Measurement of Flow Perturbation Spectra in a Mach 4.5 Corner Separation Zone

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The characterization of the M=4.5 flow over a flat plate model with a 30° compression ramp was performed with low enthalpy (T\textsubscript{0}=300K) and high enthalpy (T\textsubscript{0}=800-1250K) flow conditions for a wide range of Reynolds numbers (Re=5\cdot10^4-2\cdot10^6). Three measurement techniques were employed to measure the frequency spectrum of flow perturbations: a high frequency Shack-Hartmann wavefront sensor (aero-optical method), high frequency PCB\textsuperscript{TM} pressure sensors, and a laser differential interferometer. The magnitude and frequency of flow oscillations measured by all three methods provide comprehensive and complementary results in determining dominant frequencies within the flow. Of these measurement methods, Shack-Hartmann is shown to be the most useful tool for analysis of the high-speed flow. Aero-optical measurements detect modification to the flow structure when plasma actuation is employed or when the Re number is varied. Under the conditions of this work, characterization by the Shack-Hartmann sensor at individual points in the flow has shown three flow regimes depending on the Reynolds number: turbulent, transitional, and laminar. At higher Re number, the freestream disturbances become strong enough to significantly affect the perturbations in the boundary layer and separation zone of the compression ramp. The pressure frequency spectrum measurements during high-frequency plasma actuation (100 kHz) indicate amplification of the perturbations from the natural state that occur over the separation region of the compression ramp.

\textbf{Nomenclature}

\begin{itemize}
\item \(a\) = speed of sound (m/s)
\end{itemize}

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**I. Introduction**

Methods of supersonic and hypersonic boundary layer flow control by electrical discharges have previously been studied extensively [1-4], showing a plausible controlling effect due to a non-uniform localized heating of the near surface gas layer. Specifically of interest to this study is the effect of a pulsed plasma actuator on the downstream flow oscillations along a flat plate leading up to a compression ramp with a separation zone in hypersonic flow. Preliminary
studies have characterized the oscillatory flow structure leading up to and within the corner separation zone [4-6]. The boundary layer over flat plate compression ramp geometries is of interest for its role in scramjet inlets for effective flow conditioning prior to combustion. A number of publications have shown that the generation of streamwise vorticity within the flow leads to an accelerated transition of the boundary layer to a turbulent state [7-9], which is desirable for both reduction of the boundary layer separation and fuel mixing further downstream. The result of reduced flow separation during turbulent state supersonic boundary layer interaction with a compression ramp has been analyzed previously in [10]. It was also shown in [5] that the shallow cavity discharge is a suitable method for the generation of high frequency fluctuations in the flow, when operated at repetition frequencies greater than those of naturally occurring perturbations in the flow field.

The flow field characteristics over supersonic and hypersonic compression ramps have been discussed in many studies [11-15] involving the evolution of boundary layer perturbations over a flat plate. The presence of the first mode of instabilities (Tollmien-Schlichting) and in this case especially, second mode instabilities (of acoustic nature) are known to be dominant and grow in the hypersonic boundary layer along a flat plate leading up to the corner separation zone [16]. Within the separation zone, dynamics of the instabilities are quite complex, but their growth is known to be neutral with amplification of only discrete acoustic modes [12]. At spanwise lines near the separation and reattachment, the power spectra show the largest energy levels, exhibited as growths in unsteady fluctuations [17].

An important feature of the current work is that it examines the flow conditions with a relatively high level of initial perturbations in the core flow, which are typical for most wind tunnel tests and can simulate a flow environment such as operation in the wake of another vehicle or air with high levels of dust. Characterization of such flows is challenging, the numerical simulation is difficult, and the resulting flow structure is not obvious [18, 19].

Measurements of the flow structure, with primary interest on the oscillations occurring in the separation zone, are performed by three diagnostic tools in this study:

1. A Shack-Hartmann wavefront sensor is used to determine a spatial distribution of spectra of flow density oscillations in the flow field near a corner separation zone. The feasibility of using the Shack-Hartmann sensor for measurement of flow density oscillations was experimentally proven in [20]. Wavefront sensing is demonstrated to be a proper candidate for non-intrusive high frequency aero-optic measurements in hypersonic conditions due to the expectation of spanwise uniformity over the flat plate and the sensor’s sensitivity to gas density gradients. In addition,
the wavefront sensor is capable of providing high spatial resolution and up to 1 MHz frequency response, limited only by the imaging camera’s technical capability.

