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# Shock tunnel noise measurement with resonantly enhanced focused schlieren deflectometry

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## 1 Introduction

The character of the boundary layer noise and ambient tunnel noise are of interest in the experimental study of laminar to turbulent transition. The instability mechanism in hypersonic flow over slender bodies is the acoustic mode. A number of investigations of flow over a slender cone in high-enthalpy facilities have been performed; however, measurements of the boundary layer noise and ambient tunnel noise have not been made. In cold hypersonic facilities the frequency range of the acoustic mode typically lies below 500 kHz; in high-enthalpy facilities, 5-20 MJ/kg, the most strongly amplified acoustic mode frequency is approximately 1-3 MHz. These high frequencies are well beyond the reach of the piezo-electric pressure transducers typically used in cold hypersonic facilities. A logical approach is to investigate the use of optical methods. Measurements of the boundary layer noise and ambient tunnel noise on a five degree half angle cone in the Caltech T5 hypervelocity shock tunnel are made with a single point focused schlieren system and a resonantly enhanced focused schlieren system.

## 2 Single point focused schlieren deflectometry

Measurements of the fluctuations in density at a single point are made in T5 using the method described in [3]. This is done with a circular laser beam focused to a small point of interest in the test section. The laser is then focused onto a knife edge and then refocused onto an amplified photodiode. It is assumed that disturbances are randomly distributed in the free stream and are averaged out, except in regions where the beam diameter is smaller than the disturbance length scale. The

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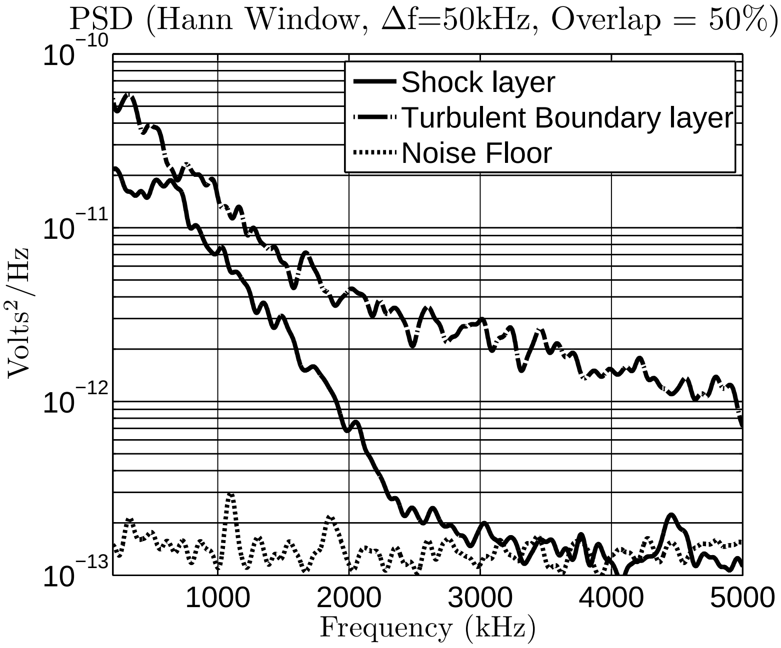


**Fig. 1** Spectra in the shock layer, a turbulent boundary layer and the noise floor of the technique on a five degree half angle cone in T5, ($p_{reservoir}$ = 30 MPa, $h_{reservoir}$ = 5.5MJ/kg).

