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Whole-field optical measurements of sound wave propagation from high-speed exhaust jets

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It is the goal of this paper to advance the field of noise measurement techniques to better understand the fundamental guiding principles of noise generation. This is accomplished in this study by demonstrating the capabilities of ultra-high speed Rainbow Schlieren Deflectometry (UHS-RSD) technique to visualize and quantify, in real-time, sound waves propagating from a supersonic cold air jet. Basic optical theory states that light rays passing through varying density transparent medium undergo deviation from their original path because of refraction. Therefore, an experimental setup was developed to direct parallel white light rays through a supersonic air jet. The variation in density field created in the jet stream causes light rays to deviate from their original path. The UHS-RSD technique employs aforementioned technique and enables mapping of the light deflection angle, a measure of deviation of a light ray from its original path due to refraction. Deflection mapping process is realized through variation in color (hue) between an image without and with test medium. Since all information in the field of view can be captured in one instant in time this technique provides us with a means to determine full field of view characteristic scalar properties of any transparent flow. The current experiment captures sound waves emanating from a supersonic cold air jet at high spatial and temporal resolution while still maintaining the high hue sensitivity needed to detect the small pressure fluctuations characteristic of sound waves. It is expected that sound probe data showing general maximum sound generation will support the visual UHS-RSD data where visible pressure gradient waves are seen propagating from the jet flow.

1. Introduction

Combustion noise generated by exhaust gas expelling from high speed jet turbines can create various health and hearing related problems for individuals in near proximity to the engine and nearby communities that experience the high power sound shock waves while aircraft is in transit. Several passive techniques such as mechanical chevrons and fluidics have been developed to dampen the noise generation, but at the cost of lower engine performance. Active techniques can be utilized to control the noise generation, however they require the ability to determine the origin of sources of sound and real-time control systems. Previous research has tracked the occurrence of jet noise to be a direct relation of turbulent structure interactions in the near-field (less than 20 nozzle diameters of the jet axis) and their propagating effect to the far-field. Velocity, pressure, and density fluctuations have been measured in numerous past experiments to gain fundamental understanding of the jet noise generation process. More conventional sound measurement techniques involve inserting a sound probe into or near the flow field to obtain sound level measurements at that point. Over the past few decades several diagnostics techniques have been developed to measure quantities within, and in the near- and far-field of the jet to develop a more fundamental aero-acoustic model. More recent research has shown that fully non-intrusive measurements can be made by correlating the time response data of two optical sensors with a given axial separation. The Ultra-High Speed Rainbow Schlieren Deflectometry (UHS-RSD) method has key advantages over these conventional means of measuring sound. First, besides the last technique mentioned, the information from the flow field is obtained non-intrusively, which prevents interferences from the measuring devices. Second, data are obtained across the whole flow field and in real-time. The current research described in this paper utilizes the capabilities of the UHS-RSD to provide a non-intrusive time-history technique to characterize jet flow parameters across the whole field. Information obtained can then be used to relate the jet parameters to the near- and far- acoustic fields in supersonic jets.

2. Background

Early as the 1950s investigations of near-field pressure fluctuations of unbound supersonic jets by Lighthill [1] attempted to understand the flow field dynamics of sound production mechanisms and the process for acoustic wave propagations from near-field to far-field. This related work tied small scale turbulent eddies as the source of the noise generation. Early experimental work was carried out exclusively with hot-wire anemometry in subsonic jets by Davies et al.[2],Bradshaw et al.[3], and Crow and Champagne [4], and others.

These results lead to the understanding that additional large scale turbulent structures also develop in the flow field and are a source of highly directional noise generation [5]. The large scale structures become more intense at high jet speeds and the combination effect of both large and small scale turbulence eddies make measuring and quantifying turbulence in supersonic jets difficult. Figure 1 taken from Tam et al [5] attempts to represent the two noise sources and their resultant acoustic field.

