” (Oldfield, 2008). This approach requires knowledge of the sampling period and sampling frequency, as given by

$$ f_s = \frac{1}{T_s}. \quad (4) $$

The equations associated with the “discrete convolution sum” are then given by

$$ T[n] = T(nT_s) \text{ for } n = \ldots, -3, -2, -1, 0, 1, 2, 3, \ldots \quad (5) $$

$$ q[n] = h[n] * T[n] = \sum_{k=-\infty}^{\infty} h[k]T[n-k] = \sum_{k=-\infty}^{\infty} h[n-k]T[k], \quad (6) $$

where $f_s$ is the sampling frequency and $T_s$ is the sampling period. Equation 6 is the discrete form of the convolution integral, where the integral is replaced with a summation and temperature is converted to a discrete signal using Equation 5. The bounds on the summation terms are limited by assuming that “all signals and impulse responses are… 0 for $n < 0$ and the signals are all of a finite length $N$ (i.e., they have been sampled for a time $NT_s$ seconds)” (Oldfield, 2008). The discrete convolution summation then becomes.
\[ q[n] = h[n] * T[n] = \sum_{k=0}^{N-1} h[k]T[n-k] = \sum_{k=0}^{N-1} h[n-k]T[k]. \]  \hspace{1cm} (7)

Practically, this discrete convolution is performed in MATLAB using the \texttt{fftshift(h, T)} function. Both quantities \( h[n] \) and \( T[n] \) are vectors of corresponding discrete data points, where \( n \) denotes an indexed position in the respective vectors. When computing the discrete convolution integral in Equation 7, the surface heat flux at each time step, \( q[n] \), requires a summation of values across the entire length \( N \) of the impulse response and temperature vectors. For example, \( h[k] \) is the value of the impulse-response function at step \( k \) in the summation, and \( h[n-k] \) is the value at an index equal to the time-step given by \( n \) minus the current summation index \( k \). Similar indexing arrangements are used for the temperature quantities \( T[n] \), \( T[k] \), and \( T[n-k] \).

The discrete impulse response function \( h[n] \) requires the knowledge of basis functions, \( q_1(t) \) and \( T_1(t) \). According to Oldfield (2008), “a step function in \( q \) and the corresponding ‘parabolic’ function in \( T \) for a semi-infinite substrate” are examples of basis functions which can be employed. Here, the subscript 1 denotes particular variations of these basis functions.

With a more general approach associated with more complex variations of \( q_1(t) \) and \( T_1(t) \), the impulse response is calculated through deconvolution using the discrete impulse function, expressed using an equation of the form

\[ q_1[n] = h[n] * T_1[n], \]  \hspace{1cm} (8)

where \( q_1 \) is a basis function for surface heat flux. \( T_1 \) is solved using the heat conduction equation given by

\[ T_1(t) = \frac{2}{\sqrt{\rho_1 c_1 k_1}} \sqrt{\frac{t}{\pi}}, \]  \hspace{1cm} (9)
where \( \rho_1 \) is the substrate material density, \( c_1 \) is the substrate material specific heat, and \( k_1 \) is the substrate material thermal conductivity. The above basis functions and the impulse function are then used as arguments within MATLAB’s filter() function to solve for the impulse response of the thin film gauge, given by

\[
\delta[n] = 1,0,0,0, \ldots \ldots
\]

\[
h[n] = \text{filter}(q_1[n], T_1[n], \delta[n]).
\]

Here, \( \delta[n] \) is the discrete impulse function.

In general, heat flux is determined using MATLAB with the impulse response and original temperature variation as arguments in the fftfilt() function, given by

\[
q[n] = \text{fftfilt}(h[n], T[n]).
\]

Within the present study, the use of these MATLAB functions allows the determination of time-varying heat flux from instantaneous time-varying temperature measurements, for the three thin film gauge locations along the bottom surface of the test section. Time-varying surface temperature data are high-pass filtered at a cut-off frequency of 1.5 Hz before the determination of heat flux data. Additional digital filtering is not applied to the heat flux data.

Oldfield (2008) provides examples of analysis results from several experimental environments, which involve complex time-variations of surface temperature and surface heat flux. For one of these, data are provided for a thin-film heat flux gauge mounted on the tip of a rotating blade within a transient turbine facility. For another, data are provided for a thin-film gauge array along the shroud surface which surrounds a rotating turbine blade row. Time-varying surface heat flux data determined using the impulse-response method for both environments are demonstrated to be more accurate and physically representative, compared to other analysis approaches. Demonstration is also provided that the method is faster, simpler to implement, and
has greater effectiveness relative to other approaches. To implement the impulse-response method, suitable basis functions $q_1(t)$ and $T_1(t)$ are derived. MATLAB analysis is then utilized to design the required discrete impulse response function $h[n]$.

Oldfield (2008) also indicates that unsteady heat transfer gauge signals decrease in magnitude as frequency increases. Note that higher frequency portions of the signals are often affected by electrical noise. As a consequence, amplifiers and filters are commonly used when processing heat transfer gauge signals.

### 3.5 Convection Heat Transfer Coefficient Determination

An alternative approach determines surface heat transfer coefficients from unsteady temperature measurements by assuming transient, one-dimensional conduction into a flat wall that acts as a semi-infinite solid with a constant convection coefficient ($h$) and constant material properties (Forster, 2023). The following equations are used to determine the normalized surface temperature variation with time when the location is subject to a step in mainstream temperature:

\[
\theta = \frac{T_w - T_0}{T_{\text{ref}} - T_0} = 1 - \exp(x^2) \text{erfc}(x) \quad (13)
\]

\[
x = h \sqrt{\frac{t\alpha}{\lambda^2}}. \quad (14)
\]

Within these equations, $T_w$ is the wall temperature at the surface at time $t$, $T_0$ is the initial wall temperature, $T_{\text{ref}}$ is a reference temperature, $\alpha$ is the wall material thermal diffusivity, $\lambda$ is the wall material thermal conductivity, and $h$ is the convection heat transfer coefficient. The investigation of Forster (2023) considers the leading-edge interior of a film-cooled turbine blade, which is coated using thermochromic liquid crystals (TLC) for surface temperature measurements. A fluid temperature step is imposed upon the flow to initiate a thermal transient along the surface of the
test section. Because the experimental fluid temperature rise is not an ideal step, Equation 13 is modified to become the equation, which is given by

\[
T_w - T_0 = \sum_{i=1}^{N} \left[ 1 - \exp \left( h^2 \frac{(t_{ind} - t_i)\alpha}{\lambda^2} \right) \right] \text{erfc} \left( h \sqrt{\frac{(t_{ind} - t_i)}{\lambda^2}} \right) x(T_{ref,i} - T_{ref,i-1}), \tag{15}
\]

where \( t_{ind} \) is the indication time associated with wall temperature \( T_w \). In addition, \( t_i \) is the current time, \( T_{ref,i} \) is the current reference temperature, and \( T_{ref,i-1} \) is the reference temperature at the previous time step. Equation 15 is solved iteratively over the course of the experiment to determine the heat transfer coefficient \( h \). To solve Equation 15, the indication time \( t_{ind} \), wall surface temperature \( T_w \), initial wall temperature \( T_0 \), and reference temperature \( T_{ref,i} \) are measured. Thermal diffusivity and thermal conductivity values are employed which are associated with the substrate material.

Forster (2023) also presents two variations of Equation 15. One accounts for a layer of paint on the blade surface, and the other accounts for surface curvature.
Chapter 4. Data Analysis Procedures

Presented in this chapter are discussions regarding shadowgraph digitization, image processing in MATLAB, shock wave tracking procedures, and frequency domain analysis. Methods for determination of power spectral density, magnitude squared coherence, time lag, and mean square values are presented in the frequency domain discussion.

4.1 Shadowgraph Data Digitization

Flow visualization video data are recorded on the Phantom v711 camera and are then saved as a Phantom cine file using Phantom Camera Control (PCC) 2.7 software. The saved software file contains the digitized flow visualization video and all of the camera settings such as frame rate, bit depth, image resolution, and exposure time. During post-processing, the Phantom cine file is converted into TIFF grayscale images using PCC 3.8 software. These images are then imported into MATLAB (versions R2022b and R2023a) in order to extract the grayscale value of pixels of interest, allowing for shock wave tracking. To process and analyze these data, a HP Z600 Workstation is used with a Windows 10 operating system. This workstation includes two Intel Xeon X5650 CPU processors, each with a processor frequency of 2.66 GHz, and 32 GB of RAM.

4.2 MATLAB Image Processing Procedures

As time sequences of grayscale values for each pixel are extracted, MATLAB’s built-in function “imread” is used to determine the intensity of each pixel. This intensity varies from 0 to 255 for 8-bit data or from 0 to 4095 for 12-bit data. After acquiring all of the time sequence data,
the pixel locations for each time sequence are saved to Microsoft Excel using MATLAB’s built-in function “writematrix.”

4.3 Processing Data from Pressure Transducers, Thermocouples, and Thin Film Gauges

After data are acquired, National Instruments (NI) LabVIEW Professional Development System version 2023 Q3 exports the time-varying signals for the Honeywell pressure transducers, Kulite pressure transducers, Omega thermocouples, and Medtherm thin film temperature gauges into a TDMS file. This TDMS file is then opened and saved in Microsoft Office Excel version 2016 using LabVIEW software. This Excel file is then imported into MATLAB using MATLAB’s built-in function “readmatrix.” The temperature data collected using the Medtherm thin film gauges are high-pass filtered at a cutoff frequency of 1.5 Hz using MATLAB’s “highpass” function. The power spectral density of each signal is then estimated with Welch’s method using 8 segments, segment overlap of 50%, and a Hanning data window.

4.4 Shock Wave Tracking Procedures

The MATLAB code is used to determine and to track the dimensional position of a shock wave from the digitized time sequence of shadowgraph images. Shock waves are generally located as a dark line next to a bright line within shadowgraph images. Typically, the dark portion has the most contrast relative to the background. Hence, streamwise shock wave positions are identified by locations of the darkest pixels within shadowgraph visualization images.

In order to track the shock wave position, the user first specifies the file path containing the time sequence of shadowgraph images. The user must specify a region of streamwise pixel coordinates where the shock wave is expected to appear. Doing this minimizes the possibility that the shock wave finding algorithm mistakes an image effect (not related to flow structure) for the shock wave. As an example, scratches on the side wall of the wind tunnel appear as dark spots
within shadowgraph images. Microsoft Paint version 22H2 is subsequently used to determine the pixel location range in which the shock wave is expected.

This requires the y-location of the line of pixels and the x-range of pixels to scan in each image. The Minimum function, “min,” in MATLAB then determines the pixel location with the lowest, or darkest, grayscale value within the specified region which is present along the horizontal line. As such, the resulting pixel location represents the location of the shock wave. This is done for each image within the time sequence. The horizontal pixel number, i for each image is then saved to an array. The three black, horizontal lines in Figure 4.1 show the range of pixels evaluated for shock wave tracking for three different locations within the flow, where one is located in the vicinity of the normal shock wave and two are located in the vicinity of the rear leg of the lambda foot.

![Figure 4.1](image_url)

**Figure 4.1** Pixels of interest for shock wave tracking during the test performed on July 31st, 2023.

The average pixel number representing the average shock wave position is determined next. This average value is subtracted from each value in the time sequence so that a value of 0 corresponds to the average shock wave location. The physical location corresponding to the pixel location is then determined. A scaling factor is used to convert the pixel coordinate of the shock
wave into a physical distance. This scaling factor is determined by dividing the physical distance between two locations by the number of pixels between those locations in the image. The variation of shock wave position is then determined with respect to time, where dimensional time is equal to the index of the time sequence array (associated with each shock wave position) divided by the sampling frequency. A positive shock wave position value denotes that the shock wave is downstream stream of the average location, and a negative shock wave position value denotes that the shock wave is upstream of the average location. Figure 4.2 shows an example of such a tracked shock wave position.

