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Stereoscopic PIV Measurements of a Screeching Supersonic Jet

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***Abstract*:** The effect of acoustic feed back on global flow response is illustrated through an example of a rectangular screeching jet operating at a nominal Mach number of 1.69. Using a stereoscopic Particle Image Velocimetry, the detailed flow characteristics within a screeching cycle are obtained with fidelity. To resolve the "bias" errors inherent with standard PIV image processing technique, a novel mesh-free and high spatial resolution scheme is implemented to yield accurate velocity measurements in a complex three-dimensional supersonic flow. The axis-switching phenomenon that arises due to unusual mixing enhancement in the minor axis plane of a rectangular jet is vividly displayed. Strong streamwise vortex structure in the jet shear layers, enhanced by the inherent instability of the shear layer, is reported.

***Keywords*:** supersonic jets, aeroacoustics, screech, 3D PIV, stereoscopic PIV, flow-acoustic interaction.

1. Introduction

A promising approach for the diffusion of high convective Mach number free shear flows utilizes the efficient energy transfer between mean and turbulent velocity fields caused by global flow instabilities. One such phenomenon, known as screech (Powell, 1953), exemplifies the dramatic effect of a self-sustained feedback loop in the global flow response (Krothapalli et al., 1986).

Unlike isolated shear layers, we find that compressible jets are unstable over a wide range of disturbances for all Mach numbers (Bearman and Ffowcs Williams, 1970). Consequently, the jet can be regarded as a high gain broadband amplifier. Any feedback loop on such an amplifier is liable to transform the system into a narrow band oscillator. A typical example exhibiting such a behavior is the screeching jet; a self-sustained oscillatory condition common to non-ideally expanded supersonic jet flows. The feedback loop as described by Powell (1953) consists of a disturbance traveling downstream that strikes a region at the end of a shock cell to scatter intense sound. This sound propagates through the subsonic ambient medium, and upon reaching the nozzle lip, excites the shear layer leading to the generation of new traveling disturbances thus closing the feedback loop. The frequency of operation is determined by the feedback loop. The instability waves that are part of this process are of convective type having negligible upstream influence. As a result, the jet could be excited at non-screech frequencies if driven by an upstream disturbance of sufficient strength. If an efficient energy transfer mechanism between the undisturbed shear layer and the oscillatory disturbance (in the region covering the first few instability wave lengths) is devised, the resulting motion of the jet could be as violent as that experienced by a screeching jet. Indeed, using the flow induced cavity resonance at the nozzle exit, Yu and Shadow (1995) have increased the initial shear layer growth rate by nearly a factor of three at high convective Mach numbers (M_c = 1.4).

The controlling effect that a self-sustained feedback loop can play in global flow response is illustrated here with a screeching rectangular jet. The measurements described here are obtained by incorporating a novel experimental technique that may prove to be useful in the application of PIV to high speed flows. Application of an accurate non-intrusive, quantitative, synoptic, velocity field measurement technique like Particle Image Velocimetry (PIV) is a key element to make detailed flow field measurements that describe the various elements of the problem. In this study, a high-resolution PIV technique is used to obtain accurate phase locked measurements of synoptic 3-D velocity and vorticity field of a screeching jet issuing from a rectangular nozzle.

2. Experimental Setup and Procedures

2.1 Facility and Operating Conditions

The experiment was performed in the blow-down free air jet facility of the Fluid Mechanics Research Laboratory which is capable of generating jets at Mach numbers up to 2.15 and total temperatures up to 810 K at Reynolds numbers in excess of 3×10^6. Large storage tanks provide a total capacity of 10 m^3 of air at a maximum storage pressure of 14 MPa. The stagnation pressure and temperature were held invariant to within 0.5% of its nominal value during each experiment using staged control valves.

