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Flow Characteristics of the Outer Part of a Circular Jet with and Without Excitation

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SUMMARY Statistics of flow reversal in the outer region of the near field of a circular jet are examined with and without acoustic excitation. These statistics, which include the mean duration and frequency of flow reversal, are obtained with a hot-wire/cold-wire arrangement, designed so that the cold wire senses the thermal wake of the hot-wire. The organisational influence of excitation on the large structure is largest near the nozzle but weakens with distance downstream. At ten diameters from the nozzle, the velocity structure parameters of the turbulence are unaffected by the excitation.

1 INTRODUCTION

It seems well established that the organised large structures in the near field of a jet plays an important role in the dynamics of the flow and in particular in mixing and in sound generation. Controlled excitation of the jet can accentuate the characteristics of these structures and provide a relatively simple means of studying them. Hussain & Zaman (1979) carried out a detailed exploration of vortex pairing in the near field of an acoustically excited circular jet (exhausting into still air) by applying phase averaging techniques. An inevitable difficulty encountered in this type of study is that the flow on the low-speed side of the mixing layer undergoes reversal. At some phases during the passage of the vortices, instantaneous measurements, by a directionally insensitive hot-wire, of the velocity vector direction and the vorticity are consequently in error. In a previous paper (Antonia et al, 1980) we investigated errors, due to flow reversal, in simultaneous measurements of temperature and velocity in the far field, of a circular jet. The experimental technique used to identify and obtain statistical information of the reverse flow regions is applied here to the near field of a circular jet, with and without excitation. The intention, in this paper, is not to attempt to correct velocity and other statistics influenced by the flow reversal but simply to ascertain the influence of excitation on the large structure through the statistics of the flow reversal regions.

2 EXPERIMENTAL ARRANGEMENT

The jet facility used in this study is described by Hussain & Zedan (1978). The nozzle (diameter D = 7.62 cm) had a cubic profile (Hussain & Ramjee, 1976) and was made from laminated wood blocks so that the jet emerged through a 30 cm dia. end plate. The exit Reynolds number $R_D = DU_j/\nu$ was 1.1×10^5. For the unexcited jet, the exit turbulence intensity at the centreline was about 0.3%. With excitation, the Strouhal number, $St = fD/U_j$ was 0.37 and the exit turbulence intensity was 3%. The exit boundary layer mean profile agreed with the Blasius profile.

The measurements presented here were made with a hot-cold wire arrangement with the wires orthogonal and normal to the axial flow direction. The cold wire was approximately 1 mm upstream of the hot wire and was used to detect flow reversals by sensing the hot wire wake. The hot wire, 5 μm dia. (Pt-10% Rh) was operated by a DISA55M10 constant temperature anemometer at an overheat of 0.8. The cold wire, 0.6 μm dia. (Pt-10% Rh), was operated by a constant current bridge, the value of the current being set at 0.1 mA. Signals from the linearised constant temperature anemometer and from the constant current bridge were recorded, following suitable signal conditioning, on a Hewlett-Packard FM3960A tape recorder. The analogue tapes were later played back and digitized on a DEC PDP 11/20 computer (sample rate ≈ 1000 Hz, record duration ≈ 50 s), for further data processing.

Measurements of flow velocity and flow reversals were made at x/D = 2, 3, 6 and 10 in the outer part ($r/r_{\frac{1}{2}} > 1.0$) of the jet. Here, r is the radial distance from the jet centreline and $r_{\frac{1}{2}}$ is the jet half radius.

3 RESULTS AND DISCUSSION

Figure 1 shows that mean axial velocity profiles at different x are essentially unaffected by the excitation. For x/D > 3, the profiles are in reasonable agreement with Chevray & Tutu's (1978) measurements at x/D = 15. The half radius (Fig. 2) is generally larger at St = 0.37 than for St = 0.

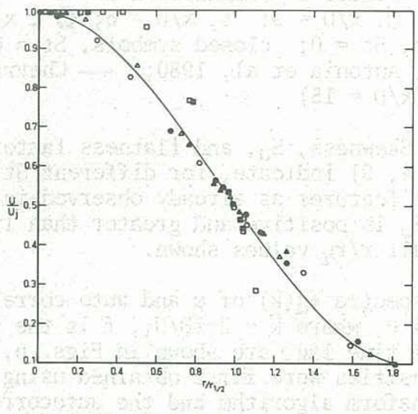

Figure 1 Distribution of mean velocity *
* Symbols same as Figure 3

The relative behaviour of $r_{\frac{1}{2}}$ at the two values of St is very similar to that of Zaman (1978) who compared the variation of $r_{\frac{1}{2}}$ for St = 0.85 ($R_D = 3.2 \times 10^4$) in the same diameter jet with that for the unexcited flow. Zaman found that the slope of $r_{\frac{1}{2}}$ vs x was roughly constant after x/D = 8 for both St = 0.85

and 0. Note that St = 0.85 corresponds to the "jet column mode" of excitation, involving stable vortex pairing of vortex rings near x/D = 1.75, irrespective of whether the initial boundary layer is laminar or turbulent.