![Shock wave position as a function of time](image)

**Figure 4.2** Normal shock wave position as a function of time for pixel coordinate locations from (510, 258) to (620, 258). Data acquired on July 31st, 2023, at a sampling frequency of 10 kHz.

### 4.5 Low-Pass Filtering of Time-Varying Shock Wave Position

After the time variation of shock wave position is determined, the resulting time sequence array is filtered with a fifth-order, low-pass Butterworth filter, using a cut-off frequency which is set to 90% of the Nyquist folding frequency. The filtering is done using the “butter” and “filter” functions within MATLAB. The data, the cut-off frequency, the type of filter (low pass, for example), and the order of the filter are inputs to this function.
The filter is a low-pass Butterworth type. A Butterworth filter is used, as opposed to another type of filter, because of its relatively uniform transfer function scaling over the frequencies of interest (Butterworth, 1930). The transfer function is the ratio of the filtered value to the unfiltered value as a function of frequency. Uniform scaling over the transfer function is important because extraneous frequency content is not added to the data. This ensures that any variations within the frequency domain data are from real events, not distortion from the filter. The fifth order filter is used in this analysis because of the abrupt decrease in magnitude of the filtered signal transfer function near the cut-off frequency.

4.6 Frequency Domain Analyses

The transformation of filtered shock wave position data from the time domain to the frequency domain is accomplished using MATLAB software. To do this, filtered data are read into MATLAB from the Excel spreadsheet using the “xlsread” function. Inputs for this function include the file path and the range of cells within the spreadsheet that contains the data. Prior to conversion, time-varying shock wave position data is filtered with a low-pass filter at 90 percent of the Nyquist folding frequency. Time-varying surface temperature data are high-pass filtered at a cut-off frequency of 1.5 Hz. Additional digital filtering is not applied to the unsteady pressure and heat flux data. After acquiring the power spectral density for all types of data, correlation analysis is then performed between pairs of signals. For example, the magnitude squared coherence is used to estimate the correlation strength between the two signals, whereas cross power spectral density is used to determine the time lag between the two signals.

4.6.1 Power Spectral Density Determination

To determine power spectral density, Welch’s method (Solomon, 1991) is performed with 8 segments using 50 percent overlap and a Hanning data window. The length of each segment,
denoted by $L_s$, is determined as follows, where the variables $L$ and $N$ correspond to the number of measurements and segments respectively:

$$L_s = \frac{L}{1 + 0.5(N - 1)}.$$  \hspace{1cm} (16)

After calculating the segment length, $L_s$ is then rounded down to the nearest even integer due to using an overlap of 50 percent. While implementing Welch’s method, the Discrete Fourier Transform (DFT) algorithm is used to transform the segments from the time domain to spectral density in the frequency domain. This results in $N$ spectrums, which are then ensemble-averaged together to obtain one spectrum that quantifies the filtered signal. After truncating this spectrum from 0 Hz to the Nyquist frequency, the power spectral density $P_{xx}$ is given by

$$P_{xx} = \frac{2|Y(f)|^2}{f_s \cdot S}.$$  \hspace{1cm} (17)

Here, the variables $Y(f)$, $f_s$, and $S$ correspond to the truncated spectrum, the sampling frequency, and a window normalization factor, respectively. Welch’s method is implemented using the MATLAB built-in function “pwelch” that calculates $P_{xx}$ as a function of frequency. The frequency resolution $\Delta f$ of $P_{xx}$ is given by

$$\Delta f = \frac{f_s}{L_s}.$$  \hspace{1cm} (18)

Examples of power spectral density distributions as a function of frequency for signals from three different Kulite pressure signals are shown in Figure 4.3.
4.6.2 Magnitude Squared Coherence Determination

The magnitude squared coherence $C_{xy}$ varies from 0 to 1, and provides correlation values as a function of frequency. The magnitude squared coherence is given by

$$C_{xy} = \frac{|P_{xy}|^2}{P_{xx} \cdot P_{yy}}.$$  (19)

Magnitude squared coherence is calculated using the MATLAB built-in function “mscohere,” which uses Welch’s method for estimating $P_{xx}$, $P_{yy}$, and $P_{xy}$. These quantities are the power spectral density for signal one, the power spectral density for signal two, and the cross power spectral density between the two signals respectively. Magnitude squared coherence is determined between the locations which are listed in Table 4.1. The resulting magnitude squared coherence distributions and power spectral density distributions are then smoothed with a moving average method, using the parameters given in Table 4.2. Examples of resulting magnitude squared coherence variations which are determined between a normal shock wave unsteady position and signals from three Kulite pressure transducers are shown in Figure 4.4.
### Table 4.1 List of Correlation Comparisons.

<table>
<thead>
<tr>
<th>Signal 1</th>
<th>Signal 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracked shock wave location</td>
<td>Kulite pressure transducer</td>
</tr>
<tr>
<td>Tracked shock wave location</td>
<td>Medtherm thin film temperature gauge</td>
</tr>
<tr>
<td>Tracked shock wave location</td>
<td>Heat flux at specific location</td>
</tr>
<tr>
<td>Kulite pressure transducer</td>
<td>Kulite pressure transducer</td>
</tr>
<tr>
<td>Kulite pressure transducer</td>
<td>Medtherm thin film temperature gauge</td>
</tr>
<tr>
<td>Kulite pressure transducer</td>
<td>Heat flux at specific location</td>
</tr>
<tr>
<td>Medtherm thin film temperature gauge</td>
<td>Medtherm thin film temperature gauge</td>
</tr>
<tr>
<td>Medtherm thin film temperature gauge</td>
<td>Heat flux at specific location</td>
</tr>
<tr>
<td>Heat flux at specific location</td>
<td>Heat flux at specific location</td>
</tr>
</tbody>
</table>

### Table 4.2 Frequency Domain Smoothing Technique.

<table>
<thead>
<tr>
<th>Frequency Range (Hz)</th>
<th>Range of Averaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \leq f \leq 10 \Delta f$</td>
<td>None</td>
</tr>
<tr>
<td>$10 \Delta f &lt; f \leq 20$</td>
<td>Moving Average ± 1 Point</td>
</tr>
<tr>
<td>$20 &lt; f \leq f_s/2$</td>
<td>Moving Average ± 0.05 $f/\Delta f$ Points</td>
</tr>
</tbody>
</table>
Figure 4.4 Magnitude squared coherence variation as a function of frequency between a location of the normal shock wave for pixel coordinate locations between (445, 258) and (610, 258), and signals from three Kulite pressure transducers. Data collected during the wind tunnel test on July 31st, 2023, at a sampling frequency of 10 kHz.

4.6.3 Time Lag Determination

The cross power spectral density is determined using the equation given by

\[
P_{xy} = \frac{2 \cdot X(f)Y(f)^*}{f_s \cdot S}.
\]  

(20)

This equation is used to determine the time lag magnitude between two signals. The cross power spectral density, denoted by \( P_{xy} \), is obtained in MATLAB by using MATLAB’s built-in function “cpsd,” which also uses Welch’s method. Within Equation 20, \( X(f) \) corresponds to the truncated spectrum for signal one, whereas \( Y(f)^* \) corresponds to the complex conjugate of the truncated spectrum for signal two. After acquiring the cross power spectral density between the two signals, MATLAB’s built-in function “angle” is implemented, which obtains the phase angle \( \phi \) from \(-\pi\) to \(\pi\) between the two signals. Due to the bounds on the phase angle, a phase angle unwrapping procedure is implemented. MATLAB’s built-in function “unwrap” is used for this purpose, which
changes the phase angle by $\pm 2\pi$ if a large physically-unrealistic phase angle increase is present. Such a jump is identified by a phase change of $\pi$ or bigger over one index change in frequency. After unwrapping the phase angles, the time lag, denoted by $\tau$, is calculated using the equation of the form

$$
\tau = -\frac{\phi}{2\pi f}. 
$$

(21)

Note that the negative sign within this equation is implemented with the convention that a negative time lag means signal one is occurring first, whereas a positive time lag means signal two is occurring first. The variable $f$ corresponds to the dimensional frequency. Examples of time lag variations as a function of frequency, which are determined between a normal shock wave unsteady position and signals from Kulite pressure transducers, are shown in Figure 4.5.

![Figure 4.5](image.png)

**Figure 4.5** Time lag variation as a function of frequency between a location of the normal shock wave for pixel coordinate locations between (445, 258) and (610, 258), and signals from three Kulite pressure transducers. Data collected during the wind tunnel test on July 31st, 2023, at a sampling frequency of 10 kHz.
4.6.4 Determination of Mean Squared Values

Mean squared values of time- and frequency-varying surface measured parameters are determined to check and verify data analysis procedures. The mean-squared value of $P_{xx}(f)$ is given by

$$\overline{x'^2} = \int_0^\infty P_{xx}(f) df$$

(22)

$$x' = x_i - \bar{x}.$$  

Here, $x'$ is the fluctuating value, where $x_i$ is the instantaneous value, and $\bar{x}$ is the time-averaged value. Magnitudes of $\overline{x'^2}$ from spectra are obtained by first recording unsteady time-series data in the form of fluctuating temperature or pressure. Next, the mean of each data set is set to zero by subtracting each respective time-averaged value. Then $P_{xx}$ values are determined. Finally, $P_{xx}$ values are summed and multiplied by the frequency step to give $\overline{x'^2}$. The same time-averaged mean-squared value, $\overline{x'^2}$, is also determined from the associated time series data.