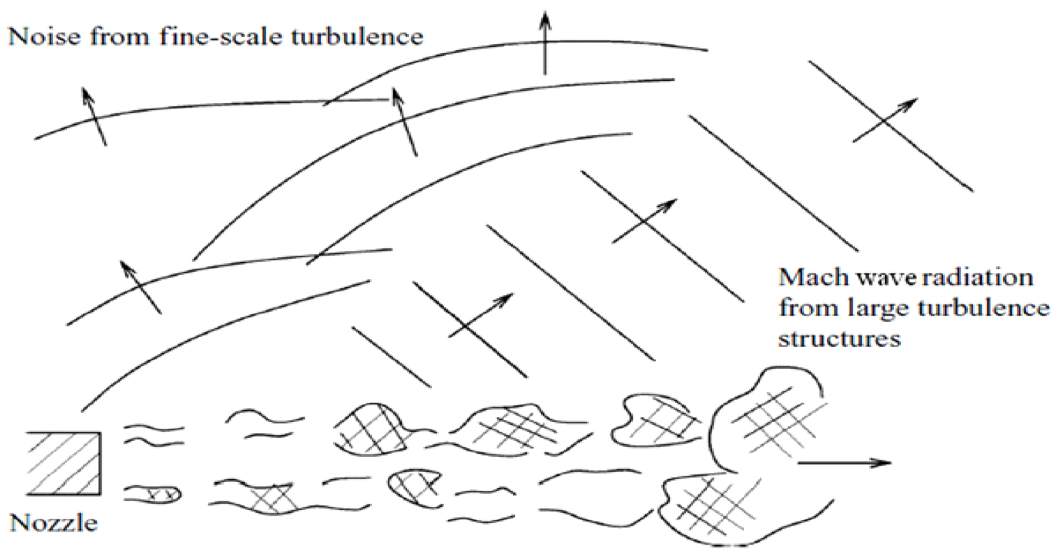

Fig 1. Schematic diagram showing the large turbulence structures of a high-speed jet, the sound fields from the fine-scale turbulence and the Mach wave radiation from the large turbulence structures (Figure 4 of Tam et al, [5])

Most commonly jet noise is studied using microphone arrays positioned outside the jet in the near- or far- field (Panda et al) [6,7]. This technique can determine the net result of complex turbulent flow by means of direct measurements, but the underlying turbulent interactions in the jet and in the very near-field cannot be resolved. In order to develop an accurate aero-acoustic model of supersonic and subsonic jets, more direct measurements must be obtained within the jet and related to the near- and far-field turbulent effects.

McLaughlin et al [8] and Troutt and McLaughlin [9] used hot-wire anemometry to measure turbulence in supersonic jets by conducting experiments in a reduced density anechoic chamber. The hot-wire technique's intrusive nature and lack of spatial diversity prove difficult to overcome for accurate results. Lau [10] and Kerherve et al [11] used laser Doppler velocimetry (LDV), but uncertainties related to non-uniform seeding of particles not accurately tracking the high speed jet flow causes difficulties in accurate prediction of sound generation. Recently, Bridges [12] and Kastner et al [13] used Particle Image Velocimetry (PIV) to characterize turbulence in high-speed jet flows. High special resolution is attainable in these experiments, but there are still issues with seeding, and temporal resolution is low because of the limited firing rate of the high-power lasers needed for this setup.

Recently, Doty and McLaughlin [14] used Optical Deflectometry (OD) to conduct measurements in supersonic jets to develop a better understanding of turbulent properties and relation to sound generation. This work was continued by Papamoschou et al [15] and Veltin et al [16] to show that the flow field data measured by the OD technique can be correlated with acoustic measurements in the near- and far- fields. The technique is based on the Schlieren principle which utilizes the fact that light rays will deflect as they pass through a test media of varying density gradients. The technique uses a parabolic mirror to collimate light rays through the test media. Deflected light rays are decollimated by a second parabolic mirror to form the source image at the focal point, where a knife-edge is placed. The knife edge converts light ray deflection into light intensity gradations, which are detected by the photodiode positioned to map a specific point in the flow field.

Similar to the schlieren technique described previously, Greenberg [17] developed the RSD technique which relies on light deflection except this technique uses an intense light source at the source aperture, collimation and decollimation optics utilizes achromatic lenses to minimize chromatic aberration, the knife-edge is replaced by a continuously graded color filter, and the filtered image of the test media is acquired by a digital camera. The RSD technique has further been developed by our research group [18, 19, 20, 21]. These studies have shown that the RSD technique can be utilized to perform a variety of flow field measurement tasks and it is the principal guide to the work reported here to visualize and quantify sound waves in real time.

