STRUCTURE OF TURBULENT BULGES IN AN AXISYMMETRIC JET

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Summary

Conditional sampling techniques are used to determine the shape of ensemble averages of the axial (u) and radial (v) velocity and temperature (θ) fluctuations and their products uv, uθ and vθ, within turbulent bulges of a slightly heated axisymmetric jet with a co-flowing external stream. Ensemble average shapes are obtained at four radial positions in the intermittent region of the flow. In bulges of relatively large duration, ensemble averages of v and θ rise fairly sharply near the front of a bulge and decrease rather gradually near the back. Ensemble averages of u are nearly symmetrical within the bulge. The mean values of ensemble averages of u and θ within a bulge are essentially independent of the duration of the bulge. The largest contribution to the Reynolds shear stress or heat flux generally arises from bulges of medium duration but, near the jet axis, bulges of relatively short duration provide a significant contribution. For a bulge of specified duration, a major contribution to the Reynolds shear stress or heat flux occurs in the vicinity of the back near the axis of the jet but close to the front elsewhere.

Introduction

The existence and importance of the large scale motion in turbulent flows has been recognised for quite some time now (see, e.g., Townsend [1]). More recent experiments (e.g., Fiedler and Head [2], Brown and Roshko [3], Falco [4]) have not only confirmed some of the early ideas but have added new information. The existence of a large scale motion in a given flow manifests itself essentially in the form of large scale bulges in a record of turbulent signals. Substantial quantitative information on the large scale motion can therefore be acquired by the use of conditional sampling and averaging techniques on turbulent signals (e.g., Kovasznay *et al.* [5], Kaplan and Laufer [6], Browand and Weidman [7]). One useful type of conditional measurement is the ensemble averaging technique, which is essentially a generalisation of the 'point averaging' technique introduced by Kovasznay *et al.* The notion of ensemble averaging has been used by Antonia [8] in a turbulent boundary layer and LaRue and Libby [9] in a heated turbulent wake.

The presence of a large scale motion in turbulent shear flows can lead to certain features of the small scale motion that may be interpreted to be in conflict with the concept of local isotropy. A good example of this possibility is the measured non-zero value of the skewness of the streamwise derivative of the temperature fluctuation or of the normal velocity fluctuation. It is therefore important to be able to assess the possible contribution of the large scale motion when properties of small scale turbulence are considered. In this paper, the ensemble averaging technique (described in the next section) is used to obtain more quantitative information on the structure of large scale bulges in an axisymmetric jet. An aspect of particular interest is the similarity of large duration bulges at different radial stations in the jet. All bulges of a specified duration (in practice within a certain interval centered on the specified duration) are ensemble averaged. This operation is performed for bulges of different durations, and at four radial positions across the jet, including the (very nearly) fully turbulent region as well as the highly intermittent region of the flow. Ensemble averages are obtained for bulges of axial (u) and radial (v) velocity fluctuations and temperature fluctuation θ, and their products uv, $u\theta$ and $v\theta$. In all these cases, temperature is used as a passive tracer in the turbulent flow.

Experimental Conditions and Techniques

The jet used for this study was supplied by a laboratory high pressure air supply at a constant velocity at the nozzle exit of 32 m s^{-1}. The air supply was heated electrically to a temperature of about 34°C above ambient. The jet exhausted into a co-flowing stream (velocity $\overline{U}_1$ = 4.8 m s^{-1}) supplied by a centrifugal blower. All measurements were made at a single streamwise station 59 diameters downstream of the nozzle exit (dia. ≈ 2.03 cm). At this station, the maximum velocity $\overline{U}_o$ and temperature $\overline{\Theta}_o$ (above ambient values) were 3.1 m s^{-1}

and 3.3°C respectively. The length scale L_0, the radial distance from the jet axis to the position corresponding to half the maximum temperature (above ambient), was 6.48 cm.