For the present investigation, the blow-down facility was fitted with a rectangular converging-diverging nozzle designed by the method of characteristics for operation at M = 1.44. The span, b and height, h of nozzle exit plane were 40 mm and 10 mm respectively. Due to the manufacturing difficulties, the side walls of the diverging portion of the nozzle were kept straight. All experiments were performed at a nozzle pressure ratio of 4.86, corresponding to an ideally expanded Mach number of 1.69. The nozzle exit pressure ratio is 1.33. Since there are no normal shocks present in the flow, the jet is considered to be moderately under expanded. The nominal convective Mach number is 0.8. Experiments were performed at a slightly increased stagnation temperature of 335 K to avoid any water condensation problems. The jet exit Reynolds number based on the nozzle exit height and the mean exit velocity is 3.3×10^5. A top-hat mean exit velocity profile with laminar boundary layers was maintained. The supersonic jet was exhausted into a quiet surrounding at ambient conditions.

The jet was seeded with small (~1 μm) oil droplets generated using a modified Wright nebulizer. The ambient air was seeded with smoke particles (~8 μm in diameter) produced by a Rosco fog generator. Larger particles are entrained into jet and are confined to mostly subsonic region. Previously, a careful study of the particle behavior in shock containing supersonic flow was carried out (Ross et al., 1994), using a similar PIV apparatus. The particle relaxation length varies significantly with the shock strength and the particle diameter. The relaxation length was 7 mm for 1 μm particle diameter with an associated shock strength parameter ($\Delta p/p$) of 1.2. In the present experiment, the compression in the flow results in much smaller values of the shock strength parameter, therefore the relaxation lengths are expected to be much shorter. In the absence of shock cells, the velocity of the particles was found to be in close agreement (±1%) with the calculated exit velocity using isentropic relations.

2.2 Implementation of Stereoscopic PIV

For 3-D velocity measurements, a PIV setup utilizing two Kodak ES.1 cameras was used to obtain the stereo view of the flow field, as shown in Fig. 1. The CCD cameras had a resolution of 1008(H)×1018(V) pixels with the size of 9×9 μm, and a maximum frame rate of 30 Hz. Both cameras were equipped with a lens of 58.37 mm focal length that was specifically designed for the wavelength of the laser light. A microcomputer, with two PentiumPro CPU's, controlled the dual camera arrangement, and was capable of acquiring up to 128 image pairs per camera, at the maximum camera rate. To illuminate the flow-field, frequency doubled Nd-Yag laser with dual cavity (Spectra-Physics PIV-400) was used synchronized with the cameras. The time Δt between the two laser pulses was kept at 1-1.5 μsec. Trigger required for the system was provided by a frequency tracker, which locks on the fundamental screech frequency obtained from a near field microphone. This system was developed and applied to subsonic measurements previously (Lourenco et al., 1999).

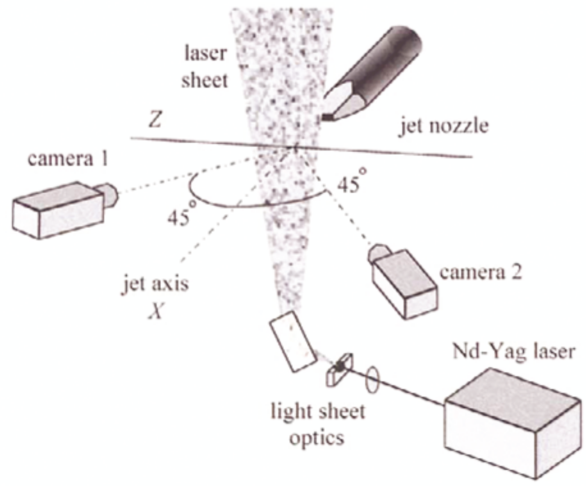

Fig. 1. Measurement setup for 3-D PIV.