diameter of the beam is 40 millimeters near the window and less than 50 microns at its focal point. The length scales of the disturbances of interest in transition work in T5 are three millimeters or less. The bandwidth of the photodiode is limited by the amplifier to 50 MHz, which is very high compared to the most amplified frequency of the boundary layer instability, 1-3 MHz. Time traces of the photodiode's output are recorded with a 14-bit oscilloscope; transients in the photodiode's output are indicative of fluctuations in density by means of the refraction of light. Advantages of this technique include ease of setup and high possible signal to noise ratio. Disadvantages of this technique include difficulty in making multiple simultaneous measurements due to limited optical access, and that the technique's focusing ability has not been thoroughly explored. Two measurements are made on a five degree half angle cone in the shock layer and in the turbulent boundary layer. The spectra of disturbances in the shock layer (shot 2583), in a turbulent boundary layer (shot 2582) and 1 millisecond before the starting shock arrives in the test section is seen in Figure 1. The last spectral estimation is included to give insight to the effects of electrical and mechanical noise on the measurement technique. It is seen that the spectral content in the shock-layer is above the noise floor of the measurement, indicating that there is ambient tunnel noise present at the most amplified frequencies of interest. The spectral content of the fully turbulent boundary layer is of larger magnitude and broader band than in the shock-layer.

## 3 Focused schlieren

It is not convenient to make measurements of multiple points in the test section with the single point focused schlieren method. A field focused schlieren system discussed in [5] and [2] is implemented in T5; with this method it is possible to interrogate numerous points in a thin stream wise slice of the flow. It is important to note that [2] and [4] show good agreement between the spectra of analog transducers in the flow and photomultiplier tubes placed in the image plane. The technique's focusing ability is demonstrated in Figure 2. In T5, signals from the fiber-coupled photomultiplier tubes were found to not have a sufficient signal to noise ratio to estimate the spectra in a hypersonic boundary layer. The extra decade of frequency response required in high-enthalpy flows significantly complicates signal processing. One way of increasing the responsiveness of such an optical setup is to resonantly enhance the light interaction with the test gas.

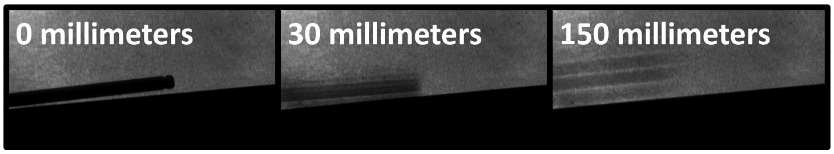


**Fig. 2** A 1.27 millimeter rod, 140% of the expected boundary layer thickness, is placed 0 millimeters, 30 millimeters and 150 millimeters from the object plane of the focused schlieren system in T5.

## 4 Resonantly enhanced focused schlieren

Resonant enhancement of the schlieren effect is achieved by using a narrow wavelength light source slightly detuned from an absorption line in the seed gas. In the method developed by [1], a continuous wave tunable laser diode with a narrow-band operating wavelength in the range of the lithium doublet is used as the light source. Lithium is introduced in the throat of T5 to provide the absorbing gas ( Figure 3).

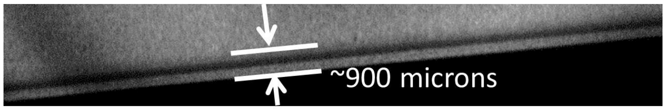
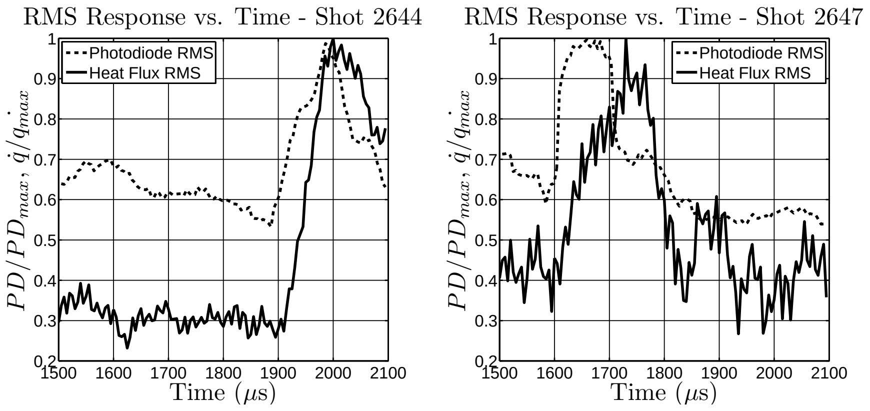


**Fig. 3** Resonantly enhanced focused schlieren photo of a laminar boundary layer on a five degree half angle cone in T5, exposure time = 14 microseconds, ($p_{reservoir}$ = 52 MPa, $h_{reservoir}$ = 8.8MJ/kg).