Velocity fluctuations u and v were obtained with a platinum-coated tungsten X-probe (5 μm dia. wires) operated with two DISA 55M01 constant temperature anemometers. Temperature fluctuation θ was measured with a 1 μm diameter Wollaston wire located approximately 1 mm below the mid-point of the X-probe. The temperature wire was operated at a constant current of 0.1 mA, which is low enough to ensure negligible velocity sensitivity. Hot wire signals were decontaminated for their sensitivity to temperature, in the manner described by Antonia *et al.* [10]. Signals proportional to (decontaminated) u and v, and θ were recorded simultaneously on a Philips ANALOG-7 FM tape recorder whose frequency response at the speed of recording was flat up to 5 kHz. The recorded signals were later played back into an A/D converter (10 bit including sign) and the digitised signals stored on magnetic tapes which were then processed on a ICL 1904A computer. The sampling frequency used was 12 kHz (real time). Each record corresponded to a real time duration of 27.7 s.

A bulge is defined to occur whenever a certain preset threshold level $\overline{\theta}_1$ is exceeded on the temperature signal. The duration of a bulge thus corresponds to the time interval between an upcrossing and the next downcrossing. It should be made clear that the term bulge is understood here to denote the signature of a physical interface bulge and not necessarily the physical bulge itself. The leading and trailing edges of the signature are associated with the front (downstream) and back (upstream) sides respectively of the interface.

As the vorticity and thermal interfaces are assumed to be coincident it is accepted that, whenever a bulge is identified using the θ signal, identical ensemble averaging operations may be performed on u, v, θ and uv, uθ and vθ. For any given quantity, all bulges within a certain given range centered around a mean bulge duration T, were ensemble averaged. First, the time interval between two successive points, at which the temperature first exceeds (during an upcrossing) and falls below (during the subsequent downcrossing) the pre-set threshold level, was determined (by linear interpolation between successive sample points, when necessary). Then, if the duration between these two points was within the range of interest, amplitude levels of u, v or θ, and uv, $u\theta$ or $v\theta$ were obtained (by interpolation) at fifty equally spaced points within the bulge. A subsequent bulge within the same range of duration was treated similarly, and the amplitudes corresponding to the fifty interior points were added to the previous set of values at corresponding locations, and so on. Finally, the ensemble average was obtained by dividing the sum at each of the fifty points by the number of bulges in the given range. Ensemble averaged quantities are denoted by $\langle\ \rangle$. Time averages are indicated by an overbar, and are evaluated according to the relation $\overline{X} = \lim_{t_1\to\infty} t_1^{-1} \int_0^{t_1} X(t)dt$. By definition, $X = \overline{X} + x$. Conditional (turbulent) time averages are given by $\overline{X}_t = \overline{IX}/\overline{I}$, where $I = 1$ or 0 depending on whether the flow is turbulent or not at a given point ($\overline{I}$ is the intermittency factor γ).

Results

Ensemble Average Bulge Shapes

Bulges comparable in duration to the characteristic mean flow time $L_o/\overline{U}_c$, where $\overline{U}_c = \overline{U}_1 + \overline{U}_o$, are defined as large. As typical examples of large bulges, Figs. 1a-f show ensemble average shapes of bulges of mean duration $T\overline{U}_c/L_o \simeq 2\text{-}5$, obtained at four values of η ($\equiv r/L_o$, where r is the radius) across the jet. No smoothing was performed on the results. In Figs. 1a-c, results are presented in the form $(\langle X\rangle - \overline{X}_1)/\overline{X}_o$ vs t/T, where $\overline{X}_1$ is the mean value of X in the external stream, $\overline{X}_o$ is the difference between the value of $\overline{X}$ on the jet axis and $\overline{X}_1$ and t is the time measured from the leading edge of a bulge. The use of $(\langle X\rangle - \overline{X}_1)/\overline{X}_o$ for the ordinate in Figs. 1 was suggested by the use of the plot $(\overline{X} - \overline{X}_1)/\overline{X}_o$ vs η when self-preservation of the quantity $\overline{X}$ is considered. Fig. 1a shows that bulges of a given duration have the largest axial velocity closer to the jet axis. When referred to the local mean velocity $\overline{U}$ (or the conditional turbulent mean velocity $\overline{U}_t$), however, ensemble averages $\langle u\rangle/\overline{U}_o$ [or $(\langle U\rangle - \overline{U}_t)/\overline{U}_o$] are smaller near the axis. This result is consistent with the notion that bursts of high momentum fluid occur away from the jet axis. In general, $\langle U\rangle$ shapes are nearly symmetrical, while $\langle V\rangle$

