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An experimental study of the role of core intermittency in equivalent jet noise sources

Tobias Ecker
Dept. of Aerospace and Ocean Engineering
Virginia Tech
215 Randolph Hall, Blacksburg (VA), USA
ecker@vt.edu

K. Todd Lowe
Dept. of Aerospace and Ocean Engineering
Virginia Tech
215 Randolph Hall, Blacksburg (VA), USA
kelowe@vt.edu

Wing F. Ng
Dept. of Mechanical Engineering
Virginia Tech
440 Goodwin Hall, Blacksburg (VA), USA
ng@vt.edu

ABSTRACT

Large-scale turbulence intermittency has been found in previous work to have a large impact in the noise emission of high speed jets. In the current study, turbulence intermittency due to motions originating from the irrotational core of heated supersonic jets is investigated. A novel multipoint Doppler Global Velocimetry (DGV) instrument with a frequency resolution of 125 kHz is employed to obtain time-resolved data of velocity fluctuations. For jet total temperatures of 1.6 and 2.0 times the ambient temperature, results from the perfectly-expanded supersonic jets at 1.65 isentropic exit Mach number help confirm key observations of convective wave speeds in these flows. In particular, it is apparent that the core region for the colder jet remains irrotational up to 10 diameters downstream of the nozzle exit—the region observed in the study. The hotter case exhibited centerline intermittency of approximately 0.4-0.6 for the stations examined at 6, 8, and 10 diameters downstream the nozzle exit. The results provide a first examination of the interplay of density ratio effects and the dynamic breakdown process of the potential core in supersonic jets—physics integral to the noise generation process.

INTRODUCTION

Juvé et al. (1980) investigated the role of intermittency in the noise emission of cold subsonic jets and found it to have a great impact at the end of the potential core. Their results indicate that motions contained within 10% of the time contributed to about 50% of the produced noise. Furthermore a connection between the interacting process of large-scale structures, specifically on the interface where entrainment causes strong deceleration or acceleration in the radial direction, and noise emission is suspected. Panda et al. (2002) experimentally correlated the data from a Rayleigh scattering based probe, measuring density and velocity fluctuations, with the data from a microphone in the far field of fully expanded unheated high subsonic and supersonic jets. Their measurements indicated the regions just downstream of the potential core on the centerline to contain strong sound-producing sources in the flow for both sub and supersonic jets. Bogey and Bailly (2007) used large eddy simulation (LES) to simulate high subsonic, low and high Reynolds number isothermal jets. Their results corroborate that the periodic and intermittent intrusion of vortical structures into the jet core near the end of the potential core could be a significant contributor to the downstream jet-noise component. Recent numerical studies have increasingly aimed at analyzing and including intermittency effects into jet noise prediction efforts (Jordan et al. 2014; Koenig et al. 2013).

Recently Lowe et al. (2012) have presented a concept for the development of a new instrument based on the Doppler Global Velocimetry (DGV) technique, capable of time resolved measurements at multiple points (from here on referred to as TR-DGV). In a first step Ecker et al. (2014a) have demonstrated the fundamental developments for the Doppler-based technique capable of very high temporal resolution three-velocity component particle measurements in supersonic jets. This technique has evolved by using high sensitivity photodetectors, FPGA-based signal processors and a continuous wave laser, to deliver instantaneous velocity data at 32 points simultaneously at data rates of 250 kHz or higher. The instrument used in this study has been applied to date in the developing shear layer downstream of a supersonic plume operated at diameter Reynolds numbers of approximately 1 million.

Indication of intermittency in turbulent jets

Hileman and Samimy (2001) studied the turbulent structures in a unheated $M = 1.3$ supersonic jet using flow visualization and a synchronized microphone pair. Periodic large-amplitude noise events were observed in the far field and their production attributed to distinct events within the flow. The chaotic motion of large-scale coherent structures dominates fourth-order statistics. Due to the interest in predicting the power spectral density of acoustic density fluctuations, a mean-square quantity, 4th order statistics hold direct application in acoustic analogies.

Ecker et al. (2014b) previously presented 2nd and 4th order space-time correlations, integral timescales, convection velocities and auto-spectra on the lip line of a hot (*TTR* = 1.6 and *TTR* = 2) supersonic perfectly expanded jet at M_d = 1.65. They also presented single point statistics indicative of the non-Gaussian nature of the statistics on the interface of the mixing layer of heated supersonic jets, confirming the contribution of large scale mixing events to the 4th order correlation (i.e., high kurtosis). The kurtosis for the flow results presented provide confirmation of this argument. In contrast to the η^* = 0 region, the shear layer edges, both outer and inner, have kurtosis values greater than the Gaussian value. This was also observed in a PIV study conducted in a screeching round jet by Edgington-Mitchell et al. (2014). The authors suggested that this might indicate regions of higher intermittency in the outer shear layer.