2. The measurement of high frequency pressure perturbations by means of surface mounted pressure sensors, which is routinely used in many experimental studies [21-23]. Using 1 MHz response PCB™ sensors, pressure perturbations along the surface of a model in a hypersonic boundary layer can be detected and analyzed in the frequency domain.

3. Laser differential interferometry (LDI) has been proven to be an effective tool in measuring high-frequency density fluctuations of supersonic and hypersonic flows [24-27]. LDI functions by measuring the phase difference between two beams which are orthogonally polarized. Given that everything in the setup of the LDI remains constant except for the flow, fluctuations in the optical path difference can be directly related to fluctuations in flow density. LDI systems can measure frequencies of flow perturbations over 1 MHz and optical path differences on the order of 10 nm and below depending on the set up. This makes it a suitable tool for spectral analysis of low density, high-speed flows where the oscillation frequencies can extend into the hundreds of kHz.

II. Experimental Methods

A. Test Arrangement

Tests were conducted in the hypersonic wind tunnel ACT-1 at the University of Notre Dame [28]. Different nozzle arrangements allow for testing at Mach 4.5, 6, and 9. This test was focused on M=4.5 conditions. The ACT-1 facility utilizes a DC arc heater to generate high enthalpy flow, simulating conditions experienced in low density hypersonic flight. In this test series, stagnation temperatures ranged from \( T_0 = 800\text{-}1250 \text{ K} \) (high enthalpy) or \( T_0 = 300 \text{ K} \) (low enthalpy). Other relevant test conditions include unit Reynolds Number \( Re_L = 4\cdot10^5\text{-}3\cdot10^7 \text{ m}^{-1} \) (low enthalpy) or \( Re_L \approx 4\cdot10^5\text{-}2.5\cdot10^6 \text{ m}^{-1} \) (high enthalpy), and stagnation pressure \( 0.8 \text{ bar} < P_0 < 5.5 \text{ bar} \). The composition of the gas mixture (typically nitrogen and oxygen) is controlled through variation of pressures and injection port arrangement. Other flow characteristics for varying stagnation pressures are shown in Table 2.1, with flow velocities determined by direct measurements taken by a Shack-Hartmann wavefront sensor [6], Reynolds number is calculated based on the model length from the leading edge to the ramp.
Table 2.1 Flow characteristics for cold and heated flow in ACT-1

<table>
<thead>
<tr>
<th>Low Enthalpy</th>
<th>At Nozzle Exit</th>
<th>High Enthalpy</th>
<th>At Nozzle Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$ (bar)</td>
<td>$\dot{m}$ (kg/s)</td>
<td>$T_0$ (K)</td>
<td>$T$ (K)</td>
</tr>
<tr>
<td>0.9</td>
<td>0.028</td>
<td>293</td>
<td>58</td>
</tr>
<tr>
<td>1.5</td>
<td>0.037</td>
<td>293</td>
<td>58</td>
</tr>
<tr>
<td>1.9</td>
<td>0.048</td>
<td>293</td>
<td>58</td>
</tr>
<tr>
<td>2.5</td>
<td>0.060</td>
<td>293</td>
<td>58</td>
</tr>
<tr>
<td>3.2</td>
<td>0.078</td>
<td>293</td>
<td>58</td>
</tr>
<tr>
<td>4</td>
<td>0.096</td>
<td>293</td>
<td>58</td>
</tr>
<tr>
<td>5.5</td>
<td>0.134</td>
<td>293</td>
<td>58</td>
</tr>
<tr>
<td>$P_0$ (bar)</td>
<td>$\dot{m}$ (kg/s)</td>
<td>$T_0$ (K)</td>
<td>$T$ (K)</td>
</tr>
<tr>
<td>1.5</td>
<td>0.020</td>
<td>1238</td>
<td>245</td>
</tr>
<tr>
<td>2.25</td>
<td>0.032</td>
<td>906</td>
<td>179</td>
</tr>
<tr>
<td>3</td>
<td>0.043</td>
<td>880</td>
<td>174</td>
</tr>
<tr>
<td>3.25</td>
<td>0.049</td>
<td>835</td>
<td>165</td>
</tr>
</tbody>
</table>