shapes have relatively sharp fronts and gradually sloped backs. This last feature applies to θ as well, and is in qualitative agreement with LaRue and Libby's ensemble averages of θ in a turbulent wake [9]. There is a significant region near the backs of a bulge where $\langle V \rangle$ is negative. This trend is especially pronounced near the jet axis.

An interesting feature of Figs. 1d-f is the gradual change with η that occurs in the average shapes of $u\theta$, uv and $v\theta$ bulges. Near the jet axis, most of the contribution to the average shear stress or heat flux occurs near the back of a bulge. A small region where $\langle uv \rangle$ and $\langle u\theta \rangle$ are large is also observed near the front. As η increases, the most significant contribution to the shear stress or heat flux is provided by the region closer to the front.

The interpretation of ensemble average shapes of small bulges is somewhat more difficult than for large bulges. For small bulges, average shapes of all quantities of interest (when referred to their local mean values) are of significant amplitude which is nearly uniformly distributed over the complete duration of the bulge. It is worth noting that an attempt was made to generate synthetic bulges (of all durations) by applying an arbitrary threshold to a Gaussian signal from a random noise generator. These bulges were found to have a uniform amplitude over almost their entire duration. It seems therefore that small turbulent bulges cannot be distinguished, on the basis of the shape of ensemble averages, from small synthetic bulges generated from a Gaussian signal.

Mean Properties of Ensemble Average Shapes

Having established the average shape of a typical large scale bulge, a few important average properties of large bulges are obtained here. As all large bulges are essentially of the same shape, the quantity that gives an average relative description of bulges of different durations is the mean amplitude defined by $\langle \bar{\bar{x}} \rangle = T^{-1} \int_0^T \langle x(t) \rangle dt$, where T is the duration of the ensemble average shape of bulges relative to the quantity x. The mean intensity associated with each average bulge is the product $\langle \bar{\bar{x}} \rangle T$. If N_ε is the number of bulges occurring within the range $\pm\,\varepsilon$ about the mean duration T, then the contribution to $\bar{X}$ from bulges of duration T is given by a quantity proportional to $\Sigma_x = \langle \overline{\overline{x}} \rangle TN_\varepsilon/\varepsilon$. This exercise is somewhat analogous to the technique of spectral decomposition.

Figs. 2a-b show mean amplitudes of ensemble averages of U and Θ bulges as a function of bulge duration. Variations of the quantities $(\langle \overline{\overline{U}} \rangle - \overline{U}_1)/u'$ and $(\langle \overline{\overline{\Theta}} \rangle - \overline{\Theta}_1)/\theta'$ with bulge duration appear to be independent of η, except for small U bulges. This suggests that large (duration) bulges have approximately the same mean shape and amplitude. This observation simplified the task of separating contributions from large and small scale motions to the measured statistics of derivatives of velocity and temperature fluctuations [11]. For large bulges, a relatively simple empirical expression may be written (Fig. 2) to relate mean amplitude and duration.

In the case of ensemble averages of uv, uθ and vθ, the relation between mean amplitude and mean duration of bulges seems to have a qualitative dependence on η (Figs. 3a,b). At $\eta = 0.89$, the mean amplitude is largest for small bulges and becomes approximately independent of duration for $T\,\overline{U}_c/L_o \gtrsim 1.5$. However, at $\eta = 1.48$, the bulge amplitude increases with duration and is maximum at $T\,\overline{U}_c/L_o \simeq 2.5$.