3. Experimental Setup

The small scale pressure fluctuations that result from the turbulence interactions in the jet result in small pressure fluctuations that can be difficult to detect. Therefore, care must be taken in the experimental setup to assure that each optical component is appropriately utilized. Since the nature of these Mach waves are that they traverse at high speeds and high frequency, an experimental setup must be employed that can provide the sensitivity and spatial and temporal resolutions needed to resolve the acute density fluctuations in the air generated by the sound waves creating pressure fluctuations. Presented in Figure 2 is a rail system positioned on an optical table that is used for UHS-RDS experimentation. A Warm Broadband 2100 mW LED light source is contained within a mounting box that is radially centered down the path of the system setup. At the exit of this mounting box is a 5 µm wide by 3 mm high source aperture. The aperture is positioned at the focal point of an achromatic collimating lens with a diameter of 82 mm and 300 mm focal length. Thus light hitting the lens is redirected into parallel light rays perpendicular to the test media. Note that, source aperture is oriented such that longitudinal direction is parallel to streamwise direction of the flow. Light passing through the test media causes a slight deflection in the light rays because of the variation in density field resulting from supersonic jet's flow field. The parallelized light rays are directed to the other side of the test media where the light hits optically aligned 52 mm decollimating lens with a focal length of 2000 mm.

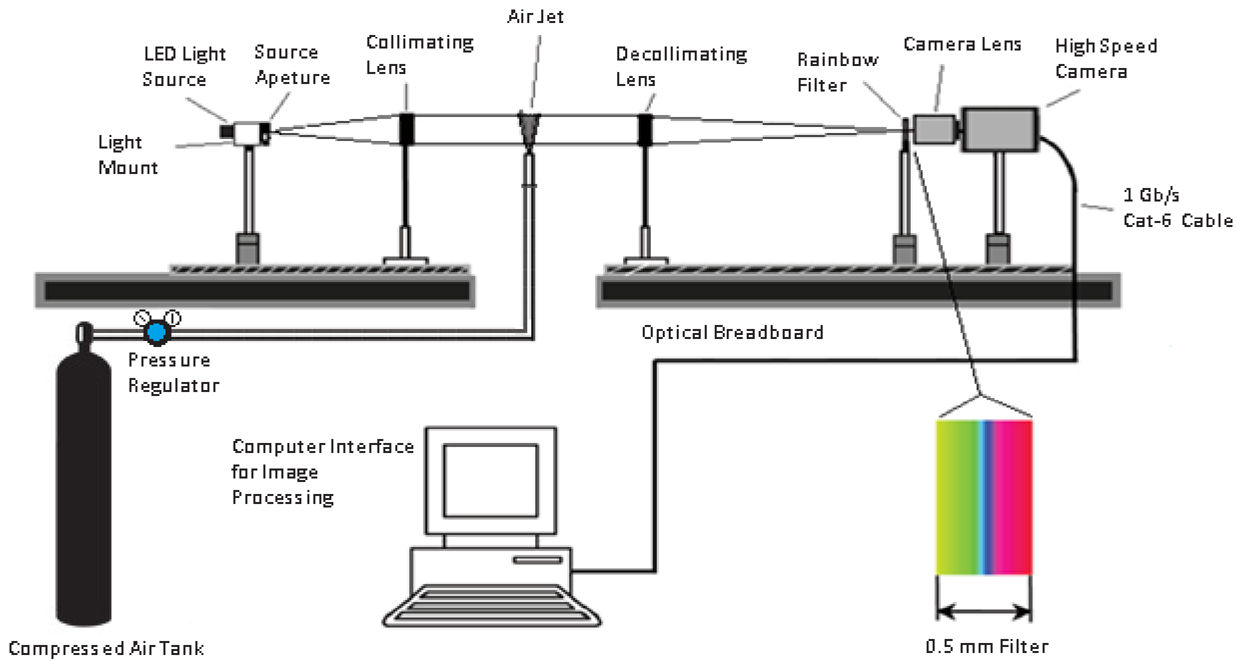

Fig 2. Experimental set up with schielren apparatus, supersonic jet, and rainbow filter