Intermittency factor

In order to give a more meaningful measure to the intermittency of a flow, Townsend (1949) introduced the intermittency factor γ.

The intermittency factor is commonly defined as the time the flow remains in turbulent state *I(t)* = 1 divided by the total time.

$$\gamma = \frac{t(I(t)=1)}{t_{total}} \qquad (1)$$

For fully developed jet flows the intermittency factor profile has been found in previous experimental studies (Stoff, 1981; Wygnanski & Fiedler, 1969).

DATA PROCESSING

Commonly the intermittency factor is found by discriminating the time-resolved velocity signal into temporary turbulent and non-turbulent sections.

Zhang et al. (2013) give a brief review on previous work in intermittency detection and intermittency detection methods for turbulent jets and boundary layers, for example the turbulent energy recognition algorithm (TERA) which is formulated as follows:

$$I(t) = \begin{cases} 1, & \overline{\left|u'\frac{\partial u'}{\partial t}\right|} > C_0\left(u'\frac{\partial u'}{\partial t}\right)_{RMS} \\ 0, & \overline{\left|u'\frac{\partial u'}{\partial t}\right|} \leq C_0\left(u'\frac{\partial u'}{\partial t}\right)_{RMS} \end{cases} \qquad (6)$$

where $C_0\left(u'\frac{\partial u'}{\partial t}\right)_{RMS}$ is the intermittency criterion or threshold.

Other works such as Corrsin and Kistler (1955) or Heskestad (1965) have used a simpler formulation,

$$I(t) = \begin{cases} 1, & (u')_{RMS} > C_0 \\ 0, & (u')_{RMS} \leq C_0 \end{cases} \qquad (7)$$

where $(u')_{RMS} = \sqrt{\overline{(u')^2}}$ and C_0 is the threshold intermittency criterion. The method of Zhang et al. implies a high pass filter function due to the time derivative, while the Corssin and Kistler method accounts only for deviation from mean velocities. For the present study, both methods produced similar values and the Corssin and Kistler method was adopted due to better random noise immunity.

In order to obtain a result with minimum subjectivity, the intermittency factor was examined as a function of threshold level C_0. The shape of this function can be considered as a measure of the detection sensitivity—a rapidly decaying intermittency factor contains fewer temporally localized events, making significant contributions to the overall intermittent timespan at the threshold levels under investigation. For each velocity signal, the threshold level was found where the derivative of the level peaked. The average level for C_0 was then used to discriminate all datasets at all locations for each *TTR*.

An example of the velocity signal and the intermittency state discriminated by $u'\partial u/dt$ are shown in figure 1, as well as for a full radial time signal shown in figure 2.

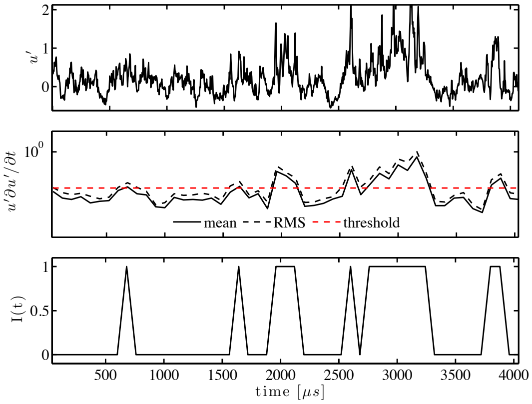

Figure 1. Example of velocity signal and intermittency discrimination at *TTR* = 2.0 and *x/D* = 10.

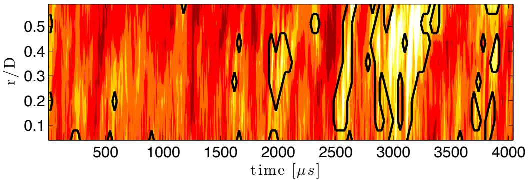

Figure 2. Example of detection of intermittency structures using binary gating at *TTR* = 2.0 and *x/D* = 10.

EXPERIMENTAL APPARATUS AND FACILITY

DGV instrument

The laser-based time-resolved DGV (TR-DGV) concept has frequency response up to 125 kHz at 32 simultaneous points in the flow and a contiguous acquisition time of greater than one second. The development and application of the TR-DGV instrument and the PMT sensor system used, are documented by Ecker et al. (2014b, 2015).