Figs. 4a,b, which show Σ_{xy} (x and y = u, v or θ) plotted as a function of the non-dimensional bulge duration, suggest that small bulges in the range (0-0.5) $L_o/\overline{U}_c$ provide a non-negligible contribution to $\overline{uv}$ and especially $\overline{u\theta}$ and $\overline{v\theta}$ at $\eta = 0.89$ (Fig. 4a). These bulges contribute little at $\eta = 1.48$ (Fig. 4b). An interesting feature of Fig. 4 is that the largest shear stress or heat flux contribution arises from the mid-range bulges [(2-5) $L_o/\overline{U}_c$ at $\eta = 0.89$ and (0.5-2.5)$L_o/\overline{U}_c$ at $\eta = 1.48$].

The total number of bulges encountered per unit time is the crossing frequency, which has an approximately Gaussian distribution [12], centered about the mean position of the turbulent/non-turbulent interface. It is of interest to examine the validity of this result when bulges that lie within a specified duration range are selected. For this purpose, the number per second of bulges N_r in a given range of duration r was counted at different positions across the jet. It was found that N_r increased with η and reached a maximum value N_{mr} at $\eta = \eta_m$ before decreasing. In fact, N_r followed the Gaussian function $N_r/N_{mr} = (\sqrt{2\pi}\,\sigma_r)^{-1} \exp\{-(\eta - \eta_m)^2/2\sigma_r^2\}$, where σ_r is the standard deviation of the Gaussian. The same behaviour was observed for bulges of all other duration ranges, but with different values of N_{mr}, η_m and σ_r. This is clearly demonstrated in Fig. 5 which lists values of N_{mr}, η_m and σ_r. It can be inferred from this figure that the number of bulges in the range (0-0.5 $L_o/\overline{U}_c$) is approximately the same both at $\eta = 0.89$ and $\eta = 1.48$. The conclusion we draw is that the negligible contribution at $\eta = 1.48$ of bulges in this range to the average shear stress or heat flux values is almost entirely due to the reduced stress or heat flux level within such bulges and not due to a reduced number of bulges.

Summary of Conclusions

The axial velocity of a bulge of specified duration is higher in the mid-region than near the edges. In general, this higher axial velocity is associated with a radial motion that is directed toward the edge of the jet. The fronts of both V and Θ bulges are sharper than the backs.

If $\langle\overline{\overline{U}}\rangle$ can be interpreted as an average convection velocity of the appropriate interface bulge, all bulges of duration greater than about 2 $L_o/\overline{U}_c$ have a velocity that is higher than the external stream speed U_1 by about twice the local axial rms velocity. Alternatively, we may think of the bulges as travelling more slowly, by approximately the same factor, than the centre-line velocity $\overline{U}_c$. The existence of a relatively large negative $\langle V\rangle$ near the backs of bulges is consistent with the possibility of significant entrainment of ambient fluid in that region.

At $\eta = 0.89$, small bulges of duration (0-0.5) $L_o/\overline{U}_c$ transport a significant amount of $\overline{uv}$ or $\overline{v\theta}$. In contrast, at $\eta = 1.48$, these bulges transport relatively little shear stress or heat flux even though the number of small bulges in the range (0-0.5) $L_o/\overline{U}_c$ is almost the same as at $\eta = 0.89$. Bulges that transport the major part of the flux are, by our classification scheme, neither small nor large.

Acknowledgement

The work described here represents part of a programme of research supported by grants from the Australian Research Grants Committee.