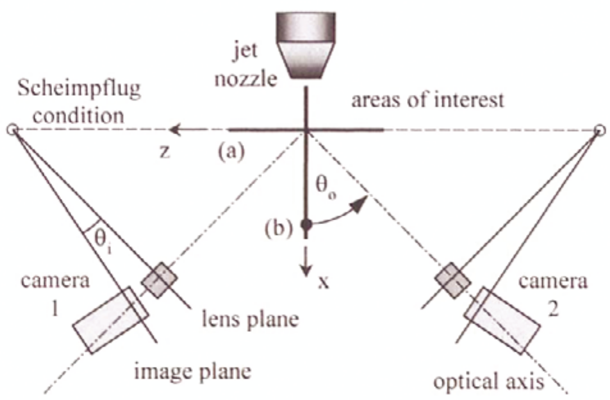

Fig. 2. Camera orientation with respect to the measurement planes; a) vertical to the jet flow (cross plane, *YZ*), b) parallel to the jet flow (minor axis plane, *XY*). The Scheimpflug condition is shown for case a.

Each camera was positioned at a certain angle, θ_o, from the normal of measurement plane to obtain a stereo view of the plane depending on the laser sheet orientation as shown in Fig. 2. There are two view modes in stereo imaging of a flow field; the first one is the same side imaging which is convenient for cross plane measurements and the second one is the opposite side imaging suitable for streamwise measurements. To attain sharp focus on the entire measurement plane, each camera was rotated with respect to the lens plane at an angle of θ_i satisfying the Scheimpflug condition for off-axis imaging (Fig. 2 case (a)). Both cameras were pre-calibrated collectively before the experiment. After processing the images acquired by each camera, the data from each view were combined to give the three-component velocity field at the measurement plane. The equations that govern both the transformation of the image plane to the object plane and the combination of the data from both views to yield a three dimensional velocity field are given in Alkislar (2000).

In order to obtain the optimal view angle for the positioning of the cameras a theoretical error minimization analysis was made. It was assumed that the two optical axes were coinciding at a point on the measurement plane and the view angles with this plane were equal but opposite. An artificial error of 0.05 pixels, which was the maximum expected error in the image processing, was imposed at a point in the image plane. Then the combination equations were applied to obtain the resultant error for the three components of the displacement error vector in the measurement plane, e_u (in plane x component), e_v (in plane y component) and e_w (out off plane component). The error magnitude, e_{tot}, is plotted in Fig. 3 with varying view angle. The minimum error was obtained when the view angle was 45°, yielding an orthogonal orientation of the two optical axes. In practice, θ_o has to be less than about 60° to avoid image distortions that occur for θ_i greater than about 15°.

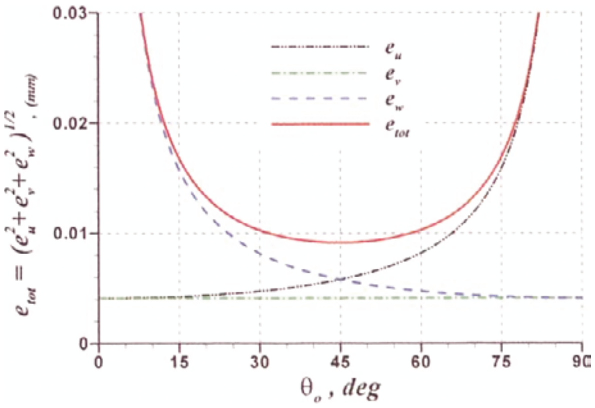

Fig. 3. Optimum view angle for stereoscopic PIV with Scheimpflug condition.

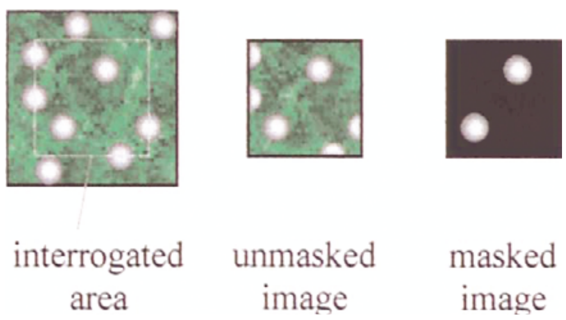

Fig. 4. The image mask operation.