(a) (b)

**Fig. 4** Normalized RMS heat transfer and RMS photodiode response, ($p_{reservoir}$ = 55 MPa, $h_{reservoir}$ = 9.1MJ/kg) (a), ($p_{reservoir}$ = 31 MPa, $h_{reservoir}$ = 6.0MJ/kg) (b). The heat transfer is recorded by a thermocouple at a point in the object plane which is coincident with the photodiode location in the image plane.

A fiber coupled amplified avalanche photodiode is placed in the image plane of the focused schlieren setup to be coincident with the location of a surface mounted thermocouple in the object plane; the thermocouple is located 683.4 millimeters from the cone tip. The resonant enhancement technique is used to increase the signal to noise ratio of the photodetector response. The reasoning for the placement of the photodetector is to find a correlation between heat transfer to the surface of the cone and response of the photodiode. Normalized RMS heat transfer is seen to strongly correlate with normalized RMS photodiode response in Figures 4(a) and 4(b). The 600$\mu s$ test time begins 1500$\mu s$ after the incident shock arrives at the nozzle reservoir. Pearson's linear correlation coefficient of the RMS photodiode response and the RMS heat flux is 0.80 +0.05/-0.07 in Figure 4(a), and 0.52 +0.09/-0.11 in Figure 4(b). The strong correlation between the RMS photodetector response and RMS thermocouple response indicate that the fluctuations recorded by the photodetector are in fact boundary layer phenomena.

The photodetector response in frequency space (Figure 5) reveals interesting phenomena at 2000$\mu s$; 150$\mu s$ segments centered at 1600$\mu s$ and 2000$\mu s$ are highlighted. This shows the spectral content of the interrogated point of boundary layer when laminar (Segment 1) and when a turbulent spot passes (Segment 2). The spectral content of the turbulent spot (Segment 2) shows small peaks at 400KHz, 600KHz, 750KHz and 970KHz.

There are interesting phenomena (Figure 6) at 1540$\mu s$ and 1660$\mu s$; 40$\mu s$ segments centered at 1540$\mu s$, 1660$\mu s$ and 1950$\mu s$ are highlighted. Segment 1 has a clear peak at 1200KHz, indicating that it may be a linear wave packet. Segment 2 has the strongest spectral response with a definite structure and peaks at 480KHz,