The light rays are decollimated causing convergence onto a rainbow filter placed at the focal point of the downstream lens. This setup provides a light aperture magnification factor of 6.67 and therefore, the resulting source image on the filter will be 33.4 µm wide. The height of the source image is not important in analysis because the deflection angles are measured in the transverse direction only. The rainbow filter is a continuous grade color filter printed on a 35 mm slide film. This filter is a 0.5 mm wide color strip that has hue variation from 40–320 degrees out of the full 360 degree hue range. An asymmetric color range filter was used and is accompanied with Figure 2. The colors vary linearly along the transverse direction of the rainbow film, and the light source is centered within this hue range to achieve the best sensitivity of the resulting schlieren image on the camera. The image passing through the filter is detected by a digital camera sensor with a camera lens. The camera lens used is a Sigma 105 mm lens. It focuses the filtered test section image onto the camera sensor. The camera is a Fastcam SA5 Photron high speed camera. The acquired image is sent through a 1 Gb/s cat6 cable to a computer for post-processing and analysis. Each acquired image is a 128x128 pixel resolution frame that is digitized and downloaded as a 16-bit color TIFF file. This resulted in a spatial resolution of 406 microns per pixel. The schlieren images are captured at a temporal resolution of 210,000 frames per second or with exposure time of 4.76 µs.

The supersonic jet flow is created by using a high pressure pneumatic system exhausting compressed air into the atmosphere through a converging diverging (C-D) nozzle. The output pressure from the regulator valve is set to 800 psi, and the valve is open long enough to obtain experimental data before closing the valve. This period last approximately only a few seconds. The C-D nozzle has a choke diameter of 2 mm and an exit diameter of 3 mm.

Schlieren images were captured at three different axial views along the jet flow to achieve the desired span. A range of Z/D from 0 to 25 was used to capture near field data from the jet exit. At each successive run the nozzle exit is traversed upstream to provide image data farther downstream of the exit. There was a 20 minute waiting period between runs to transfer data from the camera memory to the computer. However care was taken to regulate ambient conditions to maintain constant operation conditions. A Brüel & Kjær hand held sound probe was used to obtain reference sound data. This probe was inserted into the very edge of the viewing area of the RSD setup. Figure 3 shows the exact positioning of the probe by the black rectangular insert into the flow field.

After the experiments were conducted captured video images were downloaded onto a computer for post processing. Matlab software was used to transform the RBG image format into HSV format. Then the information at each measurement location can be correlated to the hue value only. Thus, non-linearities associated with saturation and intensity variations of light source do not affect the measurements.

4. Results

Many conclusions can be drawn by examining the color schlieren images obtained from the experimental setup. In Figure 3 several schleiren images are shown to visually illustrate sound wave propagations. However it should be noted that this is a very small sample of 100s of thousands of images captured. The true amount of possible wave interactions is large. However, certain trends do repeat in predictable manners. As discussed previously, Mach waves generating from large turbulent structures propagate from the shear layer of the supersonic jet at high amplitude and wave generation frequency. The waves developing from the large eddy turbulent structures are highly directional in the positive direction. These waves generate in small packets of 2 to 10 wave fronts with a small intermittency window then repeated again in a regular consistent manner. The large eddy turbulent waves generate in the near field area at about Z/D = 4 and dominate the flow up to about Z/D = 9 where the main structure of the supersonic jet breaks down and emits sound waves at a consistent Mach angle. Additionally, development of small scale turbulent structures produce lower intensity broadband waves that radiate from further downstream locations, and are seen as negative angle sound sources. The second farther downstream location where turbulence is more fully developed is beyond the total span the experimental setup traverses. These two wave patterns interact outside of the jet in the R/D direction and the dominant wave amplitude oscillates between the positive angle Mach wave and the negative angle sound wave.

