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# On the temporal analysis of acoustic waves using schlieren imaging

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## ABSTRACT

The primary objective of the present study was to develop a quantitative schlieren-imaging technique that can be used to study the dynamics of instability waves. The technique was initially validated by optically capturing a controlled acoustic wave generated by a compression driver and excellent agreement was obtained with microphone measurements. An underexpanded jet was considered as an ideal test case due to the complexity and multitude of instability mechanism. Further analysis of the underexpanded jet demonstrated that this technique can be used to capture the very high frequency mode related to the phenomenon of screech.

## 1. Introduction

Laser based optical diagnostic techniques such as Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) have contributed significantly in broadening the understanding of diverse physical mechanisms in fluid mechanics. Even though LDA has a high temporal resolution, it is only possible to measure the velocity at any one given point at a time. On the other hand, PIV technique is capable of measuring an entire two-dimensional cross section of the flow field simultaneously. Their main advantage can be considered as them being non-intrusive techniques, however in both cases seeding particles need to be introduced and there are still unanswered questions regarding their effect on the freestream environment in a low-turbulence tunnel facility and how it influences the dynamics of laminar to turbulent transition. In a review presented by Scarano [1], further issues with seeding in the supersonic regime were reported, mainly related to the inhomogeneity in seeding dispersion and poor seeding density in regions of very steep pressure gradients through shocks and expansions, and particle ejection in recirculating regions and vortices. PIV still possesses limitations for unsteady flow measurements at high subsonic, supersonic and hypersonic flow regimes due to large frequency band of interest ranging between 100 Hz and 100 kHz, whereby limitation to high sampling rate is due to finite time separation between laser pulses. Image quality degradation due to refractive index change in the compressible regime could also lead to spurious PIV measurements, therefore in this case Schlieren and Shadowgraph techniques are a better alternative since they are inherently based on refractive index gradient.

Previous studies involving underexpanded jets using schlieren and shadowgraph methods have focussed mainly on qualitative measurements, where the techniques have been used either purely as a visualisation tool, or as a qualitative-comparison tool (Mitchell et al. [2], Willert et al. [3], Castelain et al. [4], Panda and Seasholtz [5], to cite a few). Limited quantitative measurements have been reported in the literature, with only the time-averaged schlieren images being used in the analyses (Bailly et al. [6], Ben-Yakar and Hanson [7], to cite a few). The progress in high-speed camera technology and digital image processing permits quantitative analysis of unsteady data. Underexpanded jets have been a subject of much consideration as they are notorious for exciting dynamic modes which could results in catastrophic structural failures quite commonly observed on combat aircraft vertical or horizontal stabiliser [8]. In addition they are the primary source of noise and studies in the 1950's by Powell [9] demonstrated that they comprise of two dominant components namely the screech tones and broadband shock-associated noise (BBSAN). According to a more recent study by Bailly et al. [6], the secondary flow at the exhaust of transonic commercial aircraft is underexpanded, but unlike choked jets in laboratories the dominant noise constitutes purely of broadband shock-associated noise due to asymmetry.

Raman [10] presented a summary of the investigations conducted on understanding screech over a period of half a century and a pathway describing the mechanism was presented, mainly elaborating on the pioneering work of Powell. Four processes were identified, namely the 'receptivity process', 'instability wave growth', 'instability-shock interaction' and 'acoustic feedback' to constitute the loop. The most highlighted unstable mode in the literature is the acoustic feedback due to the upstream propagation of the acoustic waves. The study by Beneddine et al. [11] suggested that this mode is initiated by the disturbances travelling at a supersonic phase velocity. As such, this type of flow is a suitable case to evaluate the capability of the proposed quantitative high speed schlieren opto-acoustic technique. During the

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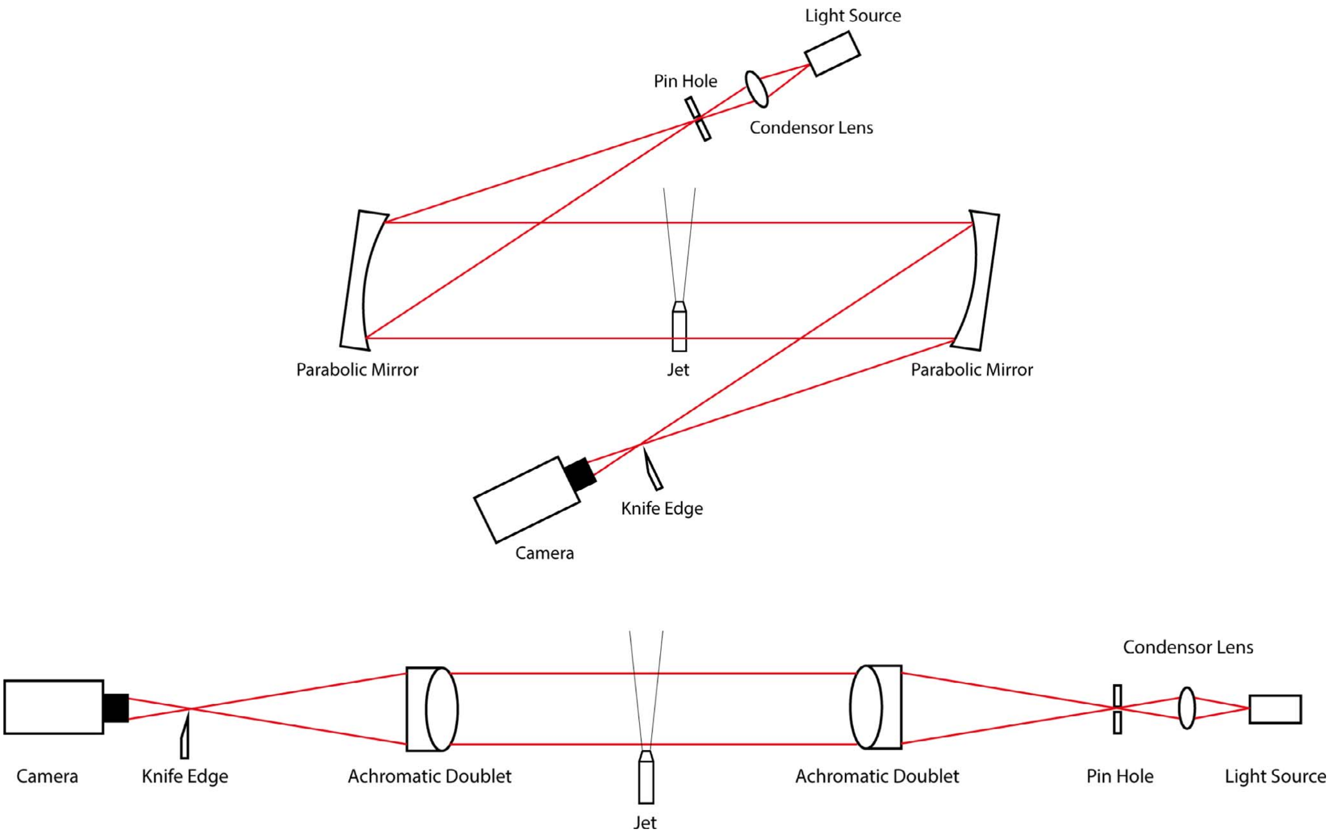