An image matching approach is used for the digital processing of the image pairs to produce the displacement field. To achieve velocity data with high spatial resolution, a novel processing algorithm was developed (Lourenco and Krothapalli, 1998). With the new processing approach, the particle images themselves comprise the interrogation region, which have sizes ranging from 3 to 4 pixel squares. In this scheme the particles images in the correlation window are detected by a threshold method based on the image intensity gradient. Then the background level is removed as well as the images of particles contained by the boundaries of the interrogation window. A correlation is then carried out with the remaining "masked" image data based on each individual particle as shown in Fig. 4.

The displacement between image pairs was found in the usual manner by means of cross-correlation, and a velocity (displacement) vector is assigned at the mid-distance between image pairs. Therefore, each particle pair contributes to a second order approximation of the velocity. However, in contrast to the traditional approach, which uses structured grids, these velocities are evaluated in an unstructured grid. The flow field at any point is described by an analytical function using a least squares fitting algorithm. The function that is used is a second order polynomial,

$$\vec{u} = \vec{a}x^2 + \vec{b}x + \vec{c}y^2 + \vec{d}y + \vec{e}xy + \vec{f} \qquad (1)$$

The marked advantage of this approach is that the field is described at any point with accuracy of second order, including the derivatives that are found by differentiating the previous equation. The error minimization approach maintains the order of the accuracy and provides a means for accurate evaluation of the field derivatives. It was demonstrated that this approach provides substantial improvement in accuracy and spatial resolution over traditional PIV methods (Lourenco and Krothapalli, 1998).

Although an unstructured grid is used for calculating the velocity, for ease of presentation, the velocity field is usually presented at regular intervals. This new scheme is very efficient and incorporates a vector validation procedure, making it independent of operator intervention. The time it takes to compute a vector field depends on the computer hardware. Processing speed ranges from 1400 interrogations/sec on a 200 MHz dual Pentium Pro PC up to several thousand on a 500 MHz Alpha based PC.

A typical instantaneous image pair obtained in the cross plane (YZ) at x/h = 10, is shown in Fig. 5a. The successful seeding of the jet and ambient fluids can be clearly seen in the figure. The resulting three-dimensional velocity field obtained from combining the corresponding stereo views is shown in Fig. 5b. Typically, the velocity field consists of 6000 vectors. For clarity, only a selected number of vectors are shown in the figure. The right figure shows the distribution of in-plane velocity components superimposed with out-of-plane component vorticity contours. The complex shear layer structure is vividly captured in the figure.

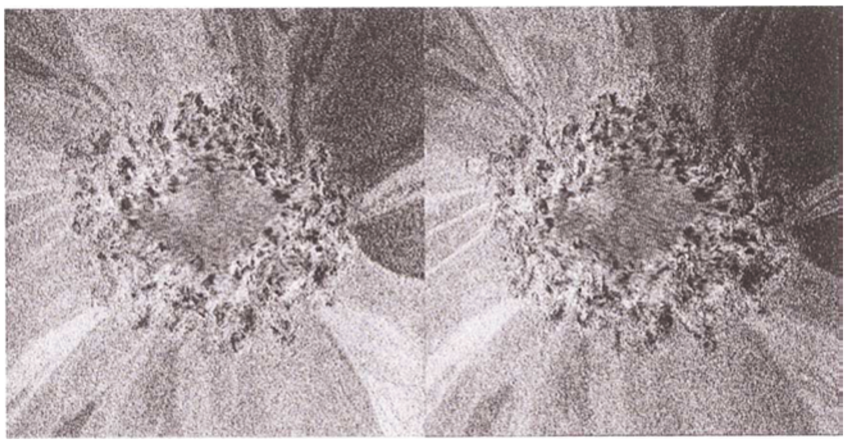

Fig. 5a. A typical instantaneous image pair from cameras 1 and 2.