Figure 2.1 presents the layout of the test setup. The experimental configuration for testing includes a compression ramp model mounted in the test section of ACT-1 (see Fig. 2.2). The experimental model consists of a flat plate with a sharp leading edge and lower surface at a fixed angle $\alpha = 15^\circ$. The second wedge is interchangeable and is mounted on top of the flat plate to form the compression ramp at angle $\beta = 30^\circ$ in these test series. In total, the model measures: length $L = 229 \text{ mm}$, width $W = 102 \text{ mm}$, and height $H = 19 \text{ mm}$. Shown in Figs. 2.1 and 2.2 is the arrangement of pressure sensors in the model. They are flush mounted at the locations labeled CH1, CH2, and CH3 in Figs. 2.1 and 2.2 to provide measurements on the flat plate surface both in the boundary layer and within the corner separation zone. Along the flow axis, the sensors were mounted 20 mm, 10 mm, and 2.5 mm upstream of the ramp corner, respectively.
A high-resolution Schlieren system was used to observe the basic flow structure, consisting of a pulsed NIR laser diode module (LS8-10-150-S10-00; 850 nm, 10 W peak power, 150 ns pulse duration) and a framing camera (Basler acA2040-180km-NIR, up to 187 frames per second at full 2k × 2k resolution). A typical image has an exposure time of 24 µs with the laser pulse duration <1 µs, thus “freezing” the flow in time. Schlieren images indicate the presence of not only a separation zone in the corner, but also a region of large density gradients downstream, related to the compression shock wave. It is challenging to use Schlieren visualization in such a low-density environment with the presence of a main flow shear layer as was the case for this work. In order to increase the signal-to-noise ratio and improve the overall quality of the final image, tens of images were averaged together. In Fig. 2.3, the average Schlieren visualization clearly shows separation of the boundary layer and its associated shocks.
B. Electrical Discharge

The Shallow Cavity Discharge actuator (SCD) [29] was used to generate artificial high-frequency disturbances in the flow. The electrodes were arranged in small cavities, a few millimeters in size, and are installed on the metallic surface of the model. It has the proper discharge geometry, reasonably low applied voltage, and a sufficient magnitude of the disturbances produced. A time resolved image of the SCD discharge in $M = 4.5$ flow taken by an Andor iStar ICCD camera is shown in Fig. 2.4a. At $F = 50 - 100 \text{ kHz}$, the discharge works as a push-pull plasma mini-jet. At lower frequencies of repetition, a second operation mode was observed [29, 30], currently considered as a cathode sheath pattern where a thin layer of plasma covers most of the model surface.

Figure 2.4 SCD in $M = 4.5$, $P = 4 \text{ mbar}$ flow in plasma mini-jet operation mode; ICCD camera image, exposure 1µs, delay time 3 µs (within the electric pulse).
Figure 2.5 a.) Voltage–current time series of the SCD operation at \( f = 100 \text{ kHz} \); b.) Calculation of the discharge pulse power and energy for 3 SCDs.

Typical records of the electric parameters in \( M=4.5 \) flow are shown in Fig. 2.5a for a frequency of repetition \( F = 100 \text{ kHz} \). The pulse energy and average power were calculated based on these data, as it is shown in Fig. 2.5b. The discharge parameters were as follows: frequency of repetition \( F = 10 - 100 \text{ kHz} \); pulse duration \( t < 4 \mu s \); voltage \( U < 1 \text{ kV} \); pulse energy \( E = 0.8 - 1.2 \text{ mJ/unit} \); average power \( W_{av} < 400 \text{ W} \). Three units of SCD have been arranged in the model.

C. Flow Measurements

To characterize the perturbations in the flow field, a series of tests were carried out to collect the data by means of three non-intrusive measuring systems. These include aero-optical measurements made by a Shack-Hartmann wavefront sensor, flush mounted surface pressure sensors, and LDI. Measurements of the flow dynamics are made in the vicinity of and within the separation zone to characterize high frequency responses and observe changes in the boundary layer separation within the ramp corner. Data collected within the separation zone was then compared with freestream measurements and baseline data to indicate differences in the spectra (see Figs. 2.7, 2.8, 2.10). In addition, the comparison between measurements made by the surface mounted pressure sensors and a laser differential interferometer (LDI) will allow more comprehensive analysis of pressure and density dynamics within the flow than previously studied [5].

