

A Shock Detection Technique Based On Light Scattering By Shock

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Introduction

It has been reported in an accompanying Technical Note¹ that when a narrow laser beam is brought to a grazing incidence on a shock, a small part of the beam scatters out in a thin, diverging sheet of light. The phenomenon disappears when the beam is moved to any other location where there is no shock or the beam pierces the shock surface, i.e., at a non-grazing incidence. Various experimental details indicate that the scattering is primarily due to diffraction of light by the sudden jump in the refractive index created across a shock.

The above optical phenomenon is conveniently used as the basis of a new shock detection technique. It depends on moving a laser beam from point to point in a shock containing flow field and sensing the presence of the scattered light using a photomultiplier tube (PMT). The incident beam locations, which correspond to a non-zero PMT signal, are the shock locations. It is demonstrated that the present method is able to provide both time-average and unsteady information in a very straightforward way.

Experimental Set-up

The present experiments were conducted in the shock-containing plume of an underexpanded, supersonic, free jet, exhausted through a 25.4 mm diameter (D) convergent nozzle, at a pressure ratio (plenum pressure/ atmospheric pressure) of 3.18 (panda²). The laser beam used for the detection system is the green line (0.514 μm wavelength) of an Argon-ion laser, transmitted by a fiber-optic system. Figure 1 shows a schematic of the set-up. The diameter of the beam out of the optical fiber is about 2 mm which is then focused at the jet centerline to a diameter of 0.16 mm. The set-up is similar to the one used for the visualization purpose¹ except for the light collecting and sensing devices. Just in front of the 60 mm diameter collecting lens is a 13 mm diameter beam stop which blocks the main beam. However, the diameter of the beam stop is small enough to allow most of the scattered light to enter the collecting optics. The collecting lens focuses this light to a 0.2 mm diameter pinhole which then passes it to a photomultiplier tube (PMT, TSI model 9162). The electrical output from the PMT is connected across a 50 Ohm terminator (not shown in figure 1). The voltage drop across the terminator is proportional to the PMT current and, therefore, is an indicator of the intensity of the collected light. The complete optical set-up was mounted on a 3-axis Klinger traversing unit which allowed it to be moved along the stream wise and the transverse directions within accuracy of .025 mm. Under normal circumstances light from the laser beam does not reach the PMT. However, if the optical arrangement is moved to a location where the laser beam becomes tangential to a shock surface, a part of the scattered light is collected and sensed by the PMT which then produces a non-zero output. The voltage signal from the PMT was digitized using a dsp Technology sample-and-hold digital converter and then stored and processed by a MicroVAX 3300 computer.

The detection technique is validated by comparing the shock locations identified by the present

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optical technique, schlieren photography and a limited velocity measurements using Laser Doppler Velocimetry. The details of the 1-component, fiber-optic, dual-beam, forward scatter, LDV system were reported earlier by Panda².

Results

Figure 2 shows a comparison between the shock positions identified using this technique and those seen in a spark-schlieren photograph of the jet. The rms value of the voltage drop across the PMT, measured as the flow field is surveyed at three radial (z) locations, are shown in figures 2(b), (c) and (d). At $z/D = 0.45$ (close to the shear layer) the schlieren photograph indicates the presence of the shock at an axial location, $x/D = 1.2$ (the markers at the bottom of the schlieren photograph are one jet diameter apart). The laser survey (figure 2b) also indicates a large rms voltage around the same axial position. At the other two radial locations, centerline and $z/D = 0.2$, the scattered light is expected to appear twice, since the laser beam becomes tangential to the shock at two locations. First, when it touches the conical shock boundary and second when it touches the base of the cone. At the latter location the shock splits into many 'legs' as it ends in the shear layer and any one of these 'legs' can be tangential to the laser beam. The laser surveys of figures 2(c) and (d) show large rms voltages exactly around these expected locations as identified from the schlieren photograph. The third spike in the centerline survey (figure 2d) is possibly due to another shock reflected from the shear layer and seen further downstream in the schlieren photograph.

The data shown in figure 2 are in the vicinity of the first shock cell only. Similar data for the complete flow field covering all the shocks are shown in figure 3. This figure also includes the Mach number distribution along the centerline, measured with a Laser Doppler Velocimetry. The spark-schlieren image (spark duration $\sim 60\mu\text{s}$) of figure 3(a) is made of two separate photographs, taken at different instances, which are pasted following the marker visible at the bottom. This was necessary due to the small size of the schlieren mirrors (100mm diameter).

