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# A note on turbulence measurements with a laser velocimeter

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In recent comparative measurements using a burst-counter type laser velocimeter and a hot-wire anemometer to assess the capabilities of the velocimeter (e.g. Barnett & Giel 1976; Lau, Morris & Fisher 1979), it was found that the laser velocimeter held good promise as an instrument for turbulence research, especially in high speed, high temperature flows where a hot-wire cannot be used. The axial mean velocities obtained with the LV compared very well with hot-wire measurements. Similarly, the characteristic shapes of the spectra and probability density distributions of the velocity fluctuations were faithfully reproduced. The trends in the distributions of the various turbulence characteristics (e.g. turbulence intensity, velocity covariances, skewness and kurtosis) in a given flow field were identical to those obtained with hot-wires. The one significant difference between LV and hot-wire results was the magnitudes of the turbulence level. Since the LV results were obtained with the help of the latest validation and discrimination techniques (Asher 1973), which have now become standard equipment (Durst, Melling & Whitelaw 1976), such a discrepancy was unexpected. The reason for the discrepancy is now fairly clear and a method has been suggested by Whiffen, Lau & Smith (1978) on how to eliminate the error. But the approach is lengthy and time-consuming. This paper describes a method which effectively accomplishes the same end with less effort.

## 1. Introduction

From the recent use of the laser velocimeter (LV) in various flow situations, it seems fairly clear that the LV holds a great deal of promise as an instrument for turbulence research. These experiments have demonstrated that the LV has practically all the capabilities of hot-wire anemometers with a few added advantages. The main advantage, of course, is that it may be used in flow environments which would be too severe for hot-wires.

In an effort to assess the capabilities and accuracy of LV measurements, Barnett & Giel (1976) and Lau *et al.* (1979) carried out studies in unheated jets at low Mach numbers in which they compared LV and hot-wire measurements. They found that the axial mean velocity obtained with the LV and hot-wire were of comparable magnitudes. The turbulence intensities from the LV were, however, systematically higher than corresponding hot-wire results even after all known corrections had been applied to both sets of results. The discrepancy was found to be almost uniform over the major part of the cross-section of the jet. In spite of this apparent error in turbulence measure-

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ments, Lau *et al.* found that the general shapes of the spectra obtained with the LV and hot-wire at corresponding positions did not differ significantly, and in particular, the narrow-band peak which is so characteristic of hot-wire spectra obtained in the potential core of jets (Ko & Davies 1971) appeared also in LV spectra and occurred at the same Strouhal number. Moreover, the radial and axial distributions of the turbulence intensity and velocity covariances had corresponding shapes and peaked at corresponding positions.

Various efforts had been made to try to understand the source of this error which appears (Whiffen, Lau & Smith 1978) in the transformation of the photomultiplier tube signal to a velocity data point. Since the PM tube signal is derived from the average of discrete photon events, it is intrinsically 'noisy' containing not only the signal frequency but also frequency components from each photoelectron pulse. This 'noise' causes small variations in the trigger points of the measurement gate which manifest themselves as small errors in the measurement of each velocity sample. The errors are random in nature and in the computation of *mean velocity* over many samples they average to zero. In the case of *turbulence level*, however, because the signals are squared first before averaging, the error is retained.

An obvious solution to the problem would be to try to increase the signal-to-noise ratio (SNR) of the PM tube signal or alternatively to restrict the sampling to only such signals as have a high SNR. Furthermore, the number ($N$) of cycles of the signal used to determine the magnitude of each velocity sample could be raised. However, in many situations, other demands of the system may necessitate the use of signals which do not have the ideal SNR or $N$. Besides, there is a diminishing return with the increase of these parameters since the noise varies inversely with SNR and $N$. There is a point therefore when the sacrifice (e.g. in terms of very low data rates) needed to achieve the ideal SNR and $N$ may make the measurement task unrealistic and almost impossible.