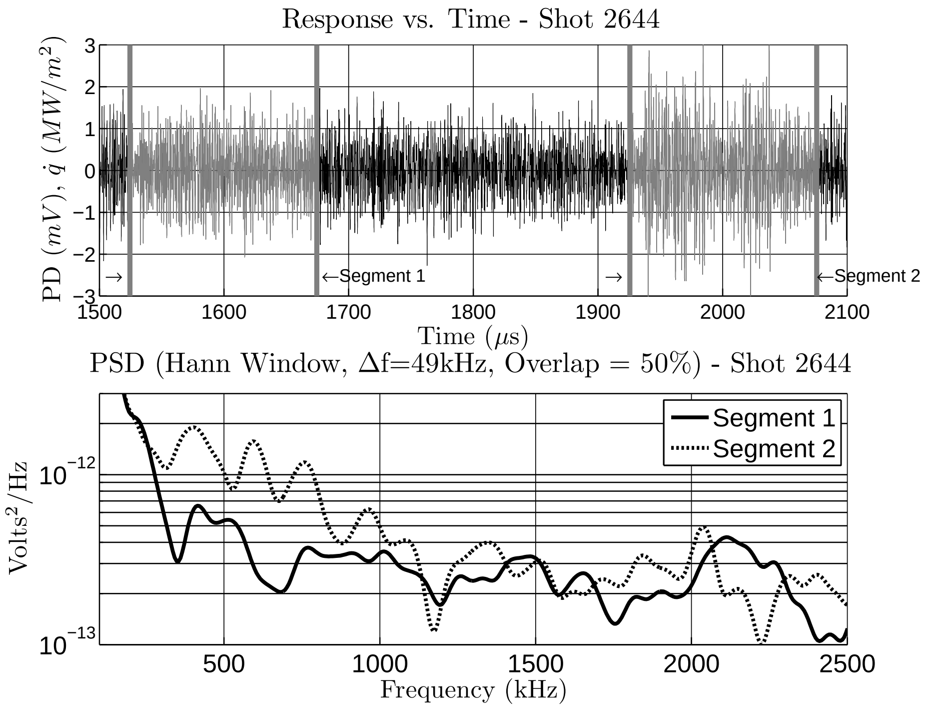


**Fig. 5** Segmented spectral analysis of the transients of the photodetector response, ($p_{reservoir}$ = 55 MPa, $h_{reservoir}$ = 9.1MJ/kg).

830KHz, 1150KHz, 1400KHz and 1600KHz, indicating that it may be a nonlinear wave packet. Segment 3 is laminar.

## 5 Conclusions

Optical measurements of boundary layer noise and ambient tunnel noise are made on a slender body in high-enthalpy hypersonic flow with a single point focused schlieren deflectometry system and a resonantly enhanced focused schlieren deflectometry system. The single point deflectometry measurements indicate that there is ambient noise in the T5 reflected shock tunnel free stream at the high frequencies associated with acoustic mode boundary layer transition on slender bodies. The resonantly enhanced focused schlieren deflectometry technique is found to make good measurements of interesting boundary layer phenomena.

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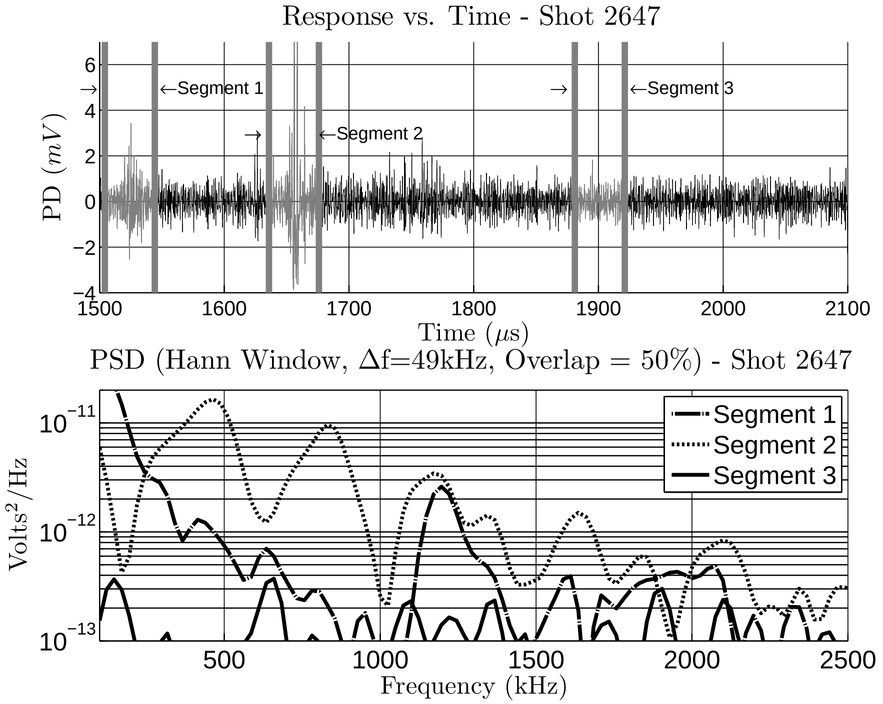

**Fig. 6** Segmented spectral analysis of the transients of the photodetector response, ($p_{reservoir}$ = 31 MPa, $h_{reservoir}$ = 6.0MJ/kg).

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