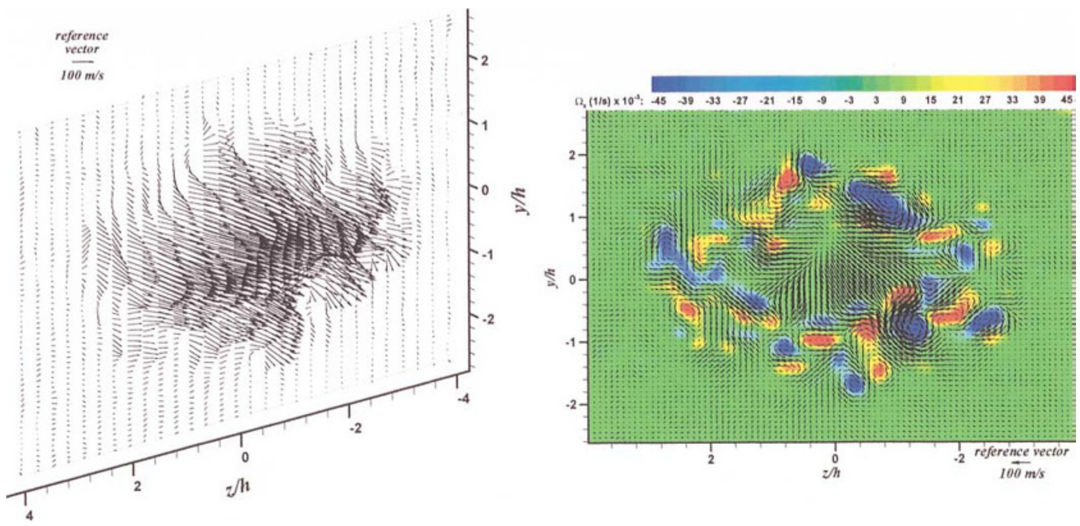

Fig. 5b. Left: The 3-D velocity field; right: in plane velocity components with out of plane vorticity contours.

2.3 Phase Locking

In periodically oscillating flow fields with certain discrete frequencies, it is possible to obtain the time evolution of the coherent motion, by using phase averaging techniques. A schematic of the setup for the phase locked measurements is shown in Fig. 6. In the phase averaging technique, the time dependent variable, $q(\vec{x}, t)$, is decomposed into two components as shown in Eq. (2). For the present study, this quantity represents the velocity vector $\vec{u}(\vec{x}, t)$, and out of plane vorticity $\Omega_t(\vec{x}, t)$

$$q(\vec{x},t) = \left\langle q(\vec{x},\tau)\right\rangle + q'(\vec{x},t) \quad (2)$$

Here, $\langle q(\vec{x}, \tau)\rangle$ is the coherent component at point $\vec{x}$ and $q'(\vec{x}, t)$ is the random component of the quantity. Phase delay τ is varied with in the period of one screech cycle. The coherent quantity is defined in Eq. (3).

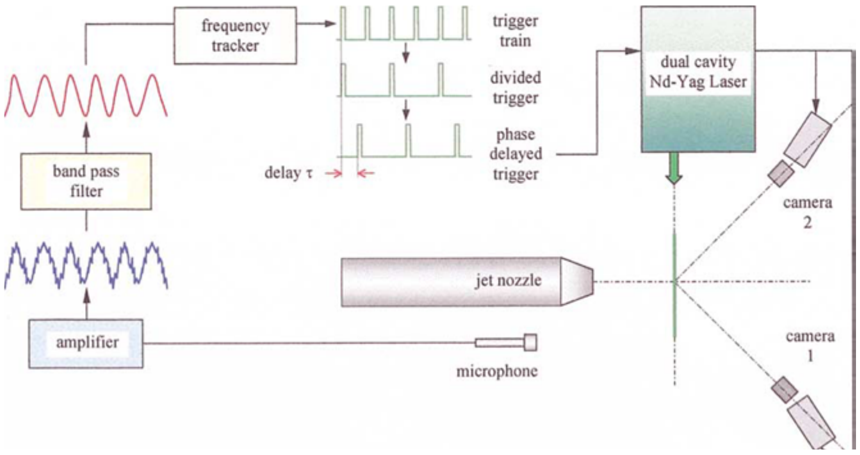

Fig. 6. A schematic of the setup for the phase locked measurements.