Tables 4.3 and 4.4 show comparisons of mean-squared values for each type of time-varying surface data. Data in Table 4.3 are provided for high inlet turbulence intensity level, and data in Table 4.4 are provided for low inlet turbulence intensity level. Percentage differences between mean-squared values calculated from the time-history signal and from the PSD are consistently less than five percent. Such agreement indicates correct and accurate determinations of frequency spectral distributions.
Table 4.3 Mean-squared value comparison for signals collected on December 8th, 2022.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Sampling Frequency</th>
<th>Signal</th>
<th>Average</th>
<th>Time History</th>
<th>PSD</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6:30 PM</td>
<td>25 kHz</td>
<td>K2 [Pa]</td>
<td>1.47E+05</td>
<td>4.79E+07</td>
<td>4.74E+07</td>
<td>1.02%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K3 [Pa]</td>
<td>1.66E+05</td>
<td>5.31E+07</td>
<td>5.15E+07</td>
<td>3.16%</td>
</tr>
<tr>
<td>12/8/2022</td>
<td>7:00 PM</td>
<td>10 kHz</td>
<td>T1 [°C]</td>
<td>2.79E-03</td>
<td>0.00638</td>
<td>0.00607</td>
<td>4.76%</td>
</tr>
<tr>
<td>(High Inlet</td>
<td></td>
<td></td>
<td>T2 [°C]</td>
<td>-1.59E-05</td>
<td>0.00629</td>
<td>0.00630</td>
<td>0.16%</td>
</tr>
<tr>
<td>Turbulence)</td>
<td></td>
<td></td>
<td>Q1 [W/m²]</td>
<td>1.32E-12</td>
<td>1.94E+10</td>
<td>1.93E+10</td>
<td>0.46%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q2 [W/m²]</td>
<td>-1.9E-12</td>
<td>1.92E+10</td>
<td>1.92E+10</td>
<td>0.26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q3 [W/m²]</td>
<td>7.52E-13</td>
<td>1.89E+10</td>
<td>1.89E+10</td>
<td>0.28%</td>
</tr>
<tr>
<td></td>
<td>7:30 PM</td>
<td>6.25 kHz</td>
<td>K1 [Pa]</td>
<td>7.97E+04</td>
<td>1.24E+08</td>
<td>1.19E+08</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>K2 [Pa]</td>
<td>1.48E+05</td>
<td>4.01E+07</td>
<td>3.97E+07</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>K3 [Pa]</td>
<td>1.67E+05</td>
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<tr>
<td></td>
<td></td>
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<td>T1 [°C]</td>
<td>7.32E-04</td>
<td>0.00453</td>
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<tr>
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<td>T2 [°C]</td>
<td>-3.62E-04</td>
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<td>0.00558</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T3 [°C]</td>
<td>7.02E-04</td>
<td>0.00517</td>
<td>0.00498</td>
<td>3.59%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q1 [W/m²]</td>
<td>1.28E-12</td>
<td>6.18E+09</td>
<td>6.19E+09</td>
<td>0.17%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q2 [W/m²]</td>
<td>8.83E-13</td>
<td>6.28E+09</td>
<td>6.28E+09</td>
<td>0.00%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q3 [W/m²]</td>
<td>-5E-14</td>
<td>5.92E+09</td>
<td>5.92E+09</td>
<td>0.10%</td>
</tr>
<tr>
<td></td>
<td>7:30 PM</td>
<td>6.25 kHz</td>
<td>K2 [Pa]</td>
<td>1.47E+05</td>
<td>4.79E+07</td>
<td>4.74E+07</td>
<td>1.02%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K3 [Pa]</td>
<td>1.66E+05</td>
<td>5.31E+07</td>
<td>5.15E+07</td>
<td>3.16%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T1 [°C]</td>
<td>9.19E-05</td>
<td>0.00385</td>
<td>0.00384</td>
<td>0.30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T2 [°C]</td>
<td>9.54E-05</td>
<td>0.00528</td>
<td>0.00510</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Q1 [W/m²]</td>
<td>8.24E-13</td>
<td>3.57E+09</td>
<td>3.56E+09</td>
<td>0.14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q2 [W/m²]</td>
<td>-2.5E-12</td>
<td>3.57E+09</td>
<td>3.57E+09</td>
<td>0.06%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q3 [W/m²]</td>
<td>1.84E-12</td>
<td>3.41E+09</td>
<td>3.41E+09</td>
<td>0.03%</td>
</tr>
</tbody>
</table>
The table below shows the mean-squared value comparison for signals collected on July 31st, 2023.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Sampling Frequency</th>
<th>Signal</th>
<th>Average</th>
<th>Time History</th>
<th>PSD</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/31/2023</td>
<td>6:00 PM</td>
<td>12.5 kHz</td>
<td>K1 [Pa]</td>
<td>7.70E+04</td>
<td>3.86E+07</td>
<td>3.87E+07</td>
<td>0.20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K2 [Pa]</td>
<td>1.48E+05</td>
<td>2.68E+07</td>
<td>2.77E+07</td>
<td>3.16%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K3 [Pa]</td>
<td>1.66E+05</td>
<td>3.21E+07</td>
<td>3.31E+07</td>
<td>2.80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T1 [°C]</td>
<td>-1.37E-03</td>
<td>7.00E-03</td>
<td>6.87E-03</td>
<td>1.96%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T2 [°C]</td>
<td>-1.51E-03</td>
<td>7.62E-03</td>
<td>7.43E-03</td>
<td>2.40%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T3 [°C]</td>
<td>-2.65E-03</td>
<td>8.11E-03</td>
<td>7.71E-03</td>
<td>4.90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q1 [W/m²]</td>
<td>1.23E-12</td>
<td>1.39E+10</td>
<td>1.37E+10</td>
<td>1.07%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q2 [W/m²]</td>
<td>1.8E-12</td>
<td>1.47E+10</td>
<td>1.46E+10</td>
<td>1.11%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q3 [W/m²]</td>
<td>4.92E-13</td>
<td>1.43E+10</td>
<td>1.4E+10</td>
<td>1.90%</td>
</tr>
<tr>
<td></td>
<td>6:20 PM</td>
<td>6.25 kHz</td>
<td>K1 [Pa]</td>
<td>7.87E+04</td>
<td>4.89E+07</td>
<td>4.78E+07</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>K2 [Pa]</td>
<td>1.50E+05</td>
<td>2.76E+07</td>
<td>2.74E+07</td>
<td>0.69%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K3 [Pa]</td>
<td>1.68E+05</td>
<td>3.48E+07</td>
<td>3.46E+07</td>
<td>0.55%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T1 [°C]</td>
<td>-1.11E-04</td>
<td>5.10E-03</td>
<td>5.15E-03</td>
<td>1.13%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T2 [°C]</td>
<td>2.41E-05</td>
<td>5.67E-03</td>
<td>5.61E-03</td>
<td>1.10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T3 [°C]</td>
<td>-3.47E-04</td>
<td>5.41E-03</td>
<td>5.47E-03</td>
<td>1.15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q1 [W/m²]</td>
<td>1.9E-12</td>
<td>6.88E+09</td>
<td>6.98E+09</td>
<td>1.52%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q2 [W/m²]</td>
<td>-3.6E-13</td>
<td>7.23E+09</td>
<td>7.37E+09</td>
<td>1.90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q3 [W/m²]</td>
<td>1.54E-12</td>
<td>7.13E+09</td>
<td>7.3E+09</td>
<td>2.38%</td>
</tr>
</tbody>
</table>

Figures 4.6a, 4.6b, and 4.6c show mean-square values related to pressure, temperature, and heat flux, respectively, as they vary with location along the bottom surface of the test section. Data within each of these figures are provided for both low and high inlet turbulence intensity levels. Triangular symbols denote high inlet turbulence (HT), and circular symbols denote low inlet turbulence.
turbulence (LT). Note that X location values are determined relative to the leading-edge tip of the shock wave holding plate, such that negative X values indicate locations upstream of the leading-edge position. The mean-squared value for pressure data, shown in Figure 15, shows a substantial decrease as position increases for the high inlet turbulence test, whereas the mean-squared value remains relatively constant for the low inlet turbulence test. Figure 16 shows the mean-squared value for temperature data and reveals a linear increase with position for data collected during the low inlet turbulence test. Temperature data collected during the high inlet turbulence test have a lower mean-squared value than the low inlet turbulence data and remain relatively constant as position varies. Mean-squared values of heat flux data, shown in Figure 17, are relatively constant as position varies, with data from the low inlet turbulence test having higher values than the high inlet turbulence data.

**Figure 4.6a** Mean-squared value as a function of location along the plate calculated from the time-history data and the PSD of the time-history data for unsteady surface pressure. Data collected at a sampling frequency of 10 kHz.
Figure 4.6b Mean-squared value as a function of location along the plate calculated from the time-history data and the PSD of the time-history data for unsteady surface temperature. Data collected at a sampling frequency of 10 kHz.

Figure 4.6c Mean-squared value as a function of location along the plate calculated from the time-history data and the PSD of the time-history data for unsteady surface heat flux. Data collected at a sampling frequency of 10 kHz.
Chapter 5. Comparisons of Results Acquired with Different Data Sampling Frequencies

Presented in this chapter are comparisons of results acquired with different data sampling frequencies. Data are provided for high and low inlet turbulence intensity values. Types of results considered include power spectral density, magnitude squared coherence, and time lag.

5.1 High Inlet Turbulence Intensity Data

The data presented within Figures 5.1 through 5.5 are provided for a high inlet turbulence intensity flow condition. Figures 5.1 through 5.3 show the variation of power spectral density (PSD) with respect to frequency, where Figure 5.1 shows results determined from shadowgraph data for positions along location A on the normal shock wave, Figure 5.2 shows results determined from the Kulite pressure transducer data at location 1 along the bottom wall of the test section, and Figure 5.3 shows results determined from the Medtherm thin film gauge data at location 1 along the bottom wall of the test section. Figures 5.4 and 5.5 show magnitude squared coherence and time lag, respectively, as a function of frequency for the Kulite pressure transducer data at location 2, relative to shadowgraph data along location A for the normal shock wave.
Figure 5.1 Power spectral density as a function of frequency from local shadowgraph data for normal shock wave location A. Data collected on December 8th, 2022.

Figure 5.2 Power spectral density as a function of frequency for Kulite pressure transducer data at location 1 along the bottom wall of the test section. Data collected on December 8th, 2022.
Figure 5.1 shows that differences between results related to normal shock wave position which are acquired at different sampling frequencies are minimal for frequencies less than 500 Hz. For frequencies above 500 Hz, PSD values for data sampled at 10 kHz are often larger than results associated with the other two acquisition rates. Figure 5.2 shows that differences in PSD values for unsteady pressure at location 1 which are acquired at different sampling frequencies are generally minimal for frequencies between 10 and 100 Hz. Below 10 Hz, data acquired with an acquisition frequency of 10 kHz are generally lower in PSD value, relative to the data sets acquired with acquisition frequencies of 6.25 kHz and 25 kHz. Above 100 Hz, PSD data for the 6.25 kHz acquisition rate are generally lower than PSD values associated with data sets acquired with acquisition frequencies of 10 kHz and 25 kHz. Figure 5.3 shows that differences in PSD values for unsteady temperature at location 1 which are acquired with different acquisition frequencies are minimal for frequencies above 5 Hz. Below this frequency, unsteady temperature data sets
acquired with the different acquisition frequencies show widely varying trends and magnitudes as frequency varies.

**Figure 5.4** Smoothed magnitude squared coherence as a function of frequency for Kulite pressure transducer data at location 2 along the bottom wall of the test section relative to shadowgraph data for normal shock wave location A. Data collected on December 8th, 2022.

**Figure 5.5** Dimensional time lag as a function of frequency for Kulite pressure transducer data at location 2 along the bottom wall of the test section relative to shadowgraph data for normal shock wave location A. Data collected on December 8th, 2022.
Smoothed magnitude squared coherence and dimensional time lag data acquired using sampling frequencies of 10 kHz and 25 kHz generally show quantitative and qualitative similarity for most all frequencies within Figures 5.4 and 5.5. However, data within these figures which are acquired with an acquisition frequency of 6.25 kHz show significant differences relative to these data sets, for most all of the frequencies which are considered.

5.2 Low Inlet Turbulence Intensity Data

The data presented within Figures 5.6 through 5.10 are provided for a low inlet turbulence intensity flow condition. Figures 5.6 through 5.8 show the variation of power spectral density (PSD) with respect to frequency, where Figure 5.6 shows results determined from shadowgraph data for positions along location A on the normal shock wave, Figure 5.7 shows results determined from the Kulite pressure transducer data at location 1 along the bottom wall of the test section, and Figure 5.8 shows results determined from the Medtherm thin film gauge data at location 1 along the bottom wall of the test section. Figures 5.9 and 5.10 show magnitude squared coherence and time lag, respectively, as a function of frequency for the Kulite pressure transducer data at location 2, relative to shadowgraph data along location A for the normal shock wave.
Figure 5.6 Power spectral density as a function of frequency from local shadowgraph data for normal shock wave location A. Data collected on July 31st, 2023.

Figure 5.7 Power spectral density as a function of frequency for Kulite pressure transducer data at location 1 along the bottom wall of the test section. Data collected on July 31st, 2023.
Figure 5.8 Power spectral density as a function of frequency for Medtherm thin film gauge data at location 1 along the bottom wall of the test section. Data collected on July 31st, 2023.