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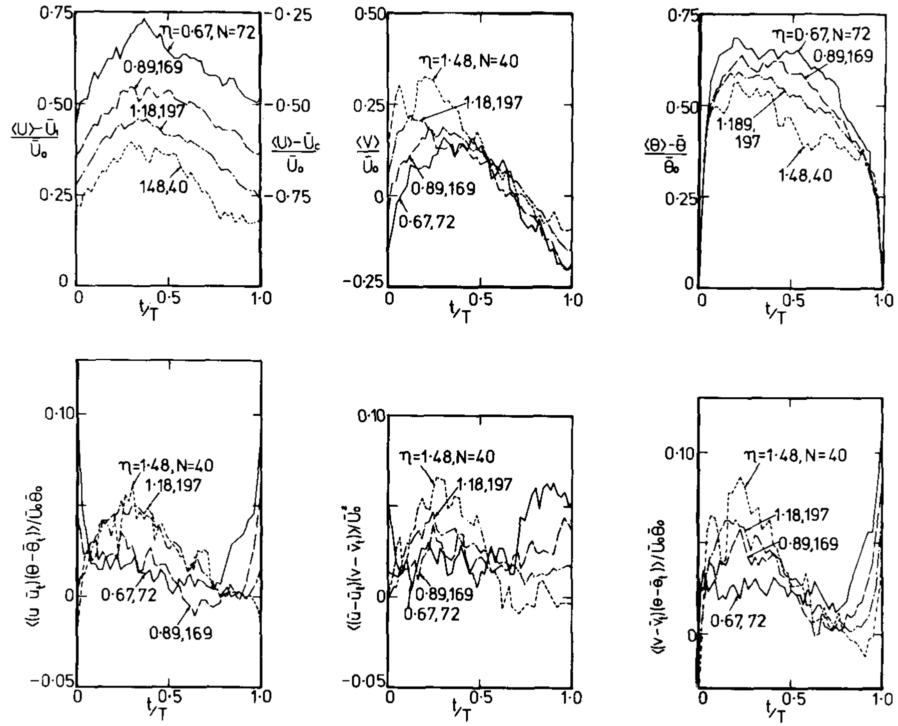
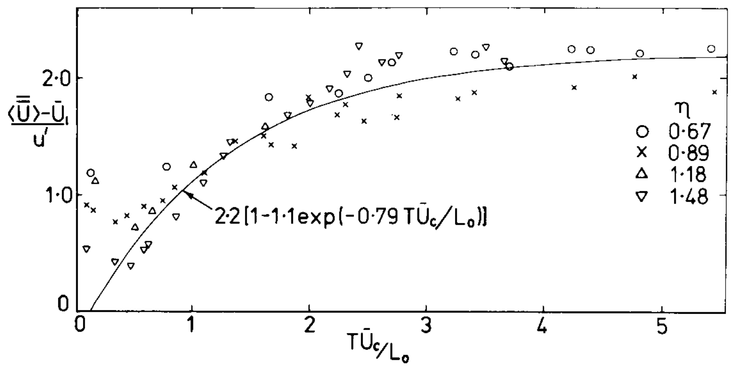


Fig. 1 Ensemble averaged distributions of U, V, Θ and of their products in bulges of duration in the range (2-5) $L_o/\bar{U}_c$. (N refers to the number of bulges found at the particular value of η).



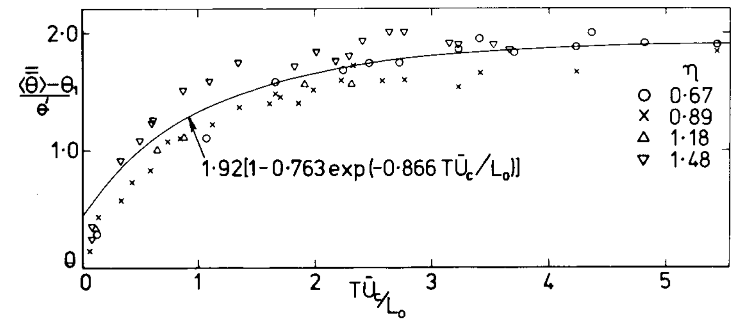


Fig. 2 Mean amplitude of ensemble averages of U and Θ as a function of bulge duration. (a) U, (b) Θ.