Hot jet facility

The Virginia Tech hot jet facility has been described in past works (Ecker et al. 2014a). This electrically heated (192 kW) free jet facility provides supersonic flow at total temperatures ratios, T_0/T_a, up to 3 (depending on nozzle diameter) at 0.12 kg/s mass flow rate. The bi-conic nozzle used ($M_d = 1.65$) was adapted from the geometry studied by Powers and McLaughlin (2012) for military-style nozzles, differing in the present study by being axisymmetric rather than azimuthally faceted. The diameter D of the nozzle is 38.1 mm (1.5 in).

A photograph of the jet facility, including the locations for seeding inlet and total pressure and temperature measurement locations, is shown in figure 5. For improved mixing of the seed an extension of 600 mm (2 ft) has been appended to the nozzle assembly. For the hot flow studied, seeding is performed by introducing Al_2O_3 particles generated by a cyclone seeder unit. Bias errors in the jet shear layer due to flow seeding gradients are minimized by co-flow seeding via entrainment from a smoke generator.

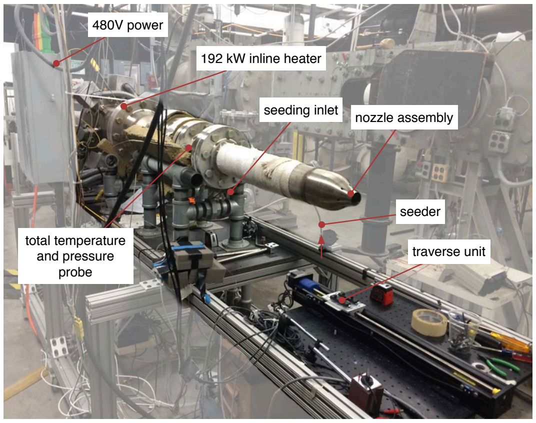

Figure 3. The Virginia Tech hot supersonic jet facility.

Test matrix and geometry

As in Ecker et al. (2015), two cases (A and B) at two different total temperature ratio (TTR) conditions are studied via time resolved measurements at 4 different streamwise locations (*x/D* = 4, 6, 8 and 10, see figure 4). The parameters of the two cases are provided in table 1. Recording time length was 1 s with an effective data rate of 250 kHz.

Table 1. Hot jet cases.

Case	*Re*	M_j	ρ_j/ρ_a	*TTR*
A	1.3M	1.68	0.96	1.6
B	1.15M	1.70	0.79	2.0

The diameter-normalized streamwise coordinate, *x/D,* on the centerline is defined as the distance from the nozzle exit plane to the center of the optical measurement plane (shown as the red grid in figure 4). The normalized radial coordinate, *r/D,* is defined as the distance from the centerline to each measurement location within the plane. The physical distance between measurement locations is 3 mm.

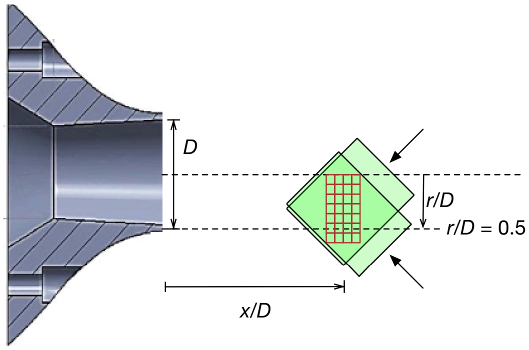

Figure 4. Nozzle and sensor configuration and nomenclature.

Mean Jet Statistics

The mean velocity and turbulence statistics have previously been investigated by Brooks and Lowe (2014). As shown in previous studies (Lau 1980), the mean velocity, as well as normal and shear stresses, of a developing shear layer can be collapsed radially with a similarity scaling based on the radial location of 50% of the jet exit velocity and accounting for linear shear layer growth:

$$\eta^* = (r - r_{0.5U_j})/x \tag{8}$$

where $r_{0.5U_j}$ is the local radius at which the velocity is half the jet exit velocity.

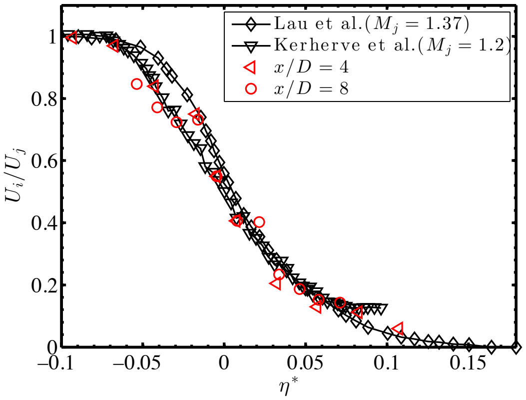

Figure 5. Similarity profiles for the streamwise mean velocity for case B at *x/D* = 4 and 8 compared to other studies.