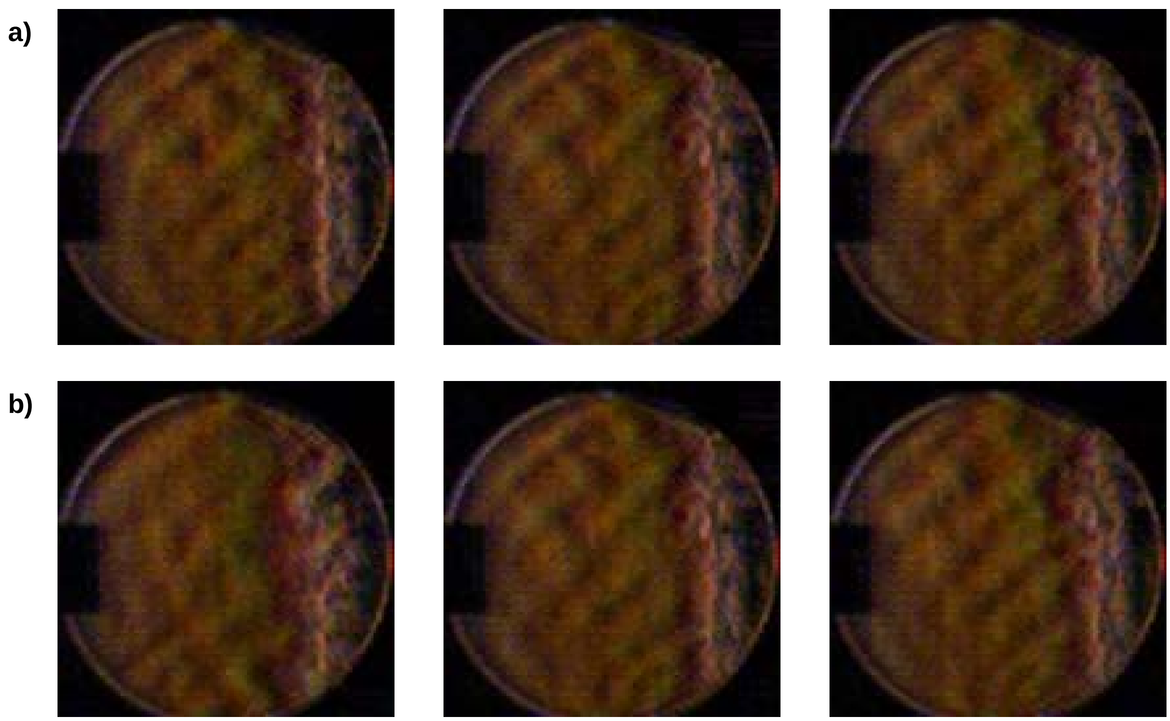

Fig 3. Actual image captures from the UHS-RSD technique. From left to right is single frame progression for 5 microseconds a) Z/D = 9 to 18, dominate wave in positive direction from large scale turbulent structures. B) Z/D = 19 to 27, more interference from small scale turbulent structures propagating in negative direction.

In previous experiments carried out at 600 psi, it was observed that lower Mach number jets would result in fine scale turbulence sound waves with less intensity and the positive Mach waves would dominate the flow almost entirely. Figure 4 shows a sample of an image captured in this experimental run. The jet in on the left side of the image in this case, and large scale turbulent waves propagate at slower speeds compared to first experimental case shown in Fig 3.

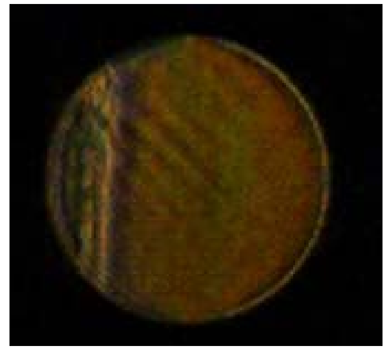

Fig 4. Mach wave radiation developed in the supersonic jet.

By tracking the wave fronts in the schlieren video files an acoustic wave speed developed by large eddy interactions can be computed. The results after averaging several interrogation waves gives us a M_a value of 1.43. The convective mach number of the jet can also be calculated by also tracking the wave fronts and determining the mach angle from the jet stream. The mach angle is computed to be 28 degrees from the jet stream. We can then predict the convective jet Mach number to be 1.19. These waves are being generated at very high frequencies approximately near the 50K Hz region.