Some of the factors which need especially to be considered are as follows. They apply particularly to LV measurements in high speed flows, but are also relevant to applications at low speeds.

(1) There is an inherent limit to the magnitude of the SNR due to the finite scattering efficiency of small irregular particles (Durst 1975).

(2) In high frequency fluctuating flows, it is necessary that the size and density of the scattering particles be small enough to allow the particles to respond adequately to the flow. The small size would adversely affect the SNR.

(3) Additionally, in high speed and high temperature flows (where the LV is supposed to have a decided advantage over the hot wire), the residence time of the particles is low. This would also cause a deterioration of the SNR.

(4) The electronics could possibly be designed to reject signals with a low SNR, but raising the threshold to too high a level may not be a desirable feature as it would bias the results towards flow characteristics of the larger particles.

(5) As for $N$, the requirement of good spatial resolution and accurate measurements in regions of high velocity gradients limits the size of the measurement volume and thereby the maximum number of fringes in the volume. The number of fringes could be increased in the smaller volume, but this would lead to signals of much higher frequencies and ultimately to poorer SNR.

(6) In highly turbulent regions where the instantaneous velocity vectors may have

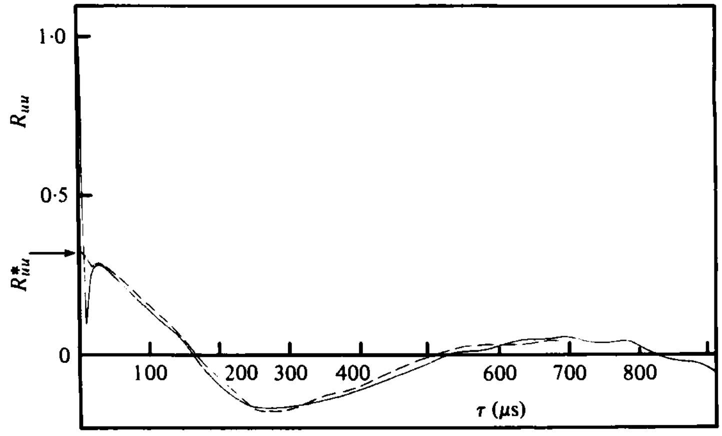


FIGURE 1. Correlograms ($M_J = 0{\cdot}5, x/D = 2{\cdot}0, r/D = 0$). ——, autocorrelation (with one photomultiplier tube); – – –, cross-correlation (with two photomultiplier tubes).

a large component in the transverse direction, a nearly isotropic polar response of the instrument is needed. The number $N$ has to be less than $N_t$, the total number of fringes in the measurement volume. As may be seen in Whiffen (1975), Whiffen *et al.* (1978), and Lau *et al.* (1979), the polar response depends on $N/N_t$. The smaller the ratio, the better is the polar response (Durst & Zaré 1974). This also has the effect of limiting $N$.

(7) Finally, it may also be expedient to try to increase the data acquisition rate by having as low a value of $N$ as possible. A high data rate is especially important in cross-correlation work and in non-stationary flow measurements.

Taking all these factors into account, it is clear therefore that the practical approach would be to accommodate the operational limitations and to try to eliminate the errors by other means.

Figure 1 shows the autocorrelation curve for axial velocity fluctuations obtained with the LV in the potential core of the jet where the turbulence levels are relatively low. Due to the quasisinusoidal nature of the velocity signals in this region, the correlograms obtained with hot-wires and microphones (e.g. Davies 1966; Lau, Fisher & Fuchs 1972) have always had the appearance of a weakly-damped cosine curve. This is reasonable since the fluctuations in the potential core of the jet apparently originate from the passage of an axial array of fairly regularly spaced vortices situated in the mixing region (Lau *et al.* 1972).