The results for the mean velocity distribution of this jet, as well as Reynolds normal stresses, are compared with results from studies by Kerhervé et al. (2004) and Lau et al. (1979) (figures 3 and 4). As in previous studies, the Reynolds stress magnitudes are the highest along the shear line, defined as $\eta^* = 0$.

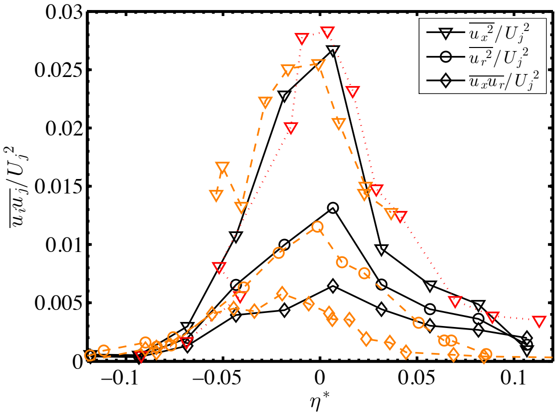

Figure 6. Normalized Reynolds stresses at $TTR = 2.0$ compared with literature values. Solid (black) line – current study, dotted (red) line – Lau et al. (Lau et al., 1979) ($M_j = 1.37$, $TTR = 1.0$), dashed (orange) line – Lau (Lau, 1981) ($M_j = 0.9$, $TTR = 2.7$).

RESULTS

Signal traces

The streamwise velocity fluctuation signals at four *x/D* stations, up to *x/D = 10,* are shown in figure 7. Where the potential core is intact (*TTR* = 1.6 case), velocity fluctuations are confined to radial locations near the nozzle lip line. As the potential core of the *TTR* = 2.0 case is shorter, the velocity fluctuation trace at the locations in the potential core breakdown region (*x/D* = 6 – 10) show strong velocity fluctuations across the entire jet radius. In this region, structures are observed to convect at velocities higher than the local mean velocity (Ecker et al. 2015). The intermittency in this region will indicate periods over which high speed, core fluid protrudes into an otherwise vortical region. This mechanism, which can be used to explain eddy convective velocity observations, is examined more to follow.

Intermittency

The profiles of the intermittency factor for both *TTR* cases are shown in figure 8. While past results for this parameter have been obtained for fully developed, the current results exhibit some differences from past observations. The intermittency of fully developed jets is caused wholly due to entrainment of ambient, irrotational fluid. To the contrary, developing shear layers exhibit intermittency due to structures entrained from both the ambient edge and core of the jet.

The *TTR* = 1.6 case (top) exhibits profiles indicating a non-turbulent flow near the jet axis for all streamwise stations. As expected, intermittency increases away from the centerline. As the potential core has not broken down, the higher intermittency near the shear line ($\eta^* = 0$) are consistent with the increased normal and shear stresses in this region (compare figure 6).

At the $x/D = 4$ location, the $TTR = 2.0$ shows similarities to the lower *TTR* case. The intermittency at this streamwise station near the centerline of the lower *TTR* case is higher than the *TTR* = 2.0 case, but both cases