One of the advantages of UHS-RSD is the ability to capture whole field measurements with high spatial and temporal resolution. This provides the ability to present time-lapse data that can capture wave phenomena by inspection of the peak and valley patterns in a contour plot. Figure 5 shows the time-lapse data of a selected region at R/D = 4.125. As can be seen in this image wave like peak and valley formations appear at angles that are not perfectly horizontal. This supports the observations of seeing highly directional wave propagations from the jet.

Alternatively one could view a similar wave pattern in the radial direction by fixing the Z/D direction. Figure 6 shows the wave form time-lapse data for R/D = 4.125. Here an overall decay in the max amplitude of the signal can be observed and verifies similar observations made in previous research that the overall signal decays in the radial direction. At the location represented repeatable wave patterns emerge from the captured data. As waves progress in the radial direction there is a trend where the spacing between the two wave maxima increases. Temporal repeatability is evident by inspecting the small red peak dots. Here sweeping time intervals as waves traverse past the R/D location have a spacing approximately 30 microseconds.

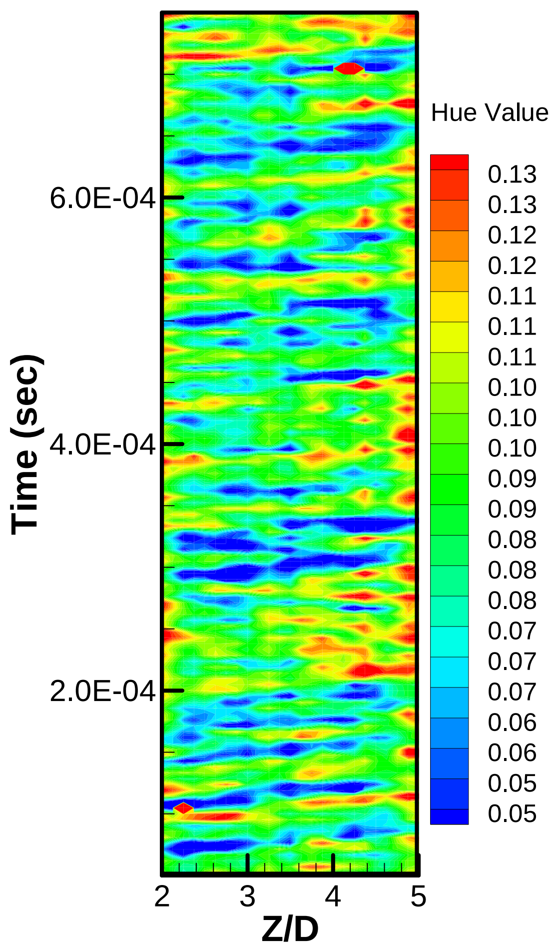

Fig 5. Time-lapse hue data of a selected radial location of R/D = 4.125

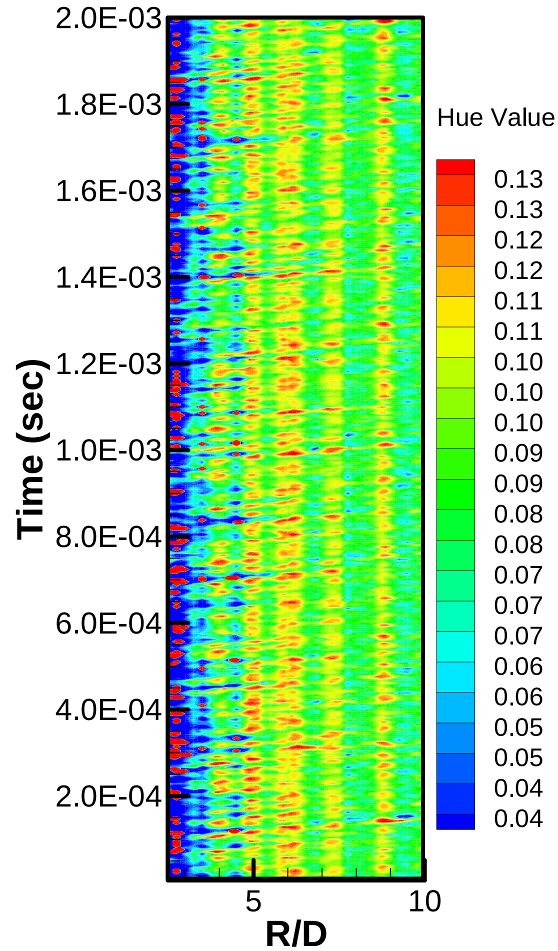