1. Aero-optical measurements were performed using a high-speed Shack-Hartmann wavefront sensor [20, 31], the layout is shown in Fig. 2.6. The system consisted of a laser beam expanded to a 50-mm-diameter collimated beam and passed along the spanwise direction over the corner region of the model mounted in the test section. The spanwise beam propagation was chosen for two reasons. First, the flow is expected to be primarily spanwise-uniform. Second, as the beam traverses the 4-inch-long region of the flow, aero-optical distortions become stronger, thus improving the signal-to-noise ratio [20]. After exiting the test section, the beam is reflected off the return mirror, which sends the beam back along the same path. This so-called double-path setup amplifies the aero-optical signal by a factor of two, as the beam traverses through the flow of interest twice, and also simplifies the optical setup. The returning beam is split off using a cube beam splitter, sent though a contracting telescope, which reduces the beam size to 12.5 mm in diameter, corresponding to a magnification ratio of 4, and recorded by a Phantom v1611 high-speed digital camera. The camera had a 38 \text{ mm} \text{ focal length} , 70×60 \text{ lenslet array} with 0.3-mm-pitch, 100% fill ratio,
attached to it. After passing through the lenslet array, the beam was split into sub-aperture beams and focused on the camera sensor, creating a series of dots. To achieve the high sampling rate of 531 kHz, only a small portion of the image (128×64-pixel) was acquired for the full duration of the wind tunnel run. Centroids of dots’ locations were extracted and converted into the local deflection angles using in-house software; more details are presented in [20, 32].

**Figure 2.6 Schematic of spanwise aero-optical measurements using Shack-Hartmann wavefront sensor.**

Flow perturbations acquired by the Shack-Hartmann sensor were analyzed at different points within the flow field (similar to shown in Fig. 3.1) to identify the spectra of flow perturbations and dominant frequencies of oscillations occurring in the flow (see Fig. 2.7). The non-dimensional frequency, defined by $f \cdot \delta / U_\infty$, allows for simple frequency analysis and comparison [33, 34]. Here, $f$ is the perturbation frequency, $\delta$ is the boundary layer thickness, and $U_\infty$ is the freestream velocity. The boundary layer thickness was chosen as a scaling factor to match expected length scales of dominating acoustic waves trapped inside the boundary layer. Values of the dominant non-dimensional frequency within the separation zone for cold and hot flow range from $f \cdot \delta / U_\infty = 0.15-0.20$. Conversion to this non-dimensional form removes the shift of the dominant physical frequency peak that occurs between various freestream unit Reynolds numbers seen previously in [6]. The shift occurred as the result of different boundary layer growth rates at each freestream Reynolds number and the boundary layer thickness at different streamwise locations. Since the boundary layer acts as an acoustic waveguide (establishing wavelength), as explained in [16], the dominant frequency of acoustic waves varies with the boundary layer thickness. In Fig. 2.7, “freestream” represents a point in the dot matrix measured in the core flow far from the surface of the model and “corner” represents the point closest to the corner (<1 mm above the surface; <1 mm in front of the ramp tip). The corner point indicates a clear reduction in the amplitude of oscillations from the freestream condition at frequencies below 0.17. This appears as a “peak” in the data shown in Fig. 2.7. The baseline measurement is presented to show the noise floor of the system. The narrow, high-amplitude peaks observed in the data are attributed to a digitizing noise and have to be neglected in the analysis.
As aero-optical effects are proportional to the freestream density, the signal-to-noise ratio of the Shack-Hartmann sensor is higher for the cold flows than it is for the hot flows, that is, lower flow temperatures have a higher density which causes larger wavefront distortions and a larger signal without producing more noise.

Figure 2.7 Shack-Hartmann deflection angle spectra versus non-dimensional frequency, measured at the ramp corner and in the freestream, compared with the baseline with no flow ($Re \approx 3.4 \cdot 10^5, T_0 = 300 K$).

2. PCB™ (132 series) microsensors provided high frequency pressure measurements along the model surface upstream of and within the corner separation zone. With a response frequency of up to 1 MHz and resolution of 7 Pa, these piezo-electric transducers are capable of detecting weak shocks and high frequency perturbations impacting the sensor’s diaphragm. Pressure data collected from the sensors provided reinforcing evidence to indicate the dominant natural frequencies present in both high and low enthalpy flows. Three sensors were located upstream of the ramp corner, with the sensing element mounted flush to the model’s top surface. Along the flow axis, the sensors labeled CH1, CH2, and CH3 were mounted 20 mm, 10 mm, and 2.5 mm upstream of the ramp corner respectively, illustrated in Fig. 2.1. This spacing allowed for measurement of the flow pressure perturbations in the corner separation zone (CH3), near the flow separation point (CH2), and within the boundary layer upstream (CH1). Schlieren images verify the location of separation and existence of the separation zone within the corner. The sensors and their cables were carefully insulated to reduce vibrational noise from the model and electromagnetic noise from surrounding electronics. Fig. 2.8 below indicates a similar trend in the pressure data compared to the Shack-Hartmann sensor results. With the exception of small spikes (due to EM noise, mainly in baseline condition), the primary feature in the pressure frequency spectrum is a peak existing at 0.17, measured at CH3. The signal-to-noise ratio has a reasonably high value in most cases without the plasma generation. The noise level is extremely high during
operation of the high-voltage, high-frequency power supply of the plasma generator due to the high sensitivity of piezo-electric sensors to EM noise.