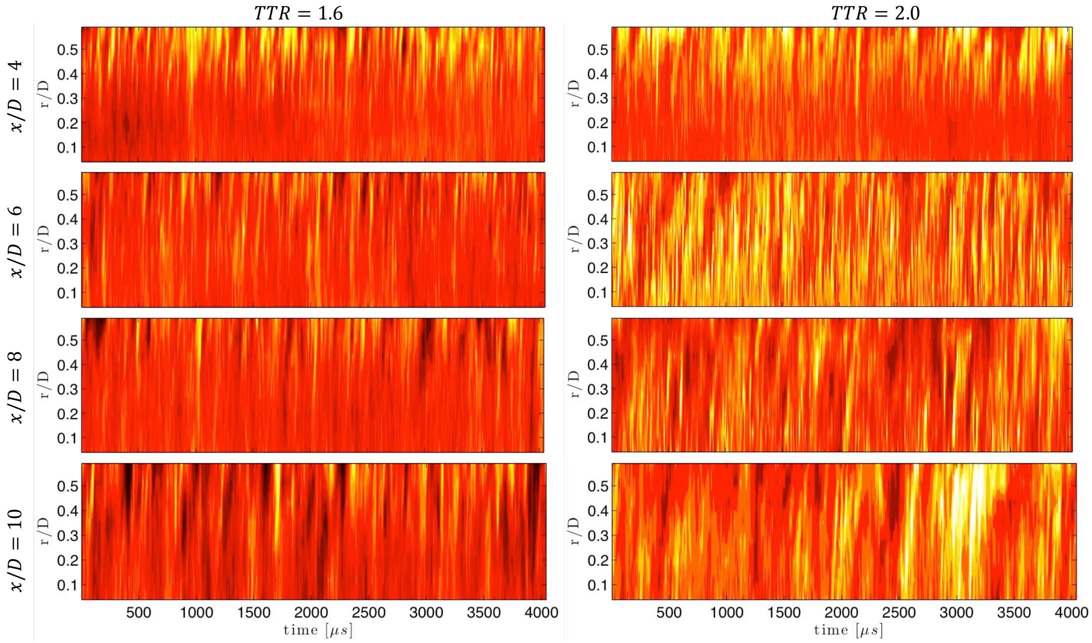

Figure 7. Velocity fluctuation signal traces for both *TTR* cases at different *x/D* stations. The colormap scaling of each plot is choosen to have a range -3 and 3 times the standard deviation of the signal trace presented.

are within the uncertainty of the technique.

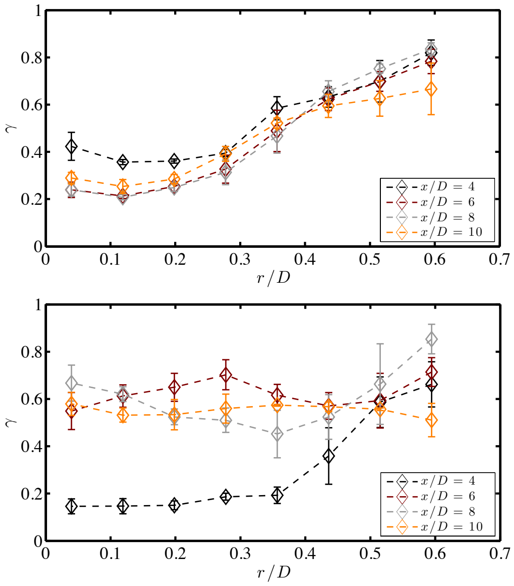

Figure 8. Profiles of intermittency factor at *TTR* = 1.6 (top) and *TTR* = 2.0 (bottom). Error bars indicate standard deviation of the 4 radial pixels used to determine intermittency factor.

At *x/D* > 4, both cases differ; intermittency factors in the core region are significantly greater for the $TTR = 2.0$ case, which coincides with regions of increased values of acoustic Mach numbers, as well as a region of increased frequency-dependent convective velocity (Ecker et al. 2015). The authors hypothesized that a mechanism in which the irrotational flow in the potential core is pinched off into downstream regions, resulting in increased convective wavespeeds. As such, jet noise implications are significant for the behavior of this region, due to the influence on Mach wave radiation (Ffowcs Williams and Maidanik 1965). This large-scale eddy effect indicated by intermittency appears to contribute to the relative reduction of noise observed for heated jets (Tanna 1977). The potential core mixing nearer the nozzle exit for hotter jets acts to reduce the relative volume occupied supersonic eddies. As such, moderate values (in contrast to irrotational or fully turbulent values) of core intermittency are an indicator of rapidly convecting disturbances that produce peak noise.

CONCLUSIONS

A heated supersonic jet at two different total temperature ratios was experimentally investigated for the intermittency of the velocity fluctuations. The data within the early developing shear layer shows a shape unlike fully developed jets. Highest intermittency factors are found close to the shear line ($\eta^* = 0$), as would be expected. Significant differences were observed, however, for the two cases with different total temperature rations examined. For the hotter case, *TTR* = 2.0, elevated intermittency factors are found near the centerline for stations $x/D \geq 6$. In contrast, the cooler $TTR = 1.6$ case exhibits a longer potential core and reduced core intermittency. The longer potential core serves to sustain eddies moving at supersonic speeds relative to the ambient fluid over a greater volume than would occur if the potential core followed the same structure as the $TTR = 2.0$ case. As such, it is likely that these mechanisms are closely related to previous observations that peak noise driven by Mach wave radiation reduce with heating, even for the same jet exit velocity.

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