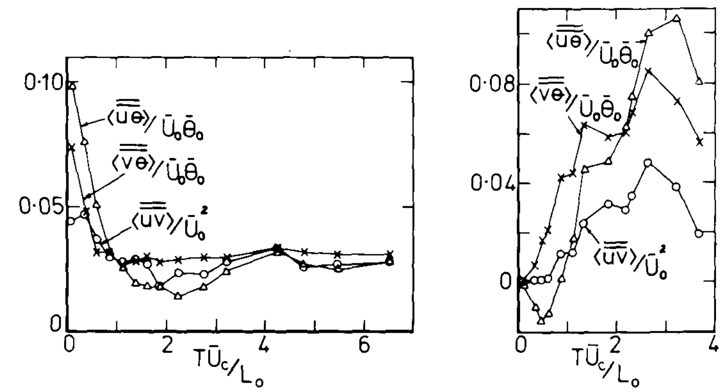


Fig. 3 Mean amplitude of ensemble averages of uv, uθ and vθ as a function of bulge duration. (a) η = 0.89 (b) η = 1.48.

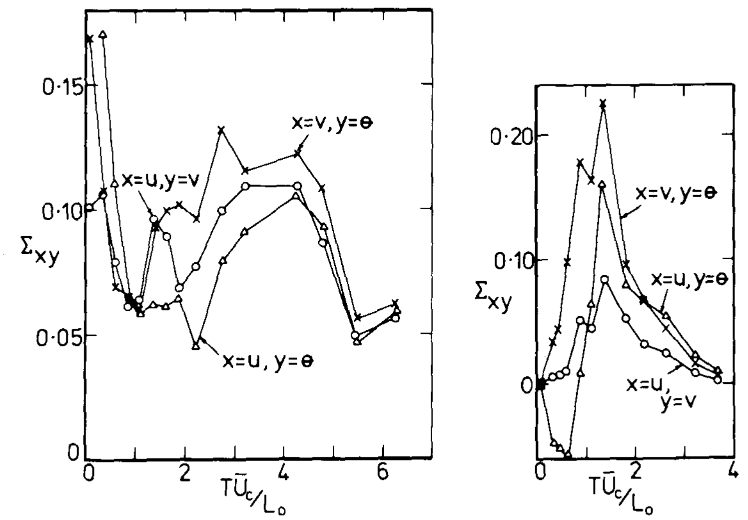


Fig. 4 Contribution to $\overline{uv}$, $\overline{u\theta}$ and $\overline{v\theta}$ from bulges of different duration. (a) η = 0.89 (b) η = 1.48.

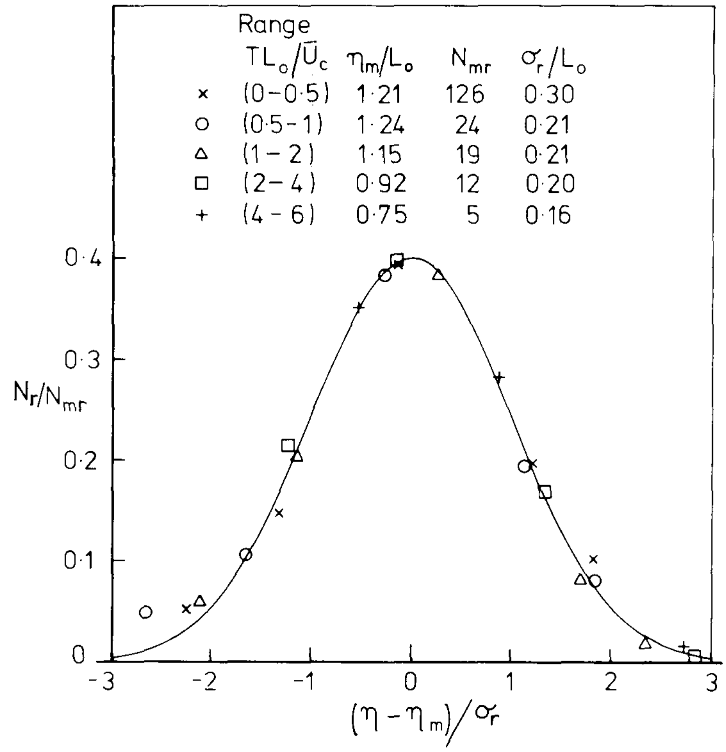


Fig. 5 Number of bulges of duration in range r as a function of position in jet.