$$\left\langle q(\vec{x}, \tau)\right\rangle = \frac{1}{N}\sum_{i=1}^{N} q(\vec{x}, t_i + \tau) \tag{3}$$

where N is the number of samples acquired with phase τ from the reference time t_i. The reference time is obtained from the signal of screech sound measured by a microphone located in the vicinity of the nozzle exit.

$$\bar{q}(\vec{x}) = \frac{1}{M}\sum_{i=1}^{M} q(\vec{x}, \tau_i) \tag{4}$$

Preliminary investigations with phase averaged PIV measurements suggest that an optimal number of samples, N, is about 30. The data was obtained for every 22.5° of the screech cycle. The mean quantity was calculated from the mean of the phase-averaged quantity as shown in Eq. (4) where M is the number of phases.

3. Results and Discussion

The global jet behavior is first examined through the detailed measurements of the velocity distributions. The cross plane mean velocity fields at different downstream locations, as shown in Fig. 7., best capture three-dimensional features of the jet evolution. The velocity distributions are represented by the contours of the axial mean velocity magnitude. A dominant feature of a rectangular jet is the axis switching phenomenon, which results from a faster growth rate of the initial jet shear layers in the minor axis plane (XY) as compared to that in the major

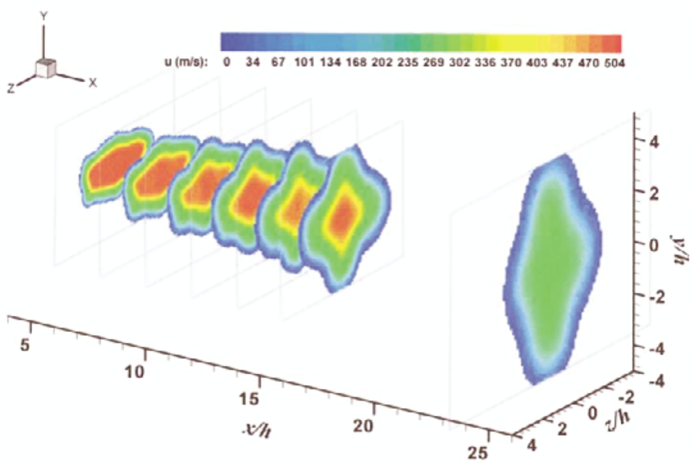

Fig. 7. Major axis or cross plane mean velocity fields at downstream locations of x/h = 6, 8, 10, 12, 14, 16, 25.

axis plane (XZ) (Krothapalli et al., 1981). The faster growth in the minor axis plane is further accentuated by the self-excitation of the screeching jet (Krothapalli et al., 1986).

The enhanced growth rate of the shear layer in the minor axis plane (XY) is due to asymmetric shedding of large scale vortical structures generated by the feedback loop. As a consequence of the vortex shedding, the entire jet column oscillates as shown in Fig. 8. Shown in the figure are the contours of phase averaged axial mean velocity magnitude for four phases of the screeching cycle separated by 90°. The shock-cell structure, with six distinct shock cells, that is representative of an underexpanded jet can be clearly seen in the figure. The frequency of the "flapping" motion observed is 4600 Hz. The resulting Strouhal number ($St = fh/U_e$; U_e is the jet exit velocity) is about 0.1, which is in accordance with the earlier measurements (Shih et al., 1992).

Figure 9 shows the contours of the phase averaged out of plane component of the vorticity magnitude at same four phases as Fig. 8. The unmistakable presence of large-scale vortical structures is easily identified. These large vortical structures are highly three dimensional in nature and as a result, the vorticity contours appear to be fragmented. The source of three dimensionality can be attributed to the generation of streamwise vortices in the shear layers (Krothapalli et al., 1991; Zapryagaev and Solotchin, 1988).