On this basis, the spike at $\tau = 0$ would be incorrect. A more appropriate value of the correlation would be given by the point ($R^*_{uu}$) obtained by extrapolating the sinusoidal curve back to $\tau = 0$, as shown by the dashed line. Because electronic switches in the processor require a finite time to reset and consequently a tolerance window of $10\,\mu$s is built into the system to allow for this, the data point at $\tau = 10\,\mu$s is not dependable. In view of this, the extrapolation is established based on the curve at $\tau \geqslant 20\,\mu$s. An erroneous correlation at $\tau = 0$ and not other values of $\tau$ would confirm that the noise samples occur at random intervals and are uncorrelated except for the case when they are multiplied by themselves, i.e. at $\tau = 0$.

The turbulence level ($\tilde{u}$) is normally obtained by taking the root-mean-square value of the fluctuating velocity signal and is equal to the square root of the autocorrelation value $(\overline{u'u'})$ at $\tau = 0$. The correlogram in figure 1 therefore indicates an essential error in turbulence measurements obtained by conventional means and suggests a possible method for correcting these results. This is accomplished by multiplying the measured $\tilde{u}$ by $R^{*\frac{1}{2}}_{uu}$, the extrapolated value of correlation coefficient at $\tau = 0$ (Whiffen *et al.* 1978). The method however suffers from one major disadvantage in that it requires the acquisition of an autocorrelogram for each correction point and is a time-consuming process.

This note presents two schemes of a method by which the correct values of the covariance $(\overline{u'u'})$ may be obtained without the aid of correlograms; and by incorporating appropriate modifications to the analysis program, the system can be made to give correct results of the turbulence level in about the same time that it took before to produce the erroneous data. For comparison, measurements are carried out over the flow field of a round jet, and the results from the two schemes and hot-wire measurements are examined.

## 2. Description of the method

### 2.1. *Scheme* 1

The essence of the method can best be viewed in the context of the optical arrangement of a conventional burst-counter type LV system. It consists essentially of a transmitting optical system (figure 2) which sends out two pairs (one green and the other blue) of coherent light beams which intersect at the measurement point in the jet, thus forming two sets of orthogonal fringes at this point. This normally allows measurement of the instantaneous velocities in two directions simultaneously. For the present experiments, one pair of the beams is blanked off, and only the axial velocities are considered.

The alternating light scattered by the individual particles of aluminium oxide powder distributed in the flow is detected by the receiving optical system placed at about 30° to the transmitting beams. Normally, a colour separator is used to isolate the green and blue light detected at the measurement point. In the present arrangement, a beam splitter replaces the colour separator, and the light from one set of colour fringes is viewed simultaneously by two photomultiplier (PM) tubes. The alternating signals from the two PM tubes are first passed through their respective validation circuits in the electronic processor before being analysed. This gives in one pass: the mean velocities $(U_1, U_2)$ measured by the two PM tubes, the turbulence levels $(\overline{u_1'^2}^{\frac{1}{2}}, \overline{u_2'^2}^{\frac{1}{2}})$ and the covariance $\overline{u_1'u_2'}$, and the statistical moments of the individual fluctuating components.

Since $u_1'$ and $u_2'$ represent the same flow signal originating from different PM tubes and the noise in the two PM tube signals is not correlated, $\overline{u_1'u_2'}^{\frac{1}{2}}$ would give the true value of the turbulence level. This approach is similar to a suggestion made earlier by George & Lumley (1973) (see also Shaughnessy & Morton 1977). However, a clear distinction needs to be made between the present and these earlier efforts. Firstly, their work was performed in a frequency tracker type of LV and they were concerned with the 'ambiguity noise' which is typical of such an LV system. As Steenstrup (1975) has pointed out succinctly, one of the reasons for opting for a burst-counter type LV is that the 'ambiguity noise' is eliminated.