Figure 5.6 shows that differences between results related to normal shock wave position which are acquired at different sampling frequencies are minimal for all frequencies considered. Figure 5.7 shows that differences between results related to unsteady pressure which are acquired at different sampling frequencies are minimal for frequencies greater than 20 Hz. For frequencies less than 20 Hz, PSD values for data sampled at 12.5 kHz are often larger than results associated with the other two acquisition rates. Figure 5.8 shows that differences in PSD values for unsteady temperature which are acquired with different acquisition frequencies for location 1 are generally minimal. However, the data set acquired with a sampling frequency of 6.25 kHz is generally somewhat lower than values associated with the other acquisition frequencies for frequencies less than 5 Hz.
Smoothed magnitude squared coherence and dimensional time lag data acquired using acquisition frequencies of 10 kHz, and 25 kHz generally show quantitative and qualitative similarity for most all frequencies within Figures 5.9 and 5.10. Magnitude squared coherence data
within Figure 5.9, which are acquired with an acquisition frequency of 6.25 kHz, show a peak near a frequency of 5 Hz that is not present within the other data sets. In addition, time lag data for an acquisition frequency of 10 kHz in Figure 5.10 show a trend which is different from the other data sets for frequencies less than 50 Hz.
Chapter 6. Analysis of Digitized Shadowgraph Flow Visualization Data

Presented in the present chapter are results which are determined from analysis of digitized instantaneous shadowgraph flow visualization data. These results are determined relative to tracked flow event locations which are associated with the normal shock wave and the downstream shock wave leg of the lambda foot. Included are comparisons and discussions of power spectral density, magnitude squared coherence, and time lag results for experimental arrangements associated with high inlet turbulence intensity, low inlet turbulence intensity, and Marko (2018) data with low inlet turbulence intensity.

6.1 Shock Wave Location Data

Figure 6.1 shows an instantaneous shadowgraph image from a test performed on April 5th, 2018 from Marko (2018) with relatively low inlet turbulence intensity. Figure 6.2 shows an instantaneous shadowgraph image from a test performed on December 8th, 2022 with high inlet turbulence intensity. Figure 6.3 shows an instantaneous shadowgraph image from a test performed on July 31st, 2023 with low inlet turbulence intensity. For all three of these figures, pixel locations for shock wave tracking are labeled A, E, and G. All dimensions are given in cm. Table 6.1 gives tracked shock wave locations for each test in terms of pixels considered and physical distance from the tip of the shock wave holding plate.
Figure 6.1 Instantaneous shadowgraph image from test performed on April 5th, 2018, from Marko (2018). Pixel locations for shock wave tracking are labeled A, E, and G. All dimensions are in cm.

Figure 6.2 Instantaneous shadowgraph image from test performed on December 8th, 2022. Pixel locations for shock wave tracking are labeled A, E, and G. All dimensions are in cm.
**Figure 6.3** Instantaneous shadowgraph image from test performed on July 31st, 2023. Pixel locations for shock wave tracking are labeled A, E, and G. All dimensions are in cm.

**Table 6.1** Tracked shock wave locations for shadowgraph flow visualizations.

<table>
<thead>
<tr>
<th>Test</th>
<th>Shock Wave Location</th>
<th>X [px]</th>
<th>Y [px]</th>
<th>X [cm]</th>
<th>Y [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marko</td>
<td>A</td>
<td>590-710</td>
<td>270</td>
<td>-1.14 – 0.73</td>
<td>-0.39</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>600-679</td>
<td>358</td>
<td>-0.98 – 0.25</td>
<td>-1.77</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>595-670</td>
<td>410</td>
<td>-1.06 – 0.11</td>
<td>-2.58</td>
</tr>
<tr>
<td>HT</td>
<td>A</td>
<td>190-310</td>
<td>162</td>
<td>-2.23 – 1.20</td>
<td>-0.66</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>258-320</td>
<td>221</td>
<td>-0.29 – 1.49</td>
<td>-2.34</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>260-320</td>
<td>242</td>
<td>-0.23 – 1.49</td>
<td>-2.94</td>
</tr>
<tr>
<td>LT</td>
<td>A</td>
<td>445-610</td>
<td>258</td>
<td>-1.95 – 0.80</td>
<td>-0.33</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>543-620</td>
<td>342</td>
<td>-0.32 – 0.97</td>
<td>-1.73</td>
</tr>
<tr>
<td></td>
<td>g</td>
<td>545-620</td>
<td>382</td>
<td>-0.28 – 0.97</td>
<td>-2.40</td>
</tr>
</tbody>
</table>

**6.2 Power Spectral Density Distributions**

Figures 6.4, 6.5, and 6.6 show power spectral density distributions of normal shock wave positions associated with A, E, and G locations, respectively, as a function of frequency. All of the associated data are acquired using a 10 kHz sampling frequency. Within Figure 6.4, the Marko data (labelled Marko) and low inlet turbulence intensity data (labelled LT) are generally in good qualitative and quantitative agreement for the entire frequency range. Higher PSD magnitudes for
the high inlet turbulent intensity data (labelled HT) indicate that more energy is associated with shock wave location A for this data set, relative to the other two data sets. Within Figures 6.5 and 6.6, the LT and HT data sets for lambda foot shock waves for the E and G locations, respectively, follow the same overall trend, and generally have close magnitudes across the entire frequency range. However, the Marko PSD data within these two figures generally show lower magnitudes compared to the LT and HT data sets, especially for frequencies below 100 Hz.

![Power spectral density of normal shock wave positions associated with A locations as a function of frequency. Data acquired at 10 kHz sampling frequency.](image)

**Figure 6.4** Power spectral density of normal shock wave positions associated with A locations as a function of frequency. Data acquired at 10 kHz sampling frequency.
Figure 6.5 Power spectral density of normal shock wave positions associated with E locations as a function of frequency. Data acquired at 10 kHz sampling frequency.

Figure 6.6 Power spectral density of normal shock wave positions associated with G locations as a function of frequency. Data acquired at 10 kHz sampling frequency.

Figures 6.7 through 6.9 show power spectral density distributions of normal shock wave position at all three locations of interest for data from the high inlet turbulence intensity arrangement, low inlet turbulence intensity arrangement, and Marko (2018), respectively. Figure 6.7 shows that variations in normal shock wave position at location A are associated with more energy than locations E or G for the entire frequency range. Small peaks in all three data sets occur
simultaneously at 5 Hz, 15 Hz, and 50 Hz. Figure 6.8 indicates that energy associated with variations in normal shock wave position at all three locations have good qualitative and quantitative agreement for the entire frequency range. Figure 6.9 also shows that variations in normal shock wave position at location A are associated with more energy than locations E or G for the entire frequency range. However, there is a smaller offset between the data for location A and locations E and G for frequencies above 50 Hz in Figure 6.9 than Figure 6.7.

![Figure 6.7](image.png)

**Figure 6.7** Power spectral density of normal shock wave positions associated with all three locations as a function of frequency. Data acquired on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
6.3 Comparisons of Magnitude Squared Coherence and Time Lag Data

Figures 6.10 and 6.11 show smoothed magnitude squared coherence variations as a function of frequency for normal shock wave location A relative to locations E and G, respectively, where E and G are positioned on the rear shock wave leg of the lambda foot. Within both figures, the LT and HT magnitude squared coherence values are generally in good quantitative and
qualitative agreement for most all considered frequencies. In contrast, the Marko data within these figures are significantly different from the LT and HT distributions for most all frequency values. In particular, numerous spectral local maxima are present within the Marko data at a number of different frequencies, and these maxima are generally not present at corresponding frequencies within the LT and HT data. In addition, the Marko coherence data are lower than the LT and HT data for frequencies between 10 and 100 Hz, and higher than the LT and HT data for frequencies greater than 1000 Hz.

Figures 6.12 and 6.13 show time lag variations as a function of frequency for normal shock wave location A relative to locations E and G, respectively, where E and G are positioned on the rear shock wave leg of the lambda foot. Here, positive time lag values indicate that events at locations E and G occur first, and negative time lag values indicate that events at location A occur first. Within both figures, the LT and HT time lag data are in reasonable quantitative and qualitative agreement with each other for the range of frequencies which are considered, except for important deviations which are present at frequencies greater than 100 Hz. Both of these data sets also show that time lag values are in the vicinity of zero at frequencies from 10 Hz to 100 Hz. The Marko data within Figures 6.12 and 6.13 show significant deviations relative to these HT and LT data, especially for frequencies less than 10 Hz and for frequencies greater than 100 Hz. Significant differences between these data sets, relative to the Marko data, are also especially apparent at frequencies between 10 Hz and 100 Hz within Figure 6.13, where G locations are considered.
**Figure 6.10** Smoothed magnitude squared coherence as a function of frequency for normal shock wave location A relative to location E on the rear leg of the lambda foot. Data acquired at 10 kHz sampling frequency.

**Figure 6.11** Smoothed magnitude squared coherence as a function of frequency for normal shock wave location A relative to location G on the rear leg of the lambda foot. Data acquired at 10 kHz sampling frequency.
Figure 6.12 Time lag as a function of frequency for normal shock wave location A relative to location E on the rear leg of the lambda foot. Data acquired at 10 kHz sampling frequency.

Figure 6.13 Time lag as a function of frequency for normal shock wave location A relative to location G on the rear leg of the lambda foot. Data acquired at 10 kHz sampling frequency.
Chapter 7. Analysis of Unsteady Surface Static Pressure Data Measured Using Kulite Pressure Transducers

Discussed in the present chapter are results which are determined from analysis of instantaneous surface static pressure data measured using Kulite pressure transducers. Included are comparisons and discussions of power spectral density, magnitude squared coherence, and time lag results for experimental arrangements associated with high inlet turbulence intensity, and low inlet turbulence intensity. The coherence and time lag results are determined from data obtained for each transducer relative to the other transducers, and also relative to tracked flow event locations which are associated with the normal shock wave.

7.1 Power Spectral Density Distributions

Figures 7.1 and 7.2 show power spectral density distributions for the signals from the three Kulite pressure transducers mounted along the bottom wall of the test section for the high inlet turbulence intensity and low inlet turbulence intensity tests, respectively. All of the associated data are acquired using a 10 kHz sampling frequency. Within Figure 7.1, the data from the Kulite pressure transducer below the lambda foot (labelled K2) and the Kulite pressure transducer downstream of the shock wave (labelled K3) are generally in good quantitative and qualitative agreement for the entire frequency range. Higher PSD magnitudes for data from the Kulite pressure transducer upstream of the shock wave (labelled K1) indicate that more energy is associated with pressure variations upstream of the shock wave, relative to the other two positions, for frequencies...
below 2,000 Hz. Above 2,000 Hz, PSD magnitudes associated with K1 are lower than the other two data sets. Figure 7.2 shows the same overall trends, with even closer agreement between K2 and K3 for the entire frequency range. However, PSD magnitudes associated with K1 for low inlet turbulence intensity become less than values for the other two data sets above 1,000 Hz, instead of above 2,000 Hz.

**Figure 7.1** Power spectral density of signals from Kulite pressure transducers for each location along the bottom wall of the test section as a function of frequency. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 7.2 Power spectral density of signals from Kulite pressure transducers for each location along the bottom wall of the test section as a function of frequency. Data collected on July 31\textsuperscript{st}, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.

7.2 Comparisons of Magnitude Squared Coherence and Time Lag Data Relative to the Normal Shock Wave

Figures 7.3 and 7.4 show smoothed magnitude squared coherence variations as a function of frequency for the signals from the Kulite pressure transducers at each location along the bottom wall of the test section relative to normal shock wave location A. These data are provided for high and low inlet turbulence intensity, respectively. In both figures, the K2 and K3 magnitude squared coherence values are generally in good quantitative and qualitative agreement for most frequency values. Between 10 Hz and 100 Hz, the K3 data have lower values than the K2 data for the high inlet turbulence intensity test, as shown in Figure 7.3. In contrast, the K1 data within these figures are significantly different from the K2 and K3 distributions for most frequency values. The K1 data also shows a sharp peak in the vicinity of 5 Hz (with a higher magnitude for the low turbulence intensity test), followed by relatively constant behavior for frequencies above 10 Hz. All three data sets show quantitative and qualitative agreement at frequencies above 1,000 Hz.
Figures 7.5 and 7.6 show time lag variations as a function of frequency for the signals from the Kulite pressure transducers at each location along the bottom wall of the test section relative to normal shock wave location A. These data are provided for high and low inlet turbulence intensity, respectively. Here positive time lag values indicate that events occur at location A first, and negative time lag values indicate that events occur at a particular Kulite transducer location along the bottom wall first. Within both figures, the K2 and K3 time lag data show good quantitative and qualitative agreement with each other for the entire frequency range. Both data sets show that time lag values are in the vicinity of zero for frequencies above 100 Hz. Below 100 Hz, the data show opposite trends wherein the high inlet turbulence intensity data show that events occur along the bottom wall first, and the low inlet turbulence intensity data show an opposite trend. The K1 data in Figure 7.5 follow the same trend but with greater variations for frequencies below 100 Hz relative to the other two data sets. Figure 7.6 shows that K1 transducer time lag values remain close to zero for the entire frequency range.