The centerline shock position data up to $x/D = 1.5$, shown in figure 3(b), is the same as presented in figure 2(d). However, a different scale used for the abscissa causes the difference in the appearance. Good agreement can be seen between the shock positions identified in the laser survey (figure 3b) and those seen along the centerline of the schlieren photograph (figure 3a). The origin of the distinct spikes around the first shock surface is explained earlier. However, the variation of the rms voltage around the subsequent shocks is difficult to explain. It is believed that the large turbulent structures, present in such jets, progressively distort the shocks formed further downstream. Further studies are necessary to understand the distortion and unsteadiness of such shocks.

The purpose of the LDV data of figure 3(c) is to identify the shock locations from the time averaged velocity measurements. The Mach number distribution, calculated from these data, shows many undulations. The regions over which the local Mach number increases correspond to the expansion regions of the jet and the axial stations where the Mach number starts to drop can be considered as the shock locations. The shock locations indicated from the LDV data match with the corresponding locations indicated by the laser survey. This reconfirms the usefulness of the present optical technique.

Measurement of shock unsteadiness

When the laser beam is positioned to touch an oscillatory shock the scattered light appears periodically, and a time trace obtained from the PMT also shows voltage spikes with the same periodicity². A spectral analysis of the unsteady PMT signal provides the frequency of shock oscillation. Since, the response time of a photomultiplier tube is extremely small (of the order of nano-seconds), very high frequency shock motion can be easily detected using this set-up. Figure 4(a) presents two spectra of the PMT signal when the laser beam was positioned individually on the first two shock surfaces in the underexpanded jet. For a

comparison, an acoustic spectrum, measured using a microphone placed near the jet, is also shown in figure 4(b). The peaks, seen in the acoustic spectrum correspond to the screech frequency and a few of its harmonics. All such peaks are also present in the shock motion spectra of figure 4(a), which indicate that each shock oscillate at the frequency of the emitted sound. This observation is supported by an earlier experiment of Lessiter and Hubbard³ who photographed shadowgraph images of the jet using high speed movie camera to determine the frequency of shock motion (also see Norum and Seiner⁴). It is worth mentioning here that the technique is also useful in providing statistics, like the PDF of shock position, for flows involving aperiodic shock motion.

In addition to the frequency information, the amplitude of shock oscillation can also be determined by using the present shock detection scheme. For this purpose, the flow field has to be scanned by the laser beam at closely spaced points over the distance through which the shock is expected to move. The spatial extent over which a non zero value of the time averaged PMT voltage is obtained represents the amplitude of the oscillating shock. This is best demonstrated through figure 2, where data from laser surveys around the first shock surface are presented. For every encounter with the shock surface, a high value of the PMT voltage is obtained over a spatial extent shown as δ in figure 2(c). The average width of all of such δ in figures 2(b), (c) and (d) is measured to be .067D (1.7 mm), which represents the average amplitude of oscillation of the first shock surface. The accuracy of the measurement is limited by the laser beam diameter, 0.16 mm for the present case.

Concluding Remarks

The primary advantage of the current method over a quantitative schlieren or shadowgraph system lies in its simplicity and accessibility. The large schlieren mirrors and other accessories are difficult to use in complex flow geometry, such as a turbomachinery flow passage. The present method, on the other hand, depends on a narrow laser beam that is far more accessible and can be used much more conveniently in complex geometries. Perhaps, the best use of this technique is in measuring unsteady shock motion where statistics, such as amplitude, frequency and probability density function of shock position, can be obtained in a very straightforward way.

Acknowledgement

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Reference

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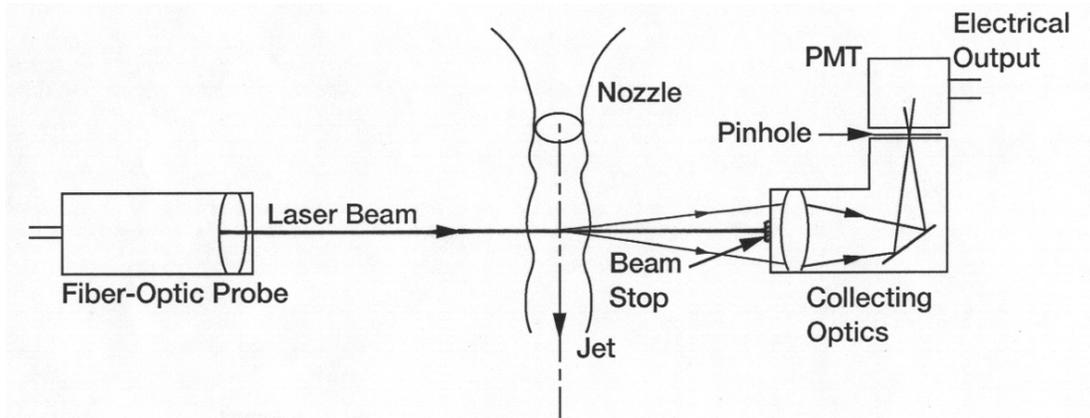


Fig. 1. Schematic of the shock detection technique.