Another difference is that in the earlier works the receiving optics were duplicated and placed so that each set of optics was viewing the light scattering region from a

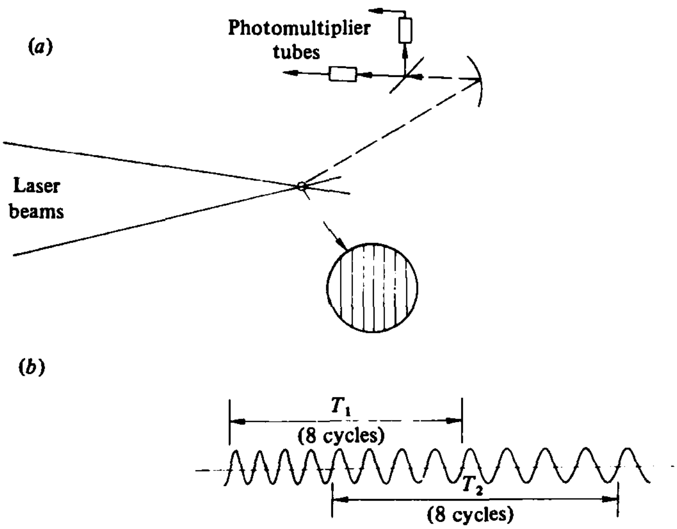


FIGURE 2. (*a*) Schematic view of LV system using two photomultiplier tubes. (*b*) Sketch of photomultiplier tube signal showing how the two velocity samples are obtained.

different angle. Our arrangement of the two PM tubes on the other hand uses only one set of receiving lens system, and views the scattering region from only *one* angle. It is therefore more compact, but at the same time imposes a greater constraint on our ability to satisfactorily eliminate the problem, because of the lower SNR caused by the division of the light intensity.

To further illustrate the method, let us consider the effect of PM tube noise on the turbulence intensity calculation for individual particle velocity measurements when one PM tube is used. The turbulence level (TL) is determined by:

$$\mathrm{TL} = \overline{u_1'^2}^{\frac{1}{2}} = \left(\frac{1}{N}\sum_{i=1}^{N}[\overline{u}-(u_i+e_i)]^2\right)^{\frac{1}{2}}$$

or

$$\left(\frac{1}{N}\Sigma(\overline{u}^2-2\overline{u}u_i+u_i^2-2\overline{u}\,e_i+2u_ie_i+e_i^2)\right)^{\frac{1}{2}}$$

in which the last three terms represent the noise contribution. If $u_i$ and $e_i$ are now assumed to be uncorrelated, the first two noise terms would reduce to zero if a sufficiently large number of samples are taken. The last term $e_i^2$, would, on the other hand, introduce an error which will not reduce to zero regardless of the quantity of data acquired. Therefore, to eliminate the error, this term must be avoided.

When two PM tubes are used, two uncorrelated noise terms, $e_{Ai}$, and $e_{Bi}$, are introduced. Thus, the turbulence level which is given by the covariance $\overline{u_1'u_2'}$ becomes

$$\mathrm{TL} = \overline{u_1'u_2'}^{\frac{1}{2}} = \left(\frac{1}{N}\Sigma[\overline{u}-(u_i+e_{Ai})]\,[\overline{u}-(u_i+e_{Bi})]\right)^{\frac{1}{2}},$$

which expands to

$$\mathrm{TL} = \overline{u_1'u_2'}^{\frac{1}{2}} = \left(\frac{1}{N}\sum_{i=1}^{n}[\overline{u}^2-2\overline{u}u_i+u_i^2-\overline{u}(e_A+e_B)_i+u_i(e_A+e_B)_i+(e_Ae_B)_i]\right)^{\frac{1}{2}}.$$

Since $u_i$, $e_{Ai}$ and $e_{Bi}$ are uncorrelated, all the noise terms average to zero. The calculation therefore gives the true turbulence level of the flow.

Figure 1 also shows (by the dashed line) the correlogram when the signals from the two PM tubes are cross-correlated, and it is clear that the technique produces the correct correlation value at $\tau = 0$.

### 2.2. *Scheme* 2

The scheme which is outlined above suffers from one major drawback, and that is, it requires *two* PM tubes to measure the velocity in one direction. Besides the extra expense of the additional PM tube and ancillary equipment required to drive it, the technique calls for a major modification of the receiving optical system if the facility is to continue to measure velocity in two orthogonal directions simultaneously. The second scheme is designed to circumvent this drawback and yet achieve the same effects as scheme 1.