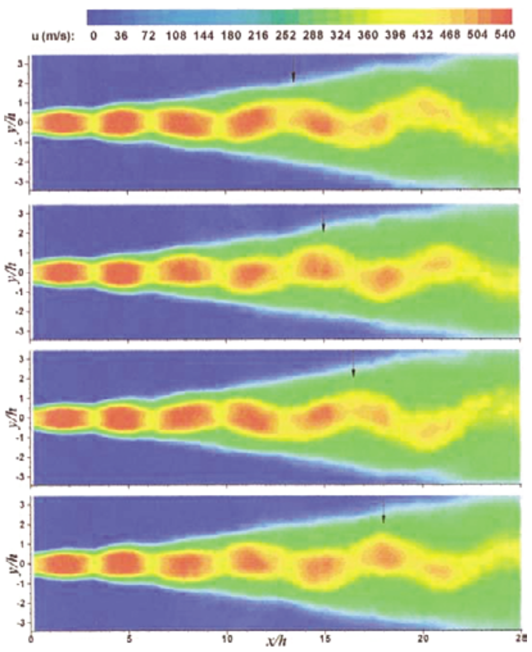

Fig. 8. Phase-locked mean axial velocity fields at different phases within a screeching cycle.

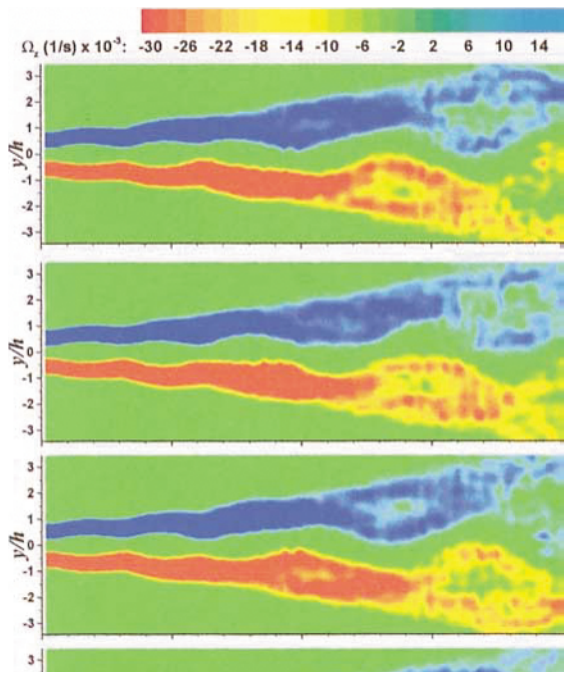

Fig. 9. Phase-locked out-of-plane component of the vorticity field at different phases of a screeching cycle.