**Fig. 1.** Schematic representation of Toepler, Z-type (top) and inline-type (bottom) focussed schlieren technique used in the present study.

current study more emphasis will be placed on the phenomenon of screech as there seem to be sufficient findings which can help to validate the high speed schlieren opto-acoustic technique.

## 2. The experiment

The experiments were conducted in the Handley Page Aeronautics Laboratory at City, University of London. An air jet was generated through a 4.5 *mm* diameter nozzle which was operated using a continuous supply of compressed air at a nozzle pressure ratio (NPR) of 5.4. The local speed of sound, *a*, was calculated to be approximately 341.6 *m/s* and using isentropic relation the flow at the exit of the nozzle was calculated to be at a Mach number, $M = 1.72$ for a specific heat ratio, $\gamma = 1.4$. Since the pressure at the exit of the nozzle was higher than the ambient air, an underexpanded jet was expected and due to the highly compressible nature of the flow schlieren technique was preferred as the method of flow diagnosis.

Two types of schlieren set-ups were used and the schematic representation of which are shown in Fig. 1. The Z-type system features two 0.2 *m* diameter, f/4 parabolic mirrors with a focal length of 1.83 *m* (details available in Settles [12]). The Z-type system provided a large field of view, which was found necessary in order to capture the acoustic waves generated by the underexpanded jet. An inline type focussed-schlieren system was also used to obtain detailed information of the flow structures in the underexpanded jet. This system used a pair of achromatic lenses to act as a collimator and a focuser. The illumination for both set-ups was provided by a cold-light source powered by a 100 *W* halogen lamp. A flexible fibre optic bundle acted as a light guide and delivered approximately 1000 lm of luminous flux. A 0.024 *m* diameter condenser lens having a focal length of 0.013 *m* helped concentrate more light from the light source on to a pinhole.

The large depth of field of the Z-type schlieren technique meant that the density gradients captured by the camera resulted from integration along the whole optical line-of-sight. This resulted in contamination from unwanted variation in density due to natural convection of air in the laboratory. This was curtailed as much as possible by turning off the laboratory ventilation and restricting personnel movement. Depending on the orientation of the knife-edge, at the focal point of both the second parabolic mirror and the focusing achromatic doublet, density gradients were visualized in a single direction ($d\rho/dx$ or $d\rho/dr$) at a time (see Fig. 5 for details).

Two types of cameras were used during this study. Preliminary work was conducted using a Phantom Miro 320 at a resolution of 768 × 576 pixels operating at a frame rate of 7200 frames per second (*fps*). Even though this frame rate could be increased, the limitations of the sensor size meant that the required field of view could not be captured. The acoustic wave visualizations were conducted using a Photron SA1.1 high-speed camera, operating at a resolution of 320 × 256 pixels and a frame rate of 60,000 *fps* with exposure time of 1.02 μs. This resulted in an increased temporal resolution, which is necessary to conduct spectral analysis of the captured schlieren images.

The feasibility of this quantitative technique was assessed by high-speed schlieren imaging of acoustic waves generated from a compression driver. A Celestion CDX1-1745 8 *Ω* ferrite driver with an exit diameter of 0.0245 *m*, a frequency range of 1.2 *kHz*-20 *kHz* and sensitivity of 110 *dB* was positioned in the schlieren target area. The compression driver was driven by a sine wave at 10 *kHz* using a Hameg HM8030 function generator module and a commercial grade 30 *W* audio amplifier. Sound pressure levels were measured using a GRAS Type 26CB-46BL condenser microphone with a frequency range of 4 *Hz*–70 *kHz* and rated at a maximum of 166 *dB*. The microphone data was acquired at a rate of 51,200 samples per second via a National Instruments NI-9234 IEPE module, and data was acquired for 60 s through NI LabVIEW software. The microphone was also used to capture the near-field acoustic spectra from the underexpanded jet which is the main practical test case.