![Smoothed magnitude coherence as a function of frequency for the signals from the Kulite pressure transducers for each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.](image)

**Figure 7.3** Smoothed magnitude coherence as a function of frequency for the signals from the Kulite pressure transducers for each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 7.4 Smoothed magnitude coherence as a function of frequency for the signals from the Kulite pressure transducers for each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.

Figure 7.5 Time lag as a function of frequency for the signals from the Kulite pressure transducers for each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 7.6 Time lag as a function of frequency for the signals from the Kulite pressure transducers for each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.

7.3 Comparisons of Magnitude Squared Coherence and Time Lag Data for Each Transducer Relative to the Other Transducers

Figures 7.7 and 7.8 show smooth magnitude squared coherence as a function of frequency for the signals from the Kulite pressure transducers at each location along the bottom wall of the test section relative to pressure signals from other locations along the bottom wall. These data are provided for high and low inlet turbulence intensity, respectively. In both figures, good qualitative and quantitative agreement is present in regard to coherence distributions for K1 to K2 and K2 to K3 transducers for most of the frequency range. Figure 7.7 shows that events between K1 and K3 are more highly correlated than the other two data sets for frequencies between 10 Hz and 200 Hz, and that coherence values between K2 and K3 are higher than values for K1 and K2 for frequencies between 10 Hz and 100 Hz. Within Figure 7.8, coherence distributions for K1 to K2, K1 to K3, and K2 to K3 transducers show qualitative and quantitative agreement for most all frequency values considered, with magnitude squared coherence values which generally decrease as frequency increases.
Figures 7.9 and 7.10 show time lag as a function of frequency for the signals from the Kulite pressure transducers at each location along the bottom wall of the test section relative to pressure signals from other locations along the bottom wall. These data are provided for high and low inlet turbulence intensity, respectively. Here, positive time lag values indicate that events at the second listed location occur first, and negative time lag values indicate that events at the first listed location occur first. In both figures, time lag values for the K2 to K3 data set remain closer to zero than the other two data sets for the entire frequency range. However, somewhat greater time lag values and variations are present for the K2 to K3 data set in Figure 7.9. Figure 7.9 also shows different quantitative variations of time lag values for the K1 to K2 and K1 to K3 data sets for frequencies less than 100 Hz. However, both data sets approach a time lag value near zero for frequencies greater than 100 Hz. Figure 7.10 shows good qualitative and quantitative agreement between the K1 to K2 and the K1 to K3 transducer data sets for the entire frequency range, with values approaching the vicinity of zero for frequencies above 100 Hz.

![Diagram of smoothed magnitude squared coherence](image)

**Figure 7.7** Smoothed magnitude squared coherence as a function of frequency for the signals from the Kulite pressure transducers relative to signals from other pressure transducers. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 7.8 Smoothed magnitude squared coherence as a function of frequency for the signals from the Kulite pressure transducers relative to signals from other pressure transducers. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.

Figure 7.9 Time lag as a function of frequency for the signals from the Kulite pressure transducers relative to signals from other pressure transducers. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 7.10 Time lag as a function of frequency for the signals from the Kulite pressure transducers relative to signals from other pressure transducers. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.
Chapter 8. Analysis of Unsteady Surface Temperature Data Measured Using Medtherm Thin Film Gauges

This chapter presents results which are determined from analysis of instantaneous surface temperature data measured using Medtherm thin film gauges. Comparisons and discussions of power spectral density, magnitude squared coherence, and time lag results for experimental arrangements associated with high inlet turbulence intensity and low inlet turbulence intensity are included. The coherence and time lag results are determined from data obtained for each thin film gauge relative to tracked flow event locations which are associated with the normal shock wave, other thin film gauges, and each Kulite pressure transducer.

8.1 Power Spectral Density Distributions

Figures 8.1 and 8.2 show power spectral density distributions for the signals from the three Medtherm thin film gauges mounted along the bottom wall of the test section for the high inlet turbulence intensity and low inlet turbulence intensity tests, respectively. All of these data are acquired using a 10 kHz sampling frequency. Within both figures, all data are in good quantitative and qualitative agreement for the entire frequency range. Data collected by the Medtherm thin film gauge upstream of the shock wave are labeled T1, data collected by the thin film gauge below the lambda foot are labeled T2, and data collected by the thin film gauge downstream of the shock wave are labeled T3. The peaks in Figure 8.1 at 60 Hz, and multiples of 60 Hz, are caused by interference of nearby wall power with the Medtherm thin film gauges. Electromagnetic shielding (EMI) is installed around the thin film gauge wires for the low turbulence intensity test and
removes the peaks at multiples of 60 Hz in Figure 8.2. All data in both figures are in qualitative and quantitative agreement, and show that PSD magnitudes associated with instantaneous surface static temperature variations generally decrease as frequency increases. Excluding peaks caused by wall power interference, PSD magnitudes for all of these arrangements are approximately constant for frequencies above 50 Hz.

![Figure 8.1](image)

**Figure 8.1** Power spectral density of signals from Medtherm thin film gauges for each location along the bottom wall of the test section as a function of frequency. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 8.2 Power spectral density of signals from Medtherm thin film gauges for each location along the bottom wall of the test section as a function of frequency. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.

8.2 Comparisons of Magnitude Squared Coherence and Time Lag Data Relative to the Normal Shock Wave

Figures 8.3 and 8.4 show smoothed magnitude squared coherence variations as a function of frequency for the signals from the Medtherm thin film gauges at each location along the bottom wall of the test section relative to normal shock wave location A. These data are provided for high inlet turbulence intensity and low inlet turbulence intensity, respectively. In Figures 8.3 and 8.4, all data show relatively good qualitative and quantitative agreement for the entire frequency range. T1 magnitude squared coherence values have the highest peaks near 11 Hz and 20 Hz for the data with high inlet turbulence intensity. Within Figure 8.4, a notable peak in T3 data is present near 10 Hz, and a notable peak in T2 data is present near 60 to 70 Hz. With the exception of numerous local maximum values, Figures 8.3 and 8.4 both show that magnitude squared coherence variations are approximately constant across the entire frequency range.

Figures 8.5 and 8.6 show time lag variations as a function of frequency for the signals from the Medtherm thin film gauges at each location along the bottom wall of the test section relative
to normal shock wave location A. These data are provided for high inlet turbulence intensity and low inlet turbulence intensity, respectively. Here positive time lag values indicate that events occur at normal shock wave location A first, and negative time lag values indicate that events occur at a particular Medtherm thin film gauge location first. Figure 8.5 shows that time lag values for T1 remain close to zero for the entire frequency range. Time lag data for T2 and T3 indicate that events occur along bottom wall Medtherm gage locations first for frequencies below 3 Hz. Above 3 Hz, time lag values for T2 and T3 are in the vicinity of zero. In Figure 8.6 for low inlet turbulence intensity, all three data sets indicate that events occur at the normal shock wave first for low frequencies and that time lag approaches zero as frequency increases. For the T1 gage, this transition to time lag values near zero occurs near a frequency of 100 Hz. Data for the T2 and T3 gages indicate that this transition occurs near a frequency of 10 Hz. Time lag values then remain in the vicinity of zero for frequencies above these transition points.

![Figure 8.3](image)

**Figure 8.3** Smoothed magnitude squared coherence as a function of frequency for the signals from the Medtherm thin film gauges for each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 8.4 Smoothed magnitude squared coherence as a function of frequency for the signals from the Medtherm thin film gauges for each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.

Figure 8.5 Time lag as a function of frequency for the signals from the Medtherm thin film gauges for each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 8.6 Time lag as a function of frequency for the signals from the Medtherm thin film gauges for each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.

8.3 Comparisons of Magnitude Squared Coherence and Time Lag Data for Each Thin Film Gauge Relative to the Other Thin Film Gauges

Figures 8.7 and 8.8 show smoothed magnitude squared coherence as a function of frequency for the signals from the Medtherm thin film gauges at each location along the bottom wall of the test section relative to temperature signals from other Medtherm gage locations along the bottom wall. These data are provided for high and low inlet turbulence intensity, respectively. In both figures, excellent qualitative and quantitative agreement is present regarding coherence distributions for T1 to T2 and T1 to T3 for the entire frequency range. Figure 8.7 shows that events between T2 and T3 are more highly correlated compared to correlation magnitudes for other two data sets, especially for frequencies between 1 Hz and 50 Hz. In Figure 8.8, all three coherence data sets show qualitative and quantitative agreement for most of the frequency range, except that correlation data between T2 and T3 show higher peaks for several frequencies below 100 Hz.

Figures 8.9 and 8.10 show time lag as a function of frequency for the signals from the Medtherm thin film gauges at each location along the bottom wall of the test section relative to
temperature signals from other Medtherm gage locations. These data are provided for high and low inlet turbulence intensity, respectively. Here, positive time lag values indicate that events at the second listed location occur first, and negative time lag values indicate that events at the first listed location occur first. In Figure 8.9, time lag values for the T1 to T3 data set remain closer to zero than the other two data sets for the entire frequency range. Time lag values for the T1 to T2 data set approach a value near zero at 10 Hz, and time lag values for the T2 to T3 data set approach a value near zero at 2 Hz. Figure 8.10 data for low inlet turbulence intensity show different trends and greater variations with frequency for all three data sets. Here, all three data sets show a time lag value near zero for frequencies of 500 Hz and greater. Below this frequency value, time lag distributions with frequency vary widely. However, above 50 Hz, the T1 to T2 and T1 to T3 data sets show good qualitative and quantitative agreement.

![Smoothed magnitude squared coherence](image)

**Figure 8.7** Smoothed magnitude squared coherence as a function of frequency for the signals from the Medtherm thin film gauges relative to signals from other Medtherm thin film gauges. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 8.8 Smoothed magnitude squared coherence as a function of frequency for the signals from the Medtherm thin film gauges relative to signals from other Medtherm thin film gauges. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.

Figure 8.9 Time lag as a function of frequency for the signals from the Medtherm thin film gauges relative to signals from other Medtherm thin film gauges. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 8.1 Time lag as a function of frequency for the signals from the Medtherm thin film gauges relative to signals from other Medtherm thin film gauges. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.

8.4 Comparisons of Magnitude Squared Coherence and Time Lag Data for Each Thin Film Gauge Relative to Instantaneous Static Pressure Data from the Kulite Pressure Transducer at Location 2

Figures 8.11 and 8.12 show smoothed magnitude squared coherence as a function of frequency for the signals from the Medtherm thin film gauges at each location along the bottom wall of the test section relative to the signal from the Kulite pressure transducer at location 2. These data are provided for high and low inlet turbulence intensity, respectively. Within Figure 8.11, all three data sets generally show good qualitative and quantitative agreement for the entire frequency range. The data sets corresponding to T2 and T3 have higher magnitude squared coherence peaks than the T1 data set below 10 Hz, but differences between the data sets above 10 Hz are minimal. Figure 8.12 shows a large peak in magnitude squared coherence for the T1 data set near a frequency of 10 Hz, with smaller peaks in the T2 and T3 data sets at the same frequency. Otherwise, the data within Figure 8.12 are in approximate agreement with the data in Figure 8.11. With the exceptions of numerous local maximum values, correlation data between the signals from the Medtherm thin
film gauges relative to the signal from the Kulite pressure transducer at location 2, have relatively low magnitudes for most of the frequency range.