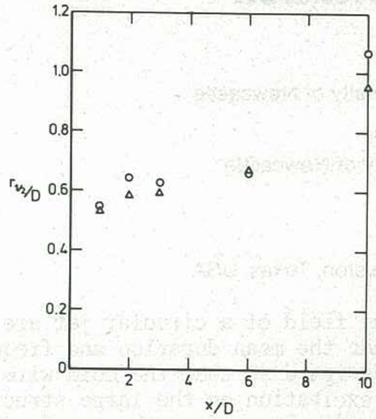

Figure 2 Variation of jet half width with x
Δ, St = 0; o, St = 0.37

Axial velocity fluctuation intensities are plotted as a function of $r/r_{½}$ in Fig. 3. Also shown are the measurements of Chevray & Tutu at x/D = 15 and of Antonia et al (1980) at x/D = 20 in the same experimental facility. For St = 0 at x/D = 2 and 3 the distributions of u' with r are similar but lower than the distributions obtained at x/D = 6 and 10 which are also similar and appear to be approaching self-preservation. For St = 0.37 the u' distribution is similar as for the unexcited flow at x/D = 2. The u' distribution increases with increasing x/D up to x/D = 6 and then relaxes to a self-preserving profile at x/D = 10.

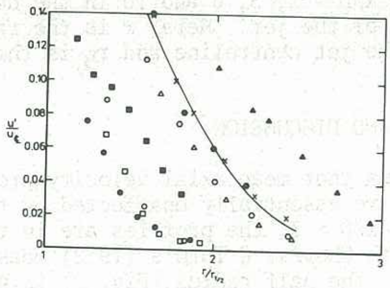

Figure 3 Profiles of u'
o, x/D = 2; □, x/D = 3; Δ, x/D = 6; ⬡, x/D = 10; open symbols, St = 0; closed symbols, St = 0.37; X, x/D = 20, Antonia et al, 1980; —— Chevray & Tutu, 1978 (x/D = 15)

Profiles of Skewness, S_u, and flatness factor, F_u, of u (Figs. 4, 5) indicate, for different St and x/D, similar features as already observed in the u' profiles. S_u is positive and greater than 1 and $F_u > 3$ for all $r/r_{½}$ values shown.

Normalised spectra $\phi_u(\hat{k})$ of u and auto correlations $R_\theta(\tau U_j/D)$ of θ, where $\hat{k} = 2\pi fD/U_j$, f is the frequency and τ the time lag, are shown in Figs. 6, 7. Spectral densities were first obtained using a fast Fourier transform algorithm and the autocorrelations were subsequently generated by doing an inverse Fourier transform. The spectra are normalised so that the integral $\int_0^\infty \phi_u \, d\hat{k} = 1$. Distributions of ϕ_u indicate the growing importance of the low frequency contribution to ϕ_u with increasing x and a-5/3 region is evident. With excitation a local peak occurs and the excitation frequency (2πSt), in ϕ_u at x/D = 2 and 3 (contains 26% and 5% respectively of the spectral energy, the area under ϕ_u between the

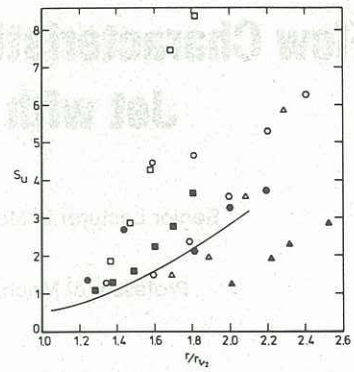

Figure 4 Profiles of S_u *
Solid line Chevray & Tutu, 1977 (x/D = 15)

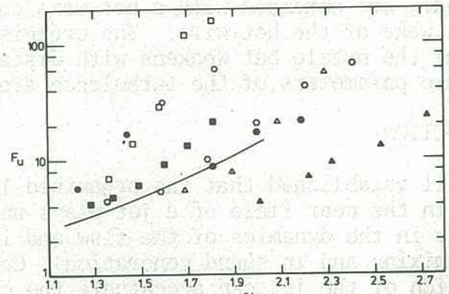

Figure 5 Profiles of F_u*
Solid line Chevray & Tutu, 1977 (x/D = 15)

frequencies neighbouring the excitation frequency). At x/D = 2 a local peak also occurs at the 2nd harmonic (24% of energy) while a weaker bump is observed at the 3rd harmonic of the excitation frequency. At x/D = 3, a small non-significant deviation occurs in ϕ_u at the 2nd harmonic. At larger values of x/D, no peaks are evident in the spectra. The reason the turbulent structure at x/D = 2 (as evidenced by u', S_u, F_u distributions) is not affected by excitation is the selective (i.e. narrow band) influence excitation exerted on the spectrum.