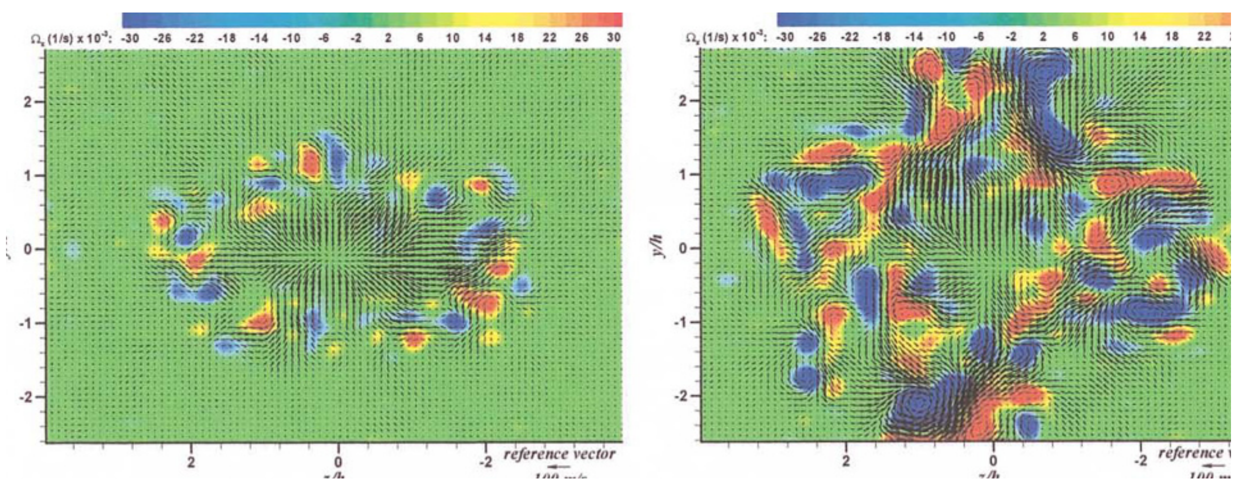

Fig. 10. In-plane velocity vector files, superimposed by the contours of the out of plane vorticity component. Left: x/h = 6, right: x/h = 16.

Anticipating that streamwise vortices would be observed, the instantaneous velocity fields in the cross plane (YZ) are examined for two different downstream locations. The in-plane velocity vector fields, superimposed by the contours of the out of plane vorticity component magnitude are shown in Fig. 10. Counter rotating vortices are prominently displayed in the figure. The strength of these vortices grows with downstream distance. For example, the strength (defined by the maximum value of the out of plane component of vorticity) of the individual vortices at x/h = 16, is almost twice to those at x/h = 6. These vortices will enhance the mixing of the jet and ambient fluids. The origin of these vortices is linked to the oblique disturbances within the diverging section of the nozzle boundary layer (Krothapalli et al., 1998). These disturbances are readily amplified by the inherent instability of the shear layers. The streamwise curvature present due to shock cell structure will further strengthen these vortices with downstream distance.

The rapid diffusion of the jet in the minor axis plane is quantified by the variation of the shear layer width with downstream distance as shown in Fig. 11. The shear layer thickness, δ is defined as the distance between $0.99U$ to $0.05U$, where U is the local centerline velocity. Also included in the figure are the data for an undisturbed shear layer at a comparable convective Mach number. The shear layer grows very rapidly as indicated by the spreading rate. The enhanced growth rate in the minor axis plane is a direct result of self-excitation generated by the feedback loop.

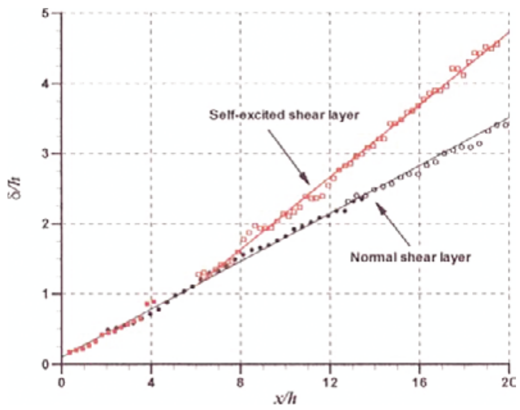

Fig. 11. Shear layer thickness growth with downstream distance.

4. Conclusions

The experiment described in this paper was conducted with two primary goals. The first is to demonstrate the capabilities of a stereoscopic PIV in the measurement of three-dimensional supersonic velocity fields; and the second is to provide an understanding of the role of self-excitation on the development of a rectangular supersonic jet.

Using, novel mesh-free and high-resolution approaches for processing of PIV images, phase locked three-dimensional supersonic flow measurements were successfully made.

The screeching jet is used here to demonstrate a free shear layer control method that exploits the inherent instability of the flow thereby eliminating the need for externally driven actuators that would require considerable power consumption. In practice, the inherent instability may effect the global development through self-excitation. The example of a screeching jet clearly demonstrates the influence of self-excitation through acoustic feedback on global flow response with rapid diffusion of the jet.

Another promising control technique for mixing enhancement is the generation of streamwise vortices in the separating boundary layer. In an underexpanded jet, while taking advantage of the inherent instability of the shear layer, these streamwise vortices grow rapidly in strength with downstream distance and aid in the mixing enhancement.

Acknowledgments

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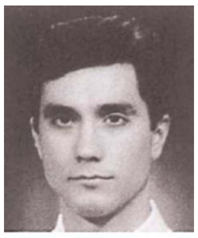

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