3. Laser Differential Interferometry (LDI). A Melles-Griot linearly polarized He-Ne laser is used as the coherent light source. It passes through a quarter-wave plate with the ordinary and extraordinary axes aligned at 45° to the axis of polarization of the laser in order to produce a circularly polarized light. The circularly polarized light passes through a Wollaston prism to produce two orthogonally polarized beams of equal intensity with a constant phase difference which are diverging from each other at 2°. The Wollaston prism is at the focal point of a 1 m focal length lens such that the orthogonally polarized beams are parallel to each other. The beams then pass through the test section with one beam isolated from the flow disturbances and the other passing through the boundary layer directly over the PCB™ inside the separation zone (CH3). The difference in density along the beam integrated path, where the beam passes through the boundary layer, introduces some new phase shift. An identical 1 m focal length lens focuses the beams back to a point on another Wollaston prism. This combines the beams into elliptically polarized light. The beams are interfered with a linear polarizer at 45° and the beam is imaged onto a photodiode. The intensity measured by the photodiode depends on where in the interference curve the recombined beam is due to the phase difference between the orthogonally polarized beams. The constructive/destructive interference is governed by the phase shift introduced by the density perturbations in the flow. The limits of the system are noise introduced (vibrational, ambient light, etc.), the response time of the photodiode (generally very short, <1 μs), the beam diameter, and the measurement circuit used.

Figure 2.8  Pressure perturbation spectra versus non-dimensional frequency, collected by PCB’s™ \( (Re \approx 3.4 \times 10^5, T_0 = 300 K) \), compared to baseline without flow.
Measurements taken by LDI further validate the Shack-Hartmann wavefront sensor and PCB™ data. For comparison, baseline and freestream tests are shown in Fig. 2.10 to compare with measurements taken in the corner separation zone. It is evident that the measurements taken in the corner separation zone indicate the same peak dominant non-dimensional frequency of 0.17 present in the Aero-optical and PCB™ data (~60kHz in dimensional frequency), perturbations existing both above and below this frequency are damped from the freestream case. The low-frequency peak in the LDI baseline spectra is caused by facility mechanical vibrations.

Figure 2.10 LDI data versus non-dimensional frequency, measured at the ramp corner and in the freestream, compared with the baseline with no flow.