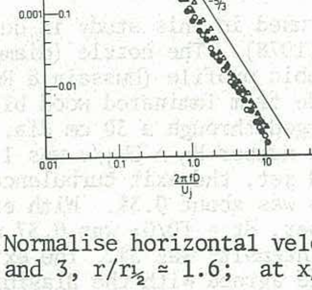

Figure 6 Normalise horizontal velocity spectra * at x/D = 2 and 3, $r/r_{½} \approx 1.6$; at x/D = 6 and 10, $r/r_{½} \approx 2.3$

Autocorrelations of θ indicate for x/D = 2 and 3 a periodic but not sinusoidal (flat troughs and peaked crests), flow reversal for St = 0.37 with the same period as the excitation. Once R_θ crosses zero, for x/D ≥ 6, it remains less than 0.05. Crow & Champagne (1971) found from spectra of u taken along

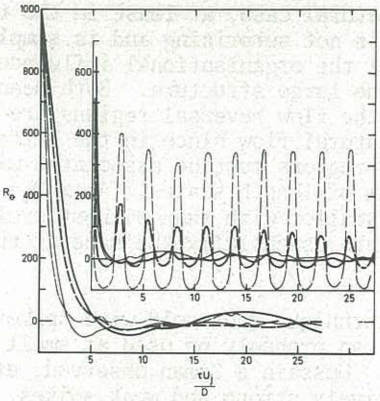

Figure 7 Autocorrelations of temperature
Solid lines, St = 0; dashed lines, St = 0.37; thin lines, x/D = 2 and 6; thick lines, x/D = 3 and 10; same r as Fig. 6

the centreline of a jet that "large eddies" (vorticity-containing regions of fluid which can be identified as coherent structures in the flow, Yule, 1978), within the first five diameters of the jet exit (R_D - 1.1 × 10^5) can be controlled by application of small excitation levels at the exit plane (St = 0.30). No control was possible for x > 8D. For the present study, effects of the "large eddies" (shown up as spikes in ϕ_u and the periodicity in R_θ) seem to disappear by x/D = 6.

The proportion of time α that the flow reversal occurs (identified by temperature spikes) was obtained by the following detection procedure. A spike occurs whenever the temperature fluctuation θ exceeds a selected threshold, Th, determined by visual scrutiny of temperature traces on the computer display terminal. The sample of θ in Fig. 8 (sign of θ inverted) clearly shows that the base line is not steady, the relatively low frequency being possibly associated with draughts in the air conditioned room. For this study, Th was selected by observing the variation of the spike frequency F_α with Th. The parameter α was found not to be as sensitive as F_α in selecting the threshold voltage. Note that there is no plateau in α with Th, a result analogous to the observed lack of independence with Th of the intermittency factor or fraction of time for which a flow is turbulent. The final choice of Th corresponded to a relatively sudden change in $\partial F_\alpha/\partial(Th)$. In Fig. 8 this occurs at a threshold level of 6.89 volts, the vertical line in the lower plot corresponding to the solid horizontal line in the θ trace.

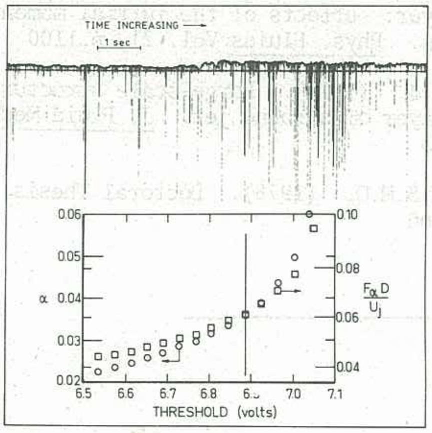

Figure 8 Distributions of α and F_α as a function of Th. Also shown is portion of θ trace with Th = 6.89 volts indicated by the solid line. ○, α; □, F_α

This technique can only be used to provide relative information, i.e. the absolute values of quantities such as α, F cannot be guaranteed but the relative effect due to variation of x, r and excitation should be reliable.

Distributions of α and F_α ~~are shown~~ in Figs. 9, 10. The distributions of α at different x either increases with r or increase at first and then decrease as r increases. The onset of reverse flow occurs at smaller $r/r_{1/2}$ for x/D = 2 and 3 than for x/D = 6 and 10. There does not appear to be any unique self-preserving curve to which the α profiles approach at larger x/D positions. The excited α profiles at x/D = 6 and 10 straddle the α distribution obtained at x/D = 20 (Antonia et al, 1980). At each station except for x/D = 2, α is larger for St = 0 than St = 0.37.