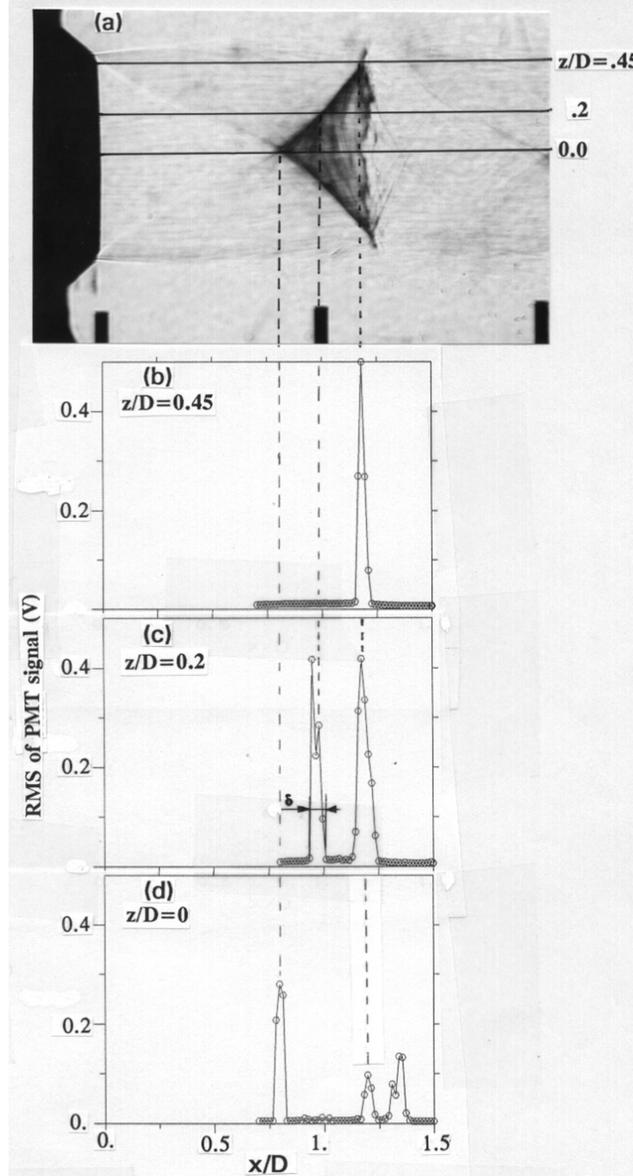


Fig. 2. Validation of the detection technique. (a) Schlieren photograph of shock formed in underexpanded jet; (b), (c) and (d) laser surveys from indicated radial positions.