Figure 2.11 presents the comparison of the spectra acquired by the three measurement methods. These tests were carried out for the lowest Reynolds number case ($Re \approx 3.4 \times 10^5$) in $T_0 = 300 \, K$ (low enthalpy) flow to ensure laminar flow over the model. Spectra presented in Figs. 2.7-2.11 display the amplitude of perturbations in arbitrary units, which allow for the normalization of the PCB™ and LDI data for comparison with the Shack-Hartmann data. LDI results at higher Re suggest a turbulent flow as evidenced by the similarity to the freestream case and lack of any distinguishable dominant frequency (discussed later with the Shack-Hartmann results). The flow configuration is a free jet for which a turbulent shear layer is expected to develop at high Re. This turbulent shear layer masks the lower
amplitude fluctuations in the core flow which causes issues for measuring the disturbances in the boundary layer and separation zone. The LDI is a path integrated system and measures differences in densities in the spanwise direction. Therefore the LDI is unable to distinguish between disturbances which are in the separation zone and those which would exist in a turbulent shear layer. The Shack-Hartmann system does not run into this same issue, as it measures disturbances occurring in the streamwise and wall normal directions. The PCB™ pressure sensors are a pointwise measurement and are unaffected by this consideration. A focused LDI system may be able to resolve this issue, but the 2-D planar geometry of the compression ramp makes it difficult to implement. In Fig. 2.11, the frequency content of the LDI data below and above the dominant frequency differs from that obtained with the Shack-Hartmann wavefront sensor. The LDI system is more susceptible to low frequency external effects, such as optical table vibrations, than the Shack-Hartmann system. These external effects along with higher sensitivity to disturbances in the shear layer contribute to the elevated amplitudes of the oscillations at frequencies below the dominant frequency as compared to the aero-optical data. The amplitude of the LDI frequency spectrum is slightly lower than that of the Shack-Hartmann at frequencies higher than the dominant frequency, and the PCB™ data has an amplitude much lower than both. The PCB™ has a lower effective level of the noise threshold and is collecting data at a single point while the two optical methods are path-integrated. Once plasma actuators are implemented, the use of pressure sensors becomes problematic due to the high level of electromagnetic noise generated by the discharge. Thus, in the case of characterizing the fluctuations for the planar hypersonic compression ramp, the Shack-Hartmann wavefront sensor has shown to be the most effective tool for data collection due to its high temporal resolution, ability to collect spatially resolved data over a region, and its relative insensitivity to perturbations present in the freestream outside of the region of interest.
Each of the diagnostics pose sources of inaccuracy in the final results. For the electric parameters during plasma actuation, an accuracy of electrical probes are $\pm 1\%$ for Pearson™ current probes and $\pm 2\%$ for LeCroy™ PPE20KV high-voltage probes. For the Shack-Hartmann wavefront sensor, some amount of uncertainty rests in the wall normal distance of the dot matrix from the model, this uncertainty is estimated to be $<0.1$ mm ($<6\%$ of $\delta$). The temporal resolution of the Shack-Hartmann system is limited by the camera system, a Phantom V1611 high speed camera measuring at 531,645 Hz. High frequency pressure measurements taken by factory calibrated PCB’s™ include high-pass filtering at 11kHz and a resonant frequency $>1$ MHz. The second mode frequencies of interest in this study exist well above the low frequency response and below the sensor’s resonant frequency. The LDI is a spanwise integrating measurement which can detect up to $+/- \lambda/4$ optical path difference without introducing phase ambiguity on the interference sine curve. Most disturbances for the tested conditions were within $+/- \lambda/8$ which is within the highly linear region of the interference curve. Due to the spanwise integration, it is difficult to quantify the uncertainty. It is within reason to use an estimated error of $+/- 5\%$ whilst the measurement remains within the linear portion of the sine curve. It is mostly the frequency content of the data which is of interest to this study. How all of these uncertainties transfer into the frequency domain is not obvious. However, all sensors employed have a much higher frequency limit than the frequency content of the flow. With this in mind it is within reason to estimate the uncertainty of the frequency content to be $+/- 2\%$ in determination of the dominant frequency.

III. Experimental Results

Initial characterization of the flow by three methods in this study has shown the Shack-Hartmann wavefront sensor to be the most suitable tool to analyze the state of the BL, including dominant frequencies within the flow spectra, in the case of electromagnetic noise. The flow structure can be further analyzed by individual regions within the flow. Figure 3.1 shows the field of measurements performed by the Shark-Hartman sensor. There are four lines with ten points in each. Points are masked by the model ramp in the corner. The X and Y distance between the points is 1.2 mm.
Figure 3.1 Dot matrix of Shack-Hartmann measurement locations; the distance is 1.2 mm between points.

Figure 3.2 shows the non-dimensional frequency spectrum of the flow along two line profiles at high and low Re in low enthalpy \((T_0 = 300 \, K)\) flow. The line profile closest to the wall (4.4 – 4.10) indicates a decrease in the amplitude of fluctuations as flow approaches the corner of the ramp (Fig. 3.2a). There is no noticeable effect far from the wall in Fig. 3.2b. It is important to note that point 1.1 is located downstream of the compression shock, which accounts for the increase in amplitude from 1.10 and 1.6. At high Re, the amplitude of disturbances increases as the flow travels downstream and is coupled with a lack of distinguishable flow features in the frequency domain. The steady decay in fluctuations, coupled with the lack of any dominant peaks at locations near and far from the wall shown in Figs. 3.2c,d indicates high levels of flow disturbances throughout the flow at this high of Re.
Figure 3.2 Non-dimensional spectrum of Shack-Hartmann data for low enthalpy flow ($T_0 = 300\,K$); a. b.) $Re \approx 5.7 \cdot 10^5$; c. d.) $Re \approx 2.1 \cdot 10^6$.

The same measurements were performed for high enthalpy flows ($T_0 = 1238\,K$ and $835\,K$), with relatively low and high Re cases. In this situation, the line profile along the wall (Figs. 3.3a,c) indicates the presence of a raised peak in the spectra occurring downstream (in the ramp corner). Figure 3.3c indicates a damping of fluctuations in the ramp corner at frequencies below $0.14$ and amplification of higher frequencies. Far from the wall, downstream locations exhibit the largest fluctuations with few distinguishable features in the frequency domain, similar to the low enthalpy flow cases.