Figures 8.13 and 8.14 show time lag as a function of frequency for the signals from the Medtherm thin film gauges at each location along the bottom wall of the test section relative to the signal from the Kulite pressure transducer at location 2. These data are provided for high and low inlet turbulence intensity, respectively. Here, positive time lag values indicate that Kulite measured pressure events at location 2 occur first, and negative time lag values indicate that temperature events at the listed location occur first. Figure 8.13 for high inlet turbulence intensity shows that time lag data for the T1, T2, and T3 gage signals have good qualitative and quantitative agreement for frequencies above about 3 Hz. Below this frequency value, the T1 and T3 data sets indicate that pressure events at location 2 occur first, and the T2 data set indicates that temperature events at the T2 gage location occur first. All three data sets approach a time lag value near zero for frequencies at and above 50 Hz. Figure 8.14 shows larger time lag value variations, compared to the data provided in Figure 8.13. Within Figure 8.14, all three data sets remain in the vicinity of a zero time lag value for frequencies above 50 Hz. Below 50 Hz, each data set shows a different trend with large variations as frequency increases.
Figure 8.11 Smoothed magnitude squared coherence as a function of frequency for the signals from the Medtherm thin film gauges for each location along the bottom wall of the test section relative to the signal from the Kulite pressure transducer at location 2 along the bottom wall of the test section. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.

Figure 8.12 Smoothed magnitude squared coherence as a function of frequency for the signals from the Medtherm thin film gauges for each location along the bottom wall of the test section relative to the signal from the Kulite pressure transducer at location 2 along the bottom wall of the test section. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.
Figure 8.13 Time lag as a function of frequency for the signals from the Medtherm thin film gauges for each location along the bottom wall of the test section relative to the signal from the Kulite pressure transducer at location 2 along the bottom wall of the test section. Data collected on December 8th, 2022, with high inlet turbulence intensity and a sampling frequency of 10 kHz.

Figure 8.14 Time lag as a function of frequency for the signals from the Medtherm thin film gauges for each location along the bottom wall of the test section relative to the signal from the Kulite pressure transducer at location 2 along the bottom wall of the test section. Data collected on July 31st, 2023, with low inlet turbulence intensity and a sampling frequency of 10 kHz.
Chapter 9. Analysis of Unsteady Surface Heat Flux Data Determined from Unsteady Surface Temperature Data

The present chapter provides results which are determined from analysis of instantaneous surface heat flux data measured using Medtherm thin film gauges. Instantaneous surface heat flux data are determined from instantaneous surface temperature data using the methods which are described in Chapter 3. Comparisons and discussions of power spectral density, magnitude squared coherence, and time lag results for experimental arrangements associated with high inlet turbulence intensity and low inlet turbulence intensity are presented. Coherence and time lag results are determined from instantaneous surface heat flux data obtained for each location along the bottom wall of the test section relative to tracked flow event locations which are associated with the normal shock wave, relative to instantaneous heat flux data at other locations along the bottom wall, relative to instantaneous surface temperature data from each Medtherm thin film gauge, and relative to instantaneous static pressure data from each Kulite pressure transducer.

9.1 Power Spectral Density Distributions

Figures 9.1 and 9.2 show power spectral density distributions for surface heat flux data for three locations along the bottom wall of the test section for the high inlet turbulence intensity and low inlet turbulence intensity arrangements, respectively. All of the data are acquired using a 10 kHz sampling frequency. Heat flux data associated with the location upstream of the shock wave are labeled Q1, heat flux data associated with the location below the lambda foot are labeled Q2, and heat flux data associated with the location downstream of the shock wave are labeled Q3.
Within both figures, all three data sets show good qualitative and quantitative agreement for the entire frequency range. The peaks in both figures at 60 Hz result from the electromagnetic interference from wall supplied power. For both high and low inlet turbulence intensity, the data show a decrease in the energy associated with heat flux variations as frequency increases from 1 Hz to 10 Hz, then a slight increase in energy as frequency increases for frequencies greater than 10 Hz.

**Figure 9.1** Power spectral density as a function of frequency for heat flux data at each location along the bottom wall of the test section. Data collected on December 8th, 2022, with high inlet turbulence intensity, and a sampling frequency of 10 kHz.
Figure 9.2 Power spectral density as a function of frequency for heat flux data at each location along the bottom wall of the test section. Data collected on July 31\textsuperscript{st}, 2023, with low inlet turbulence intensity, and a sampling frequency of 10 kHz.

9.2 Comparisons of Magnitude Squared Coherence and Time Lag Data for Heat Flux Data at Each Location Relative to Normal Shock Wave Location A

Figures 9.3 and 9.4 show smoothed magnitude squared coherence variations as a function of frequency for the heat flux data at each location along the bottom wall of the test section relative to normal shock wave location A. These data are provided for high inlet turbulence intensity and low inlet turbulence intensity, respectively. In Figure 9.3, all data from gages Q1, Q2, and Q3 show relatively good qualitative and quantitative agreement for the entire frequency range. Q1 magnitude squared coherence values have the highest peak at 11 Hz for the data with high inlet turbulence intensity. Within Figure 9.4, all three data sets generally show qualitative and quantitative agreement with each other, with the exception of a local peak in the Q3 data at 10 Hz and a local peak in the Q2 data at 80 Hz. With the exception of such local maximum values, Figures 9.3 and 9.4 show that magnitudes of squared coherence remain approximately constant across the entire frequency range, with local variations which are similar in character to instantaneous temperature magnitude squared coherence data shown in Figures 8.3 and 8.4.
Figures 9.5 and 9.6 show time lag variations as a function of frequency for the heat flux data at each location along the bottom wall of the test section relative to normal shock wave location A. These data are provided for high inlet turbulence intensity and low inlet turbulence intensity, respectively. Here positive time lag values indicate that events occur at normal shock wave location A first, and negative time lag values indicate that heat flux events occur at a particular Medtherm gage location along the bottom wall first. Figure 9.5 shows that time lag values for the Q1 and Q3 gage locations are in the vicinity of zero for the entire frequency range. Time lag data for the Q2 gage location indicates that events occur along the bottom wall first for frequencies below 3 Hz. Above 3 Hz, time lag values for the Q2 gage location also remain in the vicinity of zero. In Figure 9.6 for low inlet turbulence intensity, all three data sets indicate that events occur at the normal shock wave location A first for low frequencies less than about 4 Hz, and that time lag values approximately approach zero as frequency increases. For all three Q1, Q2, and Q3 gage locations, this transition to time lag values near zero occurs in the vicinity of 100 Hz. Data for the Q2 gage location generally remain positive for the remainder of the frequency range. Data for the Q3 gage location generally remain mostly negative for frequencies between 4 Hz and 100 Hz.
Figure 9.3 Smoothed magnitude squared coherence as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on December 8th, 2022, with high inlet turbulence intensity, and a sampling frequency of 10 kHz.

Figure 9.4 Smoothed magnitude squared coherence as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on July 31st, 2023, with low inlet turbulence intensity, and a sampling frequency of 10 kHz.
Figure 9.5 Time lag as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on December 8th, 2022, with high inlet turbulence intensity, and a sampling frequency of 10 kHz.

Figure 9.6 Time lag as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to location A on the normal shock wave. Data collected on July 31st, 2023, with low inlet turbulence intensity, and a sampling frequency of 10 kHz.

9.3 Comparisons of Magnitude Squared Coherence and Time Lag Data for Heat Flux Data at Each Location Relative to Heat Flux Data at Other Locations

Figures 9.7 and 9.8 show smoothed magnitude squared coherence as a function of frequency for the heat flux data at each location along the bottom wall of the test section relative
to heat flux data from other locations along the bottom wall. These data are provided for high and low inlet turbulence intensity, respectively. Figure 9.7 shows excellent qualitative and quantitative agreement between the coherence distributions for comparing Q1 to Q2 and Q1 to Q3 for the entire frequency range. For frequencies between 3 Hz and 40 Hz, events between Q2 and Q3 are more highly correlated than the other two data sets. Above 40 Hz, all three comparison data sets show good qualitative and quantitative agreement. Figure 9.8 for low inlet turbulence intensity shows that all three data sets have good qualitative and quantitative agreement for frequencies above 40 Hz. Below 40 Hz, the coherence distribution between Q2 to Q3 has higher peaks than the other two data sets.

Figures 9.9 and 9.10 show time lag as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to heat flux data from other locations along the bottom wall. These data are provided for high and low inlet turbulence intensity, respectively. Here, positive time lag values indicate that events at the second listed surface heat flux location occur first, and negative time lag values indicate that events at the first listed location occur first. In Figure 9.9, time lag values for the data set comparing Q1 to Q3 remain near zero for the entire frequency range. Time lag values for the data sets comparing Q1 to Q2 and Q2 to Q3 show different quantitative variations for frequencies below 30 Hz and remain near zero for frequencies above 30 Hz. Figure 9.10 shows more complex time lag variations for all three data sets. All three data sets approach a time lag value near zero for frequencies in the vicinity of and greater than 300 Hz. Below this value, time lag distributions vary widely between data sets. Above 50 Hz, the Q1 to Q2 and Q1 to Q3 data sets show good qualitative and quantitative agreement.
Figure 9.7 Smoothed magnitude squared coherence as a function of frequency for heat flux data relative to heat flux data at a different location along the bottom wall of the test section. Data collected on December 8th, 2022, with high inlet turbulence intensity, and a sampling frequency of 10 kHz.

Figure 9.8 Smoothed magnitude squared coherence as a function of frequency for heat flux data relative to heat flux data at a different location along the bottom wall of the test section. Data collected on July 31st, 2023, with low inlet turbulence intensity, and a sampling frequency of 10 kHz.
Figure 9.9 Time lag as a function of frequency for heat flux data relative to heat flux data at a different location along the bottom wall of the test section. Data collected on December 8th, 2022, with high inlet turbulence intensity, and a sampling frequency of 10 kHz.

Figure 9.10 Time lag as a function of frequency for heat flux data relative to heat flux data at a different location along the bottom wall of the test section. Data collected on July 31st, 2023, with low inlet turbulence intensity, and a sampling frequency of 10 kHz.
9.4 Comparisons of Magnitude Squared Coherence and Time Lag Data for Heat Flux Data at Each Location Relative to Instantaneous Surface Temperature Data from the Medtherm Thin Film Gauge at Location 1

Figures 9.11 and 9.12 show smoothed magnitude squared coherence as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous surface temperature data from the Medtherm thin film gauge at location 1 along the bottom wall. These data are provided for high and low inlet turbulence intensity, respectively. Both figures show coherence values near 1.0 for the Q1 distribution across the entire frequency range. Additionally, the coherence distributions corresponding to Q2 and Q3 show good qualitative and quantitative agreement for the entire frequency range. Within Figure 9.11, the Q2 and Q3 distributions show a maximum value near 1 Hz, then remain relatively low for the rest of the frequency range. Figure 9.12 shows high coherence values for the Q2 and Q3 distributions near 1 Hz, relatively lower coherence values for frequencies between 1 Hz and 10 Hz, and a gradual increase of magnitude coherence values as frequency increases further.

Figures 9.13 and 9.14 show time lag as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous surface temperature data from the Medtherm thin film gauge at location 1 along the bottom wall. These data are provided for high and low inlet turbulence intensity, respectively. Here, positive time lag values indicate that instantaneous temperature events at location 1 occur first, and negative time lag values indicate that heat flux events at the listed location occur first. Within Figures 9.13 and 9.14, Q1 time lag data values are generally near zero, with small deviations from this value for frequencies less than about 3 to 4 Hz. Within Figure 9.13, the Q2 and Q3 time lag distributions show qualitative and quantitative agreement for the entire frequency range, with negative values at frequencies less than about 2 Hz, and near-zero values at higher frequencies. Figure 9.14 shows that Q2 and Q3
distributions have much larger positive time lag values than the Q1 distribution for frequencies between 3 Hz and 100 Hz. Above 100 Hz, the Q2 and Q3 time lag distributions within this figure approach zero.