Fig 6. Time-lapse hue data of a selected axial location of Z/D = 4.125

One of the preliminary objectives of this research is to correlate data acquired by the UHS-RSD technique to other methods already developed. One initial approach is to determine how the average magnitude in hue intensity varies over the axial direction. Figure 7 shows the mean hue change over the span of the axial direction. Locally there is significant variation in the mean hue, but the general trend is a gradual positive slope. This agrees with the sound probe data that was captured simultaneously with schlieren images. However, exact correlations between the two signal types have not been developed at this time.

An indication of turbulence is the overall variance of measured data. As the variance in the measured data increases the overall turbulence would tend to increase, and higher sound levels would be detected. Figure 8 shows that such a trend is present in the measured data acquired from the UHS-RSD technique, and offers higher confidence in this techniques' ability to measure sound wave trends.

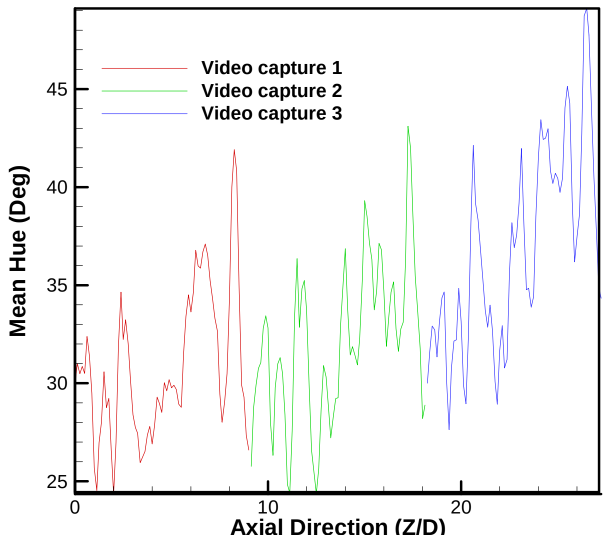

Fig 7. Time averaged mean hue spanning the entire axial direction from Z/D = 0 to 27. This information is acquired at a radial location of R/D = 4.125.

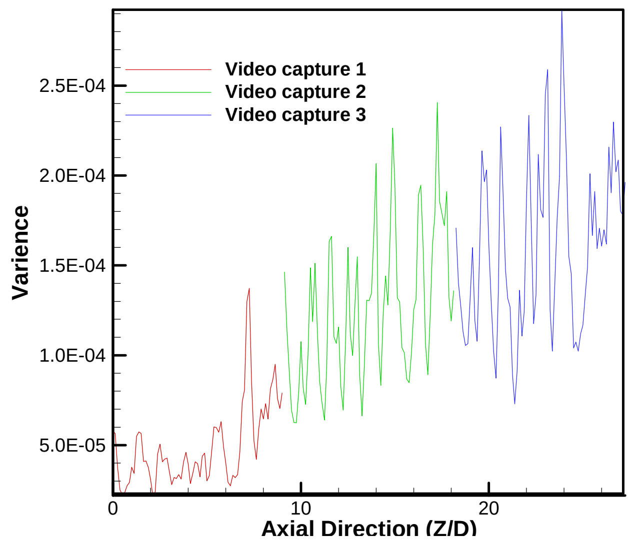

Fig 8. Time averaged variance in hue spanning the entire axial direction from Z/D = 0 to 27. This information is acquired at a radial location of R/D = 4.125.