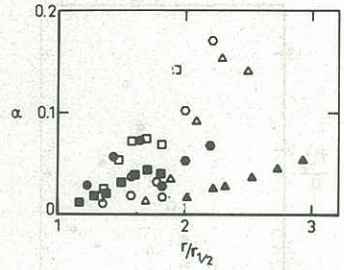

Figure 9 Distribution of α *

The frequency of flow reversals for St = 0.37, slightly less than St/2, is higher than St = 0 at x/D = 2. At x/D = 3 the frequency for the two St is similar, for x/D ≥ 6 F_α is greater for St = 0 than St = 0.37. Generally F_α first increases and then decreases as $r/r_{1/2}$ increases. At x/D ≥ 6 and St = 0.37, F_α does not change in magnitude and is, to within experimental uncertainty, independent of r.

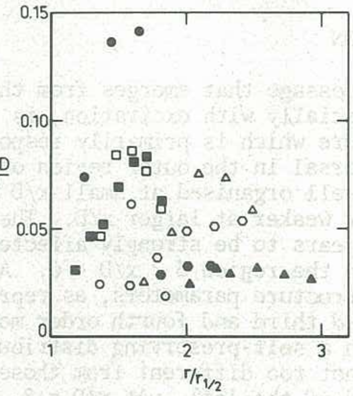

Figure 10 Distribution of F_α *

The mean duration $\overline{T}$ (Fig. 11a) of flow reversal regions and rms value T' (Fig. 11b) of the duration of these regions with respect t- the mean increase with r for the range of r covered by the absissa. The sampling time interval (normalised by U_j and D) of about 0.3 can be thought to represent a crude estimate of the experimental uncertainty in $\overline{T}$ and T'. The $\overline{T}$ and T' distributions for St = 0.37 are below those for St = 0 at the various x locations. These profiles for the excited case seem to collapse onto a single curve except at x/D = 10 where the difference between the excited and unexcited values is not great.

The skewness S_T and flatness F_T (not shown here) of the duration of flow reversal regions were also obtained. For the unexcited case S_T and F_T increase with r, the rate of increase being much greater at

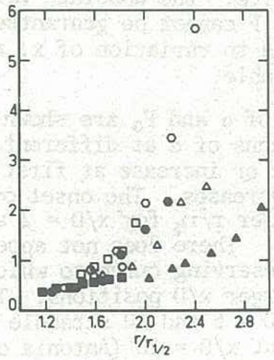

Figure 11a Mean duration of flow reversal, T *

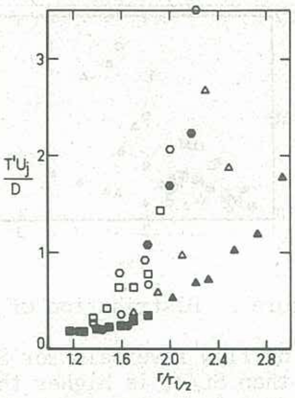

Figure 11b T' *

the two stations closer to the jet exit. Of interest are the Gaussian values $S_T \approx 0$ and $F_T \approx 3$ obtained at x/D = 2, 3 in the excited jet. Both S_T and F_T decrease with increasing r at x/D = 6, 10 with excitation.

4 CONCLUSION

The overall message that emerges from the present results, especially with excitation, is that the large structure which is primarily responsible for the flow reversal in the outer region of the flow, seems to be well organised at small x/D but becomes progressively weaker at larger x/D. The turbulence structure appears to be strongly affected by the excitation in the region 3 < x/D < 6. At x/D = 10, turbulence structure parameters, as represented by the normalised third and fourth order moments of u seem to reach a self-preserving distributions (apparently not too different from those measured in the far field of the jet). At x/D = 2, both the magnitude and frequency of flow reversal regions is large, as evidenced by the R_θ and F_α results of Figs 9, 10, when excitation is present. In particular, both α and F_α are fairly large, the latter being of the same order of magnitude as the forcing frequency Note that the influence of excitation in this region is so dominant as to be observed in the increase in the mean width of the mixing layer (Fig. 2 for x/D = 2). That α and F_α are smaller in the excited than in the natural case, at least in the region 3 < x/D < 6, is not surprising and is simply a consequence of the organisational influence excitation has on the large structure. Both mean and rms durations of the flow reversal regions are smaller than in the natural flow since in the latter case, flow reversal regions must be associated with a wider spectrum of length scales. At x/D = 10, α and F_α are still smaller with than without excitation but $\bar{T}$ and T' are essentially the same at the two values of St.

The present technique (hot-cold wire spike-catching arrangement) can probably be used at small x/D (< 2) to advantage. Hussain & Zaman observed, at x/D = 0.6, alternatively strong and weak spikes, associated with consecutive vortices prior to pairing.

5 ACKNOWLEDGEMENTS

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