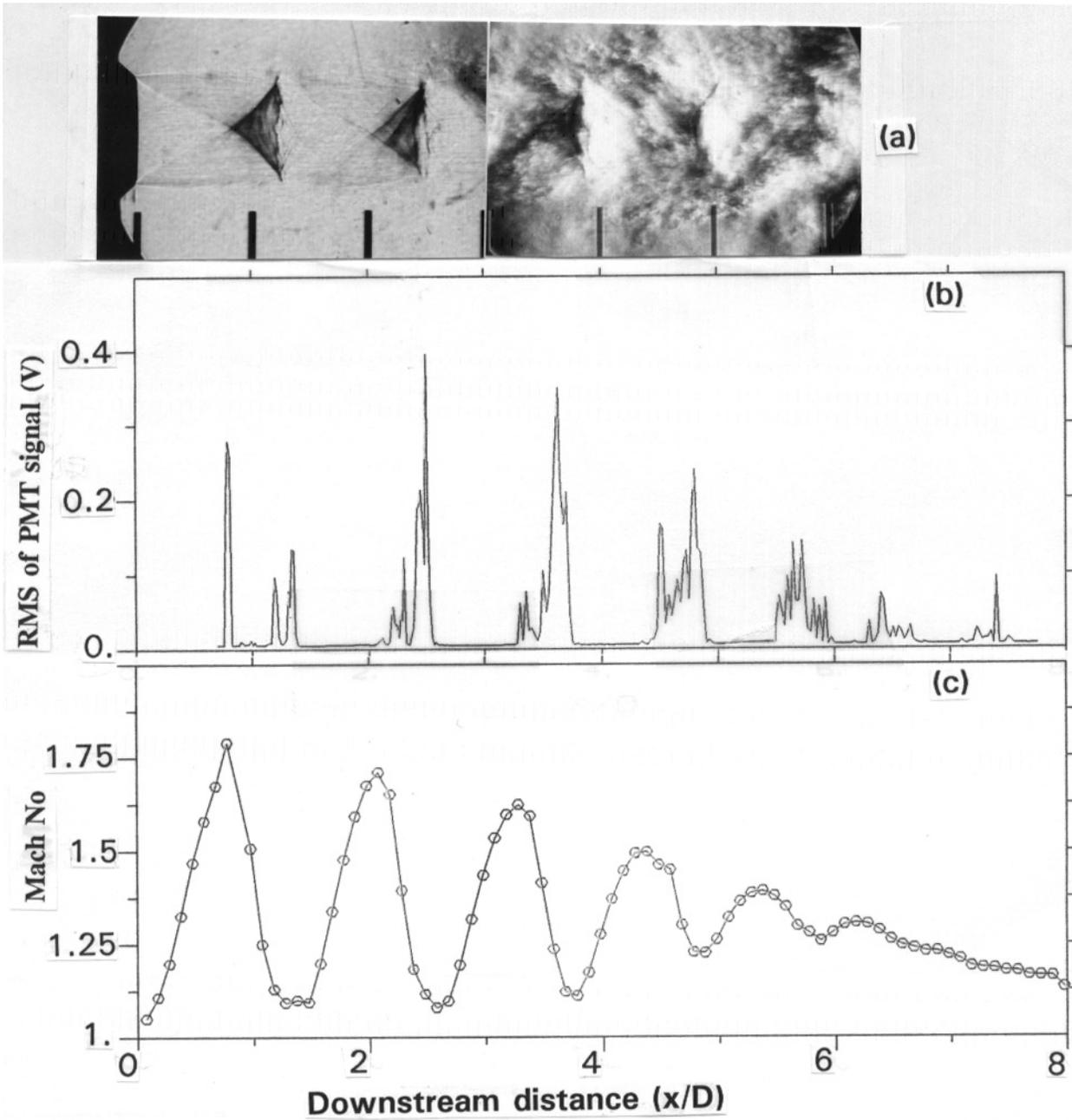


Fig. 3. Validation of the detection technique. (a) Spark schlieren photograph; (b) laser survey along jet centerline; (c) LDV measurements of centerline Mach number variation.

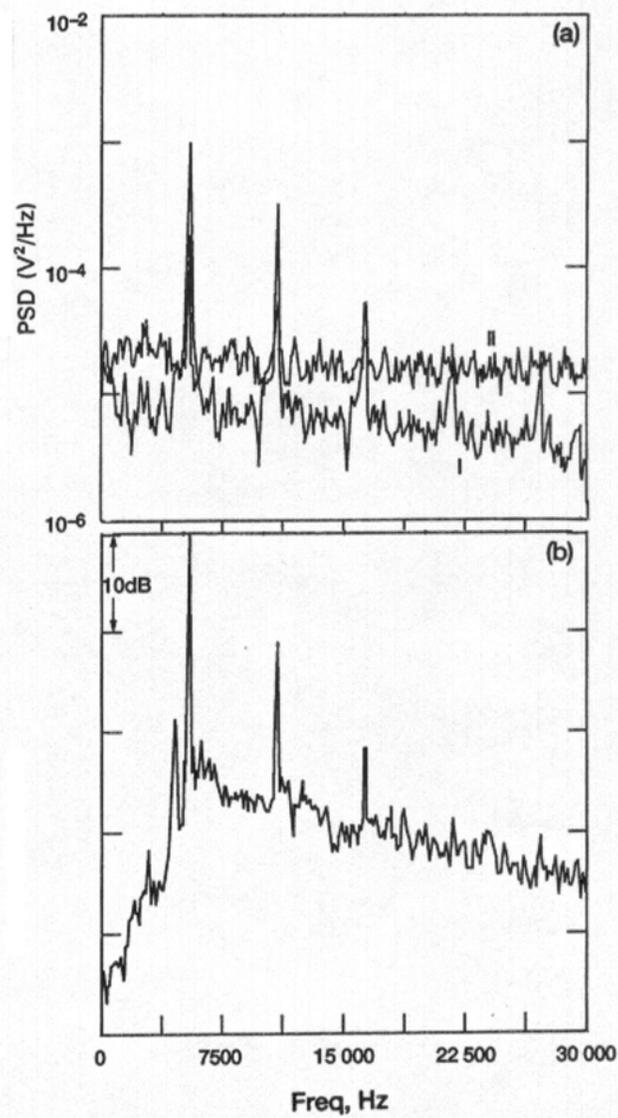


Fig. 4. Comparison between shock unsteadiness and sound spectrum. (a) spectra of the PMT signal from indicated shocks, $z/D = 0.15$; (b) Acoustic spectrum from nozzle lip.