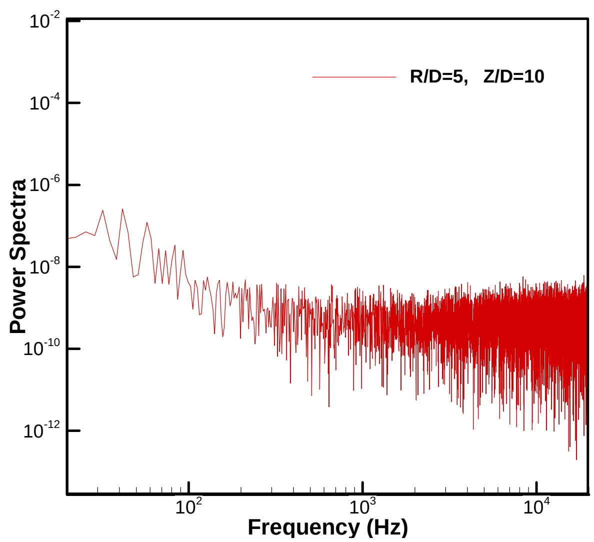

Fig 9. Power spectra of selected R/D = 5 and Z/D = 10 bound between 20 and 20,000 Hz

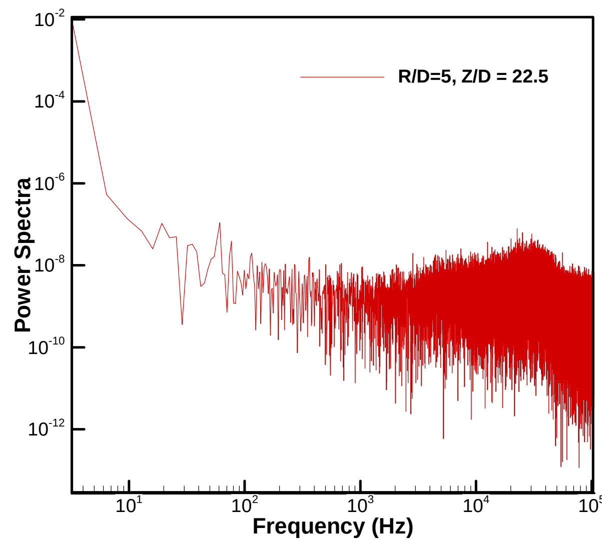

Fig 10. Full frequency range power spectra of selected R/D = 5 and Z/D = 22.5 location.

Power spectra were also obtained to further understand the frequency content of the propagating wave. Veltin [16] compared power spectra of numerous measurements techniques in Figure 7 of his paper. It is desirable to obtain similar profiles from our experimental data. However, low frequency noise appears to be causing some corruption in the signal and currently filtering techniques are being developed to alleviate the low frequency background noise. In Figure 9 a sample power spectra is presented as a preliminary indicator of the frequency content of the sound waves. The general trend of a level slope followed by a decrease in the power of higher frequencies is consistent with our measured data.

Since the dominate Mach waves from large eddy formations develop at high frequencies on the order of 50,000 Hz, it would be expected to see peak power spectra within this range. Figure 10 shows this trend at the selected location. It can also be noted that this peak frequency becomes more prominent at higher axial locations. However, as pointed out by Camussi et al. [22] the intermittency of wave packet formation can mis-represent the real frequency content by the Fourier domain especially when the Fourier transform is assessed numerically. Also, presently there is some concern in how background noise is corrupting some of the frequency content and needs to be further investigated before a more in depth analysis can be performed.

5. Conclusions

A new UHS-RSD system was developed to capture the slight density fluctuations that are produced as a supersonic cold air jet is expelled into ambient air. Since density gradient fluctuations are related to pressure fluctuations, this technique allows the study of sound wave propagation produced from high speed jets. Measurements made by the aero-acoustic community support the direct visual representations of the flow field that are seen in captured image videos from the UHS-RSD technique. Mach waves that have been detected in several past experiments can be seen to characterize strong directional large turbulent effects, and small scale turbulent broadband waves. It has also been observed that overall hue amplitude and hue variance increases with axial direction. Even though preliminary, this effect shows great similarity to trends experienced with acoustic measurements. Initial spectral analysis shows trends that although may be slightly corrupted by background noise can still show key features of sound waves.

6. References

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