![Figure 3.2](image)
The boundary layer conditions were characterized based on features of flow perturbation spectra. Figure 3.4 presents the data in terms of the Power Spectral Density (PSD), which was defined as $PSD = \bar{\rho}^2 \cdot f$ (in Hz$^{-1}$), where $\bar{\rho}$ is a wall-normal component of the deflection angle measured by the Shack-Hartmann sensor in relative units, $f$ is the frequency of perturbations. However, one should be careful to compare the data from the Shack-Hartmann sensor, which measures spanwise-integrated density perturbations [20, 35], to the local pressure sensor data. Nevertheless, as the density and the pressure are related via the equation of state, the results can be compared qualitatively. The data are shown for three cases: (a) $P_0=5.5$ Bar, $Re \approx 2.1 \cdot 10^6$; (b) $P_0=1.5$ Bar, $Re \approx 5.7 \cdot 10^5$; and (c) $P_0=1.5$ Bar, $Re \approx 5.4 \cdot 10^4$ (high enthalpy). Data is shown for freestream point 1.10 (see Fig.3.1); close to the ramp point 1.1; in the boundary layer point 4.9 which is far upstream from separation zone; and in the separation zone point 4.4. Note, the increase of the baseline with frequency indicates that the system is close to the sensitivity limit.
In case (a) the level of flow perturbations is high compared to other cases. The PSD could be attributed to turbulent flow in the freestream (point 1.10) and in the BL (point 4.9). The intensity increases even more near the ramp due to effect of the separation-related shock. The amplitude of perturbations in the separation zone is high with dominance at relatively low frequencies \( f < 100 \text{ kHz} \). In case (b) the freestream spectra looks similar to case (a) except for the amplitude, which is approximately \( \rho^2 \) times lower. Contrary to case (a), the intensity of perturbations rises in the boundary layer but is significantly damped in the separation zone. At the lowest Re in case (c), the freestream perturbations were lower than the detection threshold, demonstrating significant rise on the ramp and in the separation zone. Based on the non-dimensional frequency spectrum at location 4.9, the boundary layer is laminar. The non-dimensional frequency spectrum at location 4.4 indicates a presence of dominant frequencies with increased magnitude, which could be attributed to development of the acoustic instabilities. Based on the criteria described in Refs. [13, 14]

\[
\bar{\xi}_M = \frac{\beta Re_{l}^{1/4}}{(M_{\infty}^2 - 1)^{1/4}}
\]  

is equal to \( \bar{\xi} \approx 3 \) and this mode should experience “separation with distorted friction”. Apparently, the increase of the Reynolds number in the current configuration and a significant level of initial disturbances in the flow do not cause a secondary separation but leads to bypass transition.

Shack-Hartmann data was also collected for low and high enthalpy tests at the lowest Re conditions possible for the facility in order to maintain laminar flow to study then how plasma actuation may be applied. These consisted of
\( Re \approx 3.4 \times 10^5 \) (low enthalpy flow); and \( Re \approx 5.4 \times 10^4 \) (high enthalpy flow). These results reinforce previous characterization of the perturbations present in the hypersonic boundary layer [5]. The analysis provided shows that the same dominant natural non-dimensional frequency is detected as it is presented in Fig. 3.5. The location of points BL1 – BL9 in Fig. 3.5b,c correspond to locations in the flow field where Shack Hartmann measurements were taken. These can be referenced to Fig. 3.5a, illustrating the points of measurement in relation to the compression surface, being similar to the line 4 in Fig.3.1. The dominant frequency appears to be significantly higher for high enthalpy tests. This can be explained by two effects. The more dominant effect is due to a decrease in Reynolds Number during the high enthalpy tests. The second is due to the cooling effect of the wall on the flow, which corresponds to a reduction in boundary layer growth. A cold wall increases the stability of the boundary layer. Since arc heating during high enthalpy tests greatly increases the flow temperature in relation to the wall, there exists a mode of heat transfer between the flow and wall. In the low enthalpy tests, the wall is nearly adiabatic, whereas the high enthalpy tests do not exhibit an adiabatic behavior with the wall due to the short run time. The dominant disturbances for low Re flows, which are believed to have a laminar boundary layer, are acoustic waves. Recall that the boundary layer acts as a waveguide and traps acoustic waves in the boundary layer [16]. This results in a relation between the boundary layer thickness and the wavelength of the trapped acoustic waves; a thinner boundary layer possesses higher frequency acoustic waves. The boundary layer thickness for the high enthalpy flow conditions is smaller than the boundary layer thickness of the low enthalpy flow conditions. As a result the high enthalpy flow boundary layer will have a higher dominant frequency of perturbations which is shown in Fig. 3.5. This pathway however, is difficult to detect due to complexity of changes in the velocity, density, and pressure. The dominant frequency in the low enthalpy flow corresponds to 55 kHz and in the high enthalpy flow it is 110 kHz, approximately. It is notable that, in terms of dimensionless frequency, the value for the acoustic trapped wave is almost the same for low and high enthalpy cases. From Fig.3.5, the points measured closer to the corner position indicate higher frequency amplitudes up to some distance (BL6) and then it is damped similar to one shown in Fig.3.4.
Figure 3.5  a.) Measurement locations, distance is 1.2 mm between points; Non-dimensional spectra collected by Shack-Hartmann wavefront sensor from b.) low enthalpy test \( (T_0 = 300 \text{ K}, R_e \approx 2.0 \times 10^5) \); and c.) high enthalpy test \( (T_0 = 1238 \text{ K}, R_e \approx 5.4 \times 10^4) \).