**Figure 9.11** Smoothed magnitude squared coherence as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous surface temperature data from the Medtherm thin film gauge at location 1 along the bottom wall of the test section. Data collected on December 8th, 2022, with high inlet turbulence intensity, and a sampling frequency of 10 kHz.

**Figure 9.12** Smoothed magnitude squared coherence as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous surface temperature data from the Medtherm thin film gauge at location 1 along the bottom wall of the test section. Data collected on July 31st, 2023, with low inlet turbulence intensity, and a sampling frequency of 10 kHz.
Figure 9.13 Time lag as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous surface temperature data from the Medtherm thin film gauge at location 1 along the bottom wall of the test section. Data collected on December 8th, 2022, with high inlet turbulence intensity, and a sampling frequency of 10 kHz.

Figure 9.14 Time lag as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous surface temperature data from the Medtherm thin film gauge at location 1 along the bottom wall of the test section. Data collected on July 31st, 2023, with low inlet turbulence intensity, and a sampling frequency of 10 kHz.
9.5 Comparisons of Magnitude Squared Coherence and Time Lag Data for Heat Flux Data at Each Location Relative to Instantaneous Static Pressure Data from the Kulite Pressure Transducer at Location 1

Figures 9.15 and 9.16 show smoothed magnitude squared coherence as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous static pressure data from the Kulite pressure transducer at location 1 along the bottom wall. These data are provided for high and low inlet turbulence intensity, respectively. Within Figure 9.15, the data set correlating Q3 to K1 has two peaks which are higher in magnitude relative to other data. One of these peaks is located near to 2 Hz and another is near to 11 Hz. Aside from these peaks, all three data sets generally show good qualitative and quantitative agreement. Figure 9.16 shows that all three data sets have relatively higher magnitude squared coherence values for frequencies below about 50 Hz. Within this region, the data set associated with Q1 has the highest peak at 10 Hz. Similar to the high inlet turbulence intensity data, Figure 9.16 shows that all three data sets generally show good qualitative and quantitative agreement for frequencies above 50 Hz.

Figures 9.17 and 9.18 show time lag as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous static pressure data from the Kulite pressure transducer at location 1 along the bottom wall. These data are provided for high and low inlet turbulence intensity, respectively. Here, positive time lag values indicate that pressure events at Kulite pressure transducer location 1 occur first, and negative time lag values indicate that heat flux events at the listed location occur first. Within Figure 9.17, time lag values corresponding to Q3 remain near zero for the entire frequency range. The other two data sets have different quantitative distributions below 3 Hz, with time lag values that remain near zero for frequencies above 3 Hz. Figure 9.18 shows that all three data sets have good qualitative and
quantitative agreement for the entire frequency range, and approach time lag values near zero for frequencies above 30 Hz.

Figure 9.15 Smoothed magnitude squared coherence as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous static pressure data from the Kulite pressure transducer at location 1 along the bottom wall of the test section. Data collected on December 8th, 2022, with high inlet turbulence intensity, and a sampling frequency of 10 kHz.
Figure 9.16 Smoothed magnitude squared coherence as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous static pressure data from the Kulite pressure transducer at location 1 along the bottom wall of the test section. Data collected on July 31st, 2023, with low inlet turbulence intensity, and a sampling frequency of 10 kHz.

Figure 9.17 Time lag as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous static pressure data from the Kulite pressure transducer at location 1 along the bottom wall of the test section. Data collected on December 8th, 2022, with high inlet turbulence intensity, and a sampling frequency of 10 kHz.
Figure 9.18 Time lag as a function of frequency for heat flux data at each location along the bottom wall of the test section relative to instantaneous static pressure data from the Kulite pressure transducer at location 1 along the bottom wall of the test section. Data collected on July 31st, 2023, with low inlet turbulence intensity, and a sampling frequency of 10 kHz.
Chapter 10. Summary and Conclusions

Shock wave interactions are important for a variety of engineering applications, ranging from gas turbines and rocket nozzles to high-speed aircraft. There is much discussion regarding the physics of phenomena related to these interactions and the source of unsteadiness in regard to unsteady shock wave structure. Ideas which are proposed for the source of the low frequency unsteadiness of a normal shock wave include nearby shock waves, turbulence within the approaching flow, upstream flow behavior, downstream flow behavior, and events within and near to the separation region. The present thesis investigates related interactions through spectral analysis of shock wave tracked position and correlations between tracked shock wave position and instantaneous surface static pressure, instantaneous surface temperature, and instantaneous surface heat flux.

Within the present investigation, a Phantom V711 camera and optical apparatus components are used to obtain digitized versions of time-varying instantaneous shadowgraph flow visualizations in order to undertake shock wave tracking analysis. This is accomplished using a supersonic test section with an inlet freestream Mach number of approximately 1.54. Three Kulite pressure transducers and three Medtherm thin film gauges are installed in the bottom wall of this test section for measuring unsteady surface static pressure variations and unsteady surface temperature variations, respectively. Time-varying temperature measurements from these sensors (along with other information) are used to determine time-varying surface heat flux variations using an impulse response filter.
MATLAB versions 2022b and 2023a are used to determine and track the dimensional position of a shock wave from the digitized time sequence of shadowgraph images. After the time variation of shock wave position is determined, the resulting time sequence array is filtered with a low-pass filter at 90 percent of the Nyquist folding frequency before being converted to the frequency domain using Welch’s method (Solomon, 1991). Time-varying surface temperature data are additionally high-pass filtered at a cut-off frequency of 1.5 Hz. Unsteady pressure and heat flux data are then determined without additional digital filtering. After acquiring the power spectral density for all types of data, correlation analysis is then performed between pairs of signals and includes the magnitude squared coherence and time lag between the two signals. The associated data, which are processed using these components and procedures, are initially acquired using several National Instruments data acquisition cards and devices.

Digitized and time-varying shadowgraph flow visualization data are analyzed to determine tracked flow locations which are associated with the normal shock wave and the downstream shock wave leg of the lambda foot. The resulting time-varying shock wave position data are converted into the frequency domain as power spectral density (PSD) distributions to give energy variations as a function of frequency. Overall, complex physical variations are present as frequency, inlet turbulence intensity level, and location relative to shock wave structure are altered. With high inlet turbulent intensity (HT), higher PSD magnitudes across the entire frequency range indicate that more energy is generally associated with location A on the normal shock wave than with locations E and G on the rear shock wave leg of the lambda foot. With low inlet turbulence intensity (LT), PSD magnitudes for shock wave variations for all three locations are much closer to each other, and the data show good qualitative agreement. This indicates that similar amounts of energy are associated with tracked shock wave positions for locations A, E, and G for all
frequencies. PSD data for location A on the normal shock wave with low inlet turbulence intensity data (LT) and PSD data from Marko (2018) are generally in good qualitative and quantitative agreement for the entire frequency range which is considered. LT and HT magnitude squared coherence distributions for location A on the normal shock wave, relative to locations E and G on the rear shock wave leg of the lambda foot, are also generally in good quantitative and qualitative agreement for most considered frequencies. Qualitative conclusions are similar in relation to locations A, E, and G, when associated time lag variations are considered for the same data sets.

Results from analysis of instantaneous surface static pressure data measured using Kulite pressure transducers are presented in the form of power spectral density, magnitude squared coherence, and time lag data. Data show complex physical variations as the frequency, inlet turbulence intensity, and Kulite pressure transducer locations relative to the shock wave structure are altered. PSD data from the Kulite pressure transducers below the separation region (K2) and downstream of the shock wave (K3) are generally in good quantitative and qualitative agreement for the entire frequency range. Relatively higher PSD magnitudes are present for data from the Kulite pressure transducer upstream of the shock wave (K1), especially for lower frequencies. The K2 and K3 magnitude squared coherence and time lag values are generally in good quantitative and qualitative agreement for most frequency values when comparing each pressure signal to variations in normal shock wave tracked position associated with location A.

Results from analysis of instantaneous surface temperature data, which are measured using the three Medtherm thin film gauges mounted along the bottom wall of the test section, also provide evidence of complex physical processes. Observed trends indicate that these temperature data change as inlet turbulence intensity, frequency, and location relative to the shock wave structure are altered. PSD data for temperature variations upstream of the shock wave structure
(T1), below the separation region (T2), and downstream of the shock wave structure (T3) are generally in qualitative and quantitative agreement, and show that PSD magnitudes associated with instantaneous surface static temperature variations generally decrease as frequency increases. Temperature data for sensors T1, T2, and T3 additionally show relatively good qualitative and quantitative agreement for the entire frequency range for magnitude squared coherence relative to location A on the normal shock wave. Associated time lag values for all three comparisons approach zero as frequency increases. Instantaneous surface heat flux data also show complex physical variations that change with inlet turbulence intensity, frequency, and location relative to the shock wave structure. Surface heat flux data are determined from the temperature data, and PSD data for heat flux upstream of the shock wave (Q1), below the separation region (Q2), and downstream of the shock wave (Q3) show good qualitative and quantitative agreement for the entire frequency range that is considered. Magnitude squared coherence data which compare Q1, Q2, and Q3 heat flux data to normal shock wave tracked position for location A are relatively constant across the entire frequency range (with the exception of numerous local maxima), with frequency variations that are similar to corresponding instantaneous temperature data.

Data for high and low inlet turbulence intensity values are compared for results acquired with different data sampling frequencies. Data acquired at 6.25 kHz, 10 kHz, 12.5 kHz, and 25 kHz are compared to obtain a physically realistic assessment of how the data vary with frequency. Differences between high inlet turbulence intensity results related to normal shock wave position at different sampling frequencies are minimal for frequencies less than 500 Hz. For frequencies above 500 Hz, PSD values for data sampled at 10 kHz are often larger than results associated with the other acquisition rates. Differences between low inlet turbulence intensity results related to normal shock wave position at different sampling frequencies are minimal for all frequencies
considered. Smoothed magnitude squared coherence and time lag data acquired using sampling frequencies of 10 kHz and 25 kHz for both inlet turbulence intensities generally show quantitative and qualitative similarity for most frequencies. Data which are acquired with an acquisition frequency of 6.25 kHz show significant differences relative to these data sets. In view of these data trends and considerations, the data presented within Chapters 6, 7, 8, and 9 of the present thesis are acquired with an acquisition frequency of 10 kHz.

Results presented in this thesis will be further investigated by examining the physical processes resulting in the observed spectra, correlations, and time lag variations. This includes interpretations of the effects of low and high inlet turbulence intensity on shock wave structural characteristics. Altering the test section geometry by adjusting the position of the shock wave holding plate or choking flap will also provide a different shock wave structure for investigation.
References


McClure, W. B., 1992 An Experimental Study of the Driving Mechanism and Control of the Unsteady Shock Induced Turbulent Separation in a Mach 5 Compression Corner Flow. University of Texas at Austin, PhD Dissertation.


## Appendix A. Data File Directory

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PDF document with all graphs related to pressure data during the low turbulence test (all three sampling frequencies). This includes Figures 14, 15, and 16.

Excel spreadsheet with all data and graphs for pressure correlations during the low turbulence test (all three sampling frequencies). This includes Figures 14, 15, and 16.

Word document with a table comparing mean squared values for all collected data at each sampling frequency. Tables 8 and 9

Excel spreadsheet with a table comparing mean squared values for all collected data at each sampling frequency, and graphs of key comparisons. Figures 17a, 17b, and 17c

File Folder

Word document with all graphs related to pressure data during the high turbulence test (all three sampling frequencies). This includes Figures 18, 19, 21, and 22.

PDF document with all graphs related to pressure data during the high turbulence test (all three sampling frequencies). This includes Figures 18, 19, 21, and 22.

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Excel spreadsheet with all data and graphs for heat flux correlations during the high turbulence test (all three sampling frequencies). This includes Figures 65, 67, 69, 71, 73, 75, 77, 79, and 81.