The effect of pulsed plasma actuation at a 100 kHz repetition rate on the dominant frequencies in the spectra is shown in Fig. 3.6. Points of interest include 4.7 and 4.4 along the model wall leading up to the corner, where a small plasma effect appears to exist. Higher amplitude fluctuations during plasma actuation at location 2.4 may indicate a Y shift of the separated boundary layer and a modification of the separation zone dimensions. Point R4, located near the root part of the shock generated by the ramp shows a significant response to the plasma actuation. This effect, shown in Fig. 3.6d exists as an amplification of flow disturbances for all observed frequencies. Point R4 is approximately where the boundary layer reattaches to the ramp and this location is often the location of transition from a laminar to turbulent boundary layer [11]. At the same time, the effect is negligibly small in the BL and in the separation area.
Figure 3.6  Non-dimensional spectra of Y-component of the deflection-angle Shack-Hartmann data, plasma excitation \( f = 100 \, kHZ \); a.) location 4.7; b.) location 4.4; c.) location 2.4; d.) location R4.

IV. Summary

Measurements of the disturbances present in the hypersonic boundary layer and the corner separation zone by the high frequency Shack-Hartmann wavefront sensor, high frequency PCB\(^{TM}\) pressure sensors, and the laser differential interferometer provide a better understanding of the airflow’s pressure and density dynamics occurring within the geometry of a planar hypersonic compression ramp. Optical methods have shown to be especially useful in this environment, as they are non-intrusive to the flow and capable of obtaining spatially and temporally resolved data. Of the optical methods employed in the study of this flow, Shack-Hartmann wavefront sensing has proved to be the best due to its ability to collect temporally resolved streamwise and wall normal data at many points in the flow field. It is also relatively insensitive to vibrations and electromagnetic noise and easier to employ compared to other optical diagnostics. Of the other methods, Schlieren imaging provides a visualization of the flow structure and is used to study the geometry and dynamics of the boundary layer, the separation zone, and the shock waves. Laser Differential Interferometry provides high frequency measurements similar to the Shack-Hartmann wavefront sensor, but instead it only measures phase differences in the spanwise direction and it is not ideal for flows with shear layers outside the region of interest. While frequency data from these optical methods are the result of measurements in the density gradient within the flow, pressure perturbations at the surface can also be measured by surface mounted sensors. Each of these methods detected the same dominant non-dimensional frequency (of approximately 0.17) in the boundary layer/separation zone and therefore reinforce the results obtained via each other method. With further characterization performed by the Shack-Hartmann wavefront sensor, higher levels of disturbances occurred at higher \( \text{Re} \) in the BL.
and separation zone. In such cases, gas disturbances within the main flow affect the BL and can lead to a bypass transition to turbulence along the model. Only in the lowest Re cases does the presence of laminar flow allow for the detection of trapped acoustic instabilities in the separation zone. In most intermediate Re cases, the flow is characterized as transitional.

It was shown that plasma actuation has a significant effect at multiple points in the flow field which suggests it to be a robust technique for promoting the amplification of perturbations in the boundary layer near the flow reattachment region in a ramp configuration. Future work will focus on studying what flow conditions are most receptive to plasma actuation and what geometries/actuator locations can be most effective in introducing and promoting flow instabilities.

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