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V.3 Low-Turbulence Heat Flux Analysis 2023-11-01.pdf

PDF document with all graphs related to heat flux data during the low turbulence test (all three sampling frequencies). This includes Figures 66, 68, 70, 72, 74, 76, 78, 80, and 82.

V.3 LT Heat Flux Correlations 2023-11-01.xlsx

Excel spreadsheet with all data and graphs for heat flux correlations during the low turbulence test (all three sampling frequencies). This includes Figures 66, 68, 70, 72, 74, 76, 78, 80, and 82.

Raw Data Files

File Folder

Archive

File Folder

HT_A_1830.m

MATLAB data file of tracked location A at each time step for data collected at 25 kHz during the high turbulence test

HT_A_1900.m

MATLAB data file of tracked location A at each time step for data collected at 10 kHz during the high turbulence test

HT_A_1930.m

MATLAB data file of tracked location A at each time step for data collected at 6.25 kHz during the high turbulence test

HT_E_1900.m

MATLAB data file of tracked location E at each time step for data collected at 10 kHz during the high turbulence test

HT_G_1900.m

MATLAB data file of tracked location G at each time step for data collected at 10 kHz during the high turbulence test

LT_A_1735.m

MATLAB data file of tracked location A at each time step for data collected at 10 kHz during the low turbulence test

LT_A_1750.m

MATLAB data file of tracked location A at each time step for data collected at 10 kHz during the low turbulence test

LT_A_1800.m

MATLAB data file of tracked location A at each time step for data collected at 12.5 kHz during the low turbulence test
LT_A_1820.m MATLAB data file of tracked location A at each time step for data collected at 6.25 kHz during the low turbulence test

LT_E_1750.m MATLAB data file of tracked location E at each time step for data collected at 10 kHz during the low turbulence test

LT_G_1750.m MATLAB data file of tracked location G at each time step for data collected at 10 kHz during the low turbulence test

Marko_A.m MATLAB data file of tracked location A from data collected by Marko (2018)

Marko_E.m MATLAB data file of tracked location E from data collected by Marko (2018)

Marko_G.m MATLAB data file of tracked location G from data collected by Marko (2018)

2022-12-08 Test File folder containing raw data (.m files) for the signals at each location along the bottom wall during the high turbulence test

2022-07-31 Test File folder containing raw data (.m files) for the signals at each location along the bottom wall during the low turbulence test

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2022-12-08-1830_Q.xlsx Excel spreadsheet containing time history and PSD data for unsteady heat flux signals collected at 25 kHz during the high turbulence test

2022-12-08-1830_RAW_DATA.xlsx Excel spreadsheet containing raw pressure and temperature data collected at 25 kHz during the high turbulence test

2022-12-08-1830_TEMP_FILTERED.xlsx Excel spreadsheet containing raw pressure and filtered temperature data collected at 25 kHz during the high turbulence test
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2022-12-08-1930_FINAL_PSD.xlsx  Excel spreadsheet containing PSD data for unsteady pressure and temperature signals collected at 6.25 kHz during the high turbulence test

2022-12-08-1930_Q.xlsx  Excel spreadsheet containing time history and PSD data for unsteady heat flux signals collected at 6.25 kHz during the high turbulence test

2022-12-08-1930_RAW_DATA.xlsx  Excel spreadsheet containing raw pressure and temperature data collected at 6.25 kHz during the high turbulence test

2022-12-08-1930_TEMP_FILTERED.xlsx  Excel spreadsheet containing raw pressure and filtered temperature data collected at 6.25 kHz during the high turbulence test

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### Shadowgraph Images

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<td>File folder containing shadowgraph images from Marko (2018)</td>
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<td>PNG image showing pixels of interest for the high turbulence test sampled at 10 kHz</td>
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<td><strong>LT Tracked Locations.png</strong></td>
<td>PNG image showing pixels of interest for the low turbulence test sampled at 10 kHz</td>
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<td><strong>Marko Tracked Locations.png</strong></td>
<td>PNG image showing pixels of interest for the data from Marko (2018)</td>
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<td>Powerpoint presentation with the above images labeled</td>
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<td>Excel spreadsheet containing time-history and PSD data for the tracked position of the shockwave at location A during the high turbulence test sampled at 10 kHz</td>
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<td>Excel spreadsheet containing time-history and PSD data for the tracked position of the shockwave at location E during the high turbulence test sampled at 10 kHz</td>
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<td>Shock Wave Positions 2023-07-31.xlsx</td>
<td>Excel spreadsheet comparing shock wave position from the low turbulence test</td>
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123
Marko_A.xlsx
Excel spreadsheet containing time-history and PSD data for the tracked position of the shockwave at location A for data collected by Marko (2018)

Marko_E.xlsx
Excel spreadsheet containing time-history and PSD data for the tracked position of the shockwave at location E for data collected by Marko (2018)

Marko_G.xlsx
Excel spreadsheet containing time-history and PSD data for the tracked position of the shockwave at location G for data collected by Marko (2018)

Testing Data 2023-07-18
File Folder (raw data from tests on 2023-07-18)

Testing Data 2023-07-31
File Folder (raw data from tests on 2023-07-31)

Video
File Folder

2023_07_31_1750.mp4
Slowed down video of shock wave position from the low turbulence test with a sampling frequency of 10 kHz

2023_07_31_1750_realtime.mp4
Realtime video of shock wave position from the low turbulence test with a sampling frequency of 10 kHz
# Appendix B. Software Directory

## MATLAB 2022a – 2023a

<table>
<thead>
<tr>
<th>File Name</th>
<th>Description</th>
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<tbody>
<tr>
<td>ShockWave_Tracking.m</td>
<td>Determines streamwise shock wave locations</td>
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<tr>
<td>PSD_Sensor_Analysis.m</td>
<td>Convert sensor time history values into PSD data</td>
</tr>
<tr>
<td>smoothPSD.m</td>
<td>Smooth PSD curves using a running average</td>
</tr>
<tr>
<td>Correlation_Two_Point_Analysis.m</td>
<td>Compute magnitude squared coherence and time lag for two signals</td>
</tr>
<tr>
<td>desT2qsiimp1.m</td>
<td>Digital impulse response filtering function from Oldfield (2008)</td>
</tr>
<tr>
<td>Temp_to_Heat_Flux.m</td>
<td>Convert temperature data to heat flux data</td>
</tr>
</tbody>
</table>

## LabVIEW

- Phantom Control Camera Applications: Acquire and save shadowgraph data
- Microsoft Excel: Process data and create graphs
- Microsoft Powerpoint: Create, modify, and annotate figures
- Microsoft Paint: Take measurements from pixels
- Microsoft Word
- Draw.io: Schematic diagram of NI acquisition system and shadowgraph system

## Other Tools
- Snipping Tool
- Google Chrome
## Appendix C. Thesis Figures Directory

<table>
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<tr>
<th>Folder</th>
<th>Description</th>
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<td>Calibration Certificate for Kulite Pressure Transducer 1. Figure D1</td>
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<td>K2 Calibration Certificate (Fig D2).jpg</td>
<td>Calibration Certificate for Kulite Pressure Transducer 2. Figure D2</td>
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<tr>
<td>K3 Calibration Certificate (Fig D3).jpg</td>
<td>Calibration Certificate for Kulite Pressure Transducer 3. Figure D3</td>
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<td><strong>Chapter 1 Figures</strong></td>
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<td>Normal Shock Wave Schematic (Fig 1).jpg</td>
<td>Schematic of normal shock wave structure from Babinsky and Harvey (2011). Figure 1</td>
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<td>Static Pressure Variations (Fig 2).jpg</td>
<td>Static pressure variations across the normal shock wave structure from Babinsky and Harvey (2011). Figure 2</td>
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<td>JPG file for block diagram of DAQ system. Figure 9</td>
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<td>DAQ Block Diagram.drawio</td>
<td>Source file for block diagram of DAQ system. Figure 9</td>
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<td>JPG file for image of a Kulite pressure transducer (from Kulite, 2023). Figure 7</td>
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<td>Kulite Pressure Transducer Locations (Fig 8).jpg</td>
<td>JPG file showing drawing of Kulite pressure transducer locations. Figure 8</td>
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<td>Pressure Tap Locations (Fig 6).jpg</td>
<td>JPG file showing drawing of pressure tap locations. Figure 9</td>
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<td>JPG file showing picture of the shadowgraph flow visualization system in the laboratory. Figure 5</td>
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<td>Shadowgraph System Schematic (Fig 4).png</td>
<td>PNG file for schematic of the shadowgraph system. Figure 4</td>
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Shadowgraph System Schematic.drawio
Source file for schematic of the shadowgraph system. Figure 4

Surface Measurement Locations (Fig 3).jpg
JPG file showing labeled test section and surface measurement locations. Figure 3

Chapter 3 Figures
File Folder

Medtherm Thin Film Gauge Drawing (Fig 11).jpg
JPG file showing drawing of the Medtherm thin film gauge. Figure 11

V.FINAL Tracked Location Schematic 2023-12-17.pptx
Labeled shadowgraph images denoting shock wave tracking locations and surface measurement locations. Figure 10

Chapter 4 Figures
File Folder

2023_07_31_1750_A.xlsx
Excel spreadsheet containing time-history and PSD data for the tracked position of the shockwave at location A during the low turbulence test sampled at 10 kHz. Figure 13

V.FINAL Tracked Location Schematic 2023-12-17.pptx
Labeled shadowgraph images denoting shock wave tracking locations and surface measurement locations. Figure 12

V.2 Low-Turbulence Pressure Analysis 2023-10-11.docx
Word document with all graphs related to pressure data during the low turbulence test (all three sampling frequencies). This includes Figures 14, 15, and 16.

V.2 Low-Turbulence Pressure Analysis 2023-10-11.pdf
PDF document with all graphs related to pressure data during the low turbulence test (all three sampling frequencies). This includes Figures 14, 15, and 16.

V.2 LT Kulite Correlations 2023-10-11.xlsx
Excel spreadsheet with all data and graphs for pressure correlations during the low turbulence test (all three sampling frequencies). This includes Figures 14, 15, and 16.

V.FINAL Mean Squared Values 2023-12-02.docx
Word document with a table comparing mean squared values for all collected data at each sampling frequency. Tables 8 and 9
Excel spreadsheet with a table comparing mean squared values for all collected data at each sampling frequency, and graphs of key comparisons. Figures 17a, 17b, and 17c

Chapter 5 Figures

Word document with all graphs related to pressure data during the high turbulence test (all three sampling frequencies). This includes Figures 18, 19, 21, and 22.

PDF document with all graphs related to pressure data during the high turbulence test (all three sampling frequencies). This includes Figures 18, 19, 21, and 22.

Word document with all graphs related to temperature data during the high turbulence test (all three sampling frequencies). This includes Figure 20.

PDF document with all graphs related to temperature data during the high turbulence test (all three sampling frequencies). This includes Figure 20.

Excel spreadsheet with all data and graphs for pressure correlations during the high turbulence test (all three sampling frequencies). This includes Figures 18, 19, 21, and 22.

Excel spreadsheet with all data and graphs for temperature correlations during the high turbulence test (all three sampling frequencies). This includes Figures 18, 19, 21, and 22.

Word document with all graphs related to pressure data during the low turbulence test (all three sampling frequencies). This includes Figures 23, 24, 26, and 27.

PDF document with all graphs related to pressure data during the low turbulence test (all three sampling frequencies). This includes Figures 23, 24, 26, and 27.
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<td>Labeled shadowgraph images denoting shock wave tracking locations and surface measurement locations. Figures 28 through 30</td>
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<td>V.FINAL Chapter 6 Figures 2023-11-26.xlsx</td>
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Appendix D. Kulite Pressure Transducer Calibration Certificates

Figure D.1 Kulite pressure transducer 1 calibration certificate.
Figure D.2 Kulite pressure transducer 2 calibration certificate.
Figure D.3 Kulite pressure transducer 3 calibration certificate.