The instantaneous velocity of a particle is determined from the period of eight continuous cycles of the signal being processed. In general, when a particle enters the measurement volume, more than eight cycles are generated so that more than one sample of the particle velocity may be obtained for that particle. This is illustrated in figure 2(*b*) which shows the second sample overlapping the first by four cycles. The error in the instantaneous velocity reading of any one sample originates from uncertainties in defining the starting and ending points of the eight-cycle measurement period due to the superimposed noise on the signal. Since the noise is random in nature, the error in one segment of eight cycles is not expected to be correlated with that in a second segment provided the segments are staggered. Thus, the two samples shown in figure 2(*b*) may, to all intents and purposes, be considered as samples from two separate PM tubes.

In the second scheme, the signal from a single PM tube is fed into two electronic processors which are slaved to each other. The first processor would initiate the sampling process and determine the velocity by the eight-cycle period in the same manner as before. At the end of the fourth cycle, however, the second processor is also triggered and the velocity similarly obtained from the period of the succeeding eight cycles.† The samples from the two processors are then correlated in the same way that the data from the two PM tubes were analyzed before to give $U_i$, $\overline{u_i'^2}^{\frac{1}{2}}$ and $\overline{u_i' u_j'}$.

In principle, the same effects could be obtained when the samples are separated by no more than one cycle of the signal. However, because a common heterodyne and bandpass filter is employed in this mode of operation, it is necessary, in practice, to provide a larger time lag between samples to allow any residual coherence, which may be caused by having common electronic components, to die down sufficiently.

## 3. Apparatus

A 5 cm diameter jet issuing from a contoured nozzle is used for these experiments. It is part of a coannular facility which was recently used for studying the flow field of coannular jets of inverted velocity profiles (Lau 1979*a*). In the present arrangement, no flow issues from the secondary annular nozzle. Dry air is supplied from a plant air

† This technique should not be mistaken for the $\frac{4}{8}$ and $\frac{5}{8}$ validation checks which are now found in many developmental and commercial LV's, and have been part of the present LV system for some time (Lau *et al.* 1976, 1979).

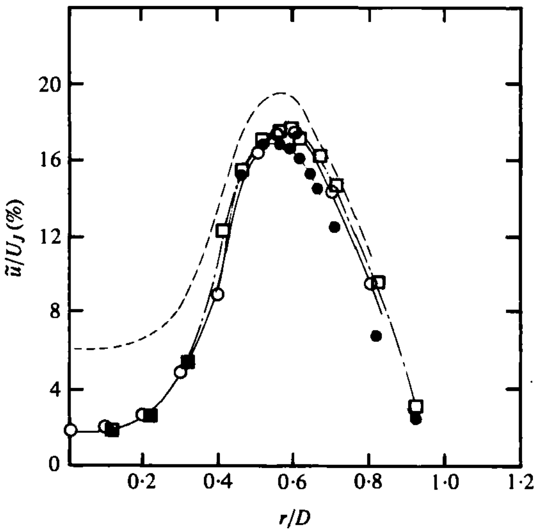


FIGURE 3. Radial distributions of turbulence intensity ($M_J = 0{\cdot}28$, $x/D = 2{\cdot}0$). LV data: ---, by the conventional method; ○, by the dual sampling method. Hot-wire data: ●, uncorrected; □, corrected.

compressor facility at 2 MN $m^{-2}$ and heating is achieved by a sudden expansion burner using propane gas as a fuel. Measurements are conducted in the jet using the LV at exit Mach numbers of 0·28 and 0·9. In the latter case, the air is heated initially so that the jet emerges at the same temperature as the ambient.

The LV is essentially the same system as that employed in the earlier study (Lau *et al.* 1979) and the processor is provided with a zero crossing detector which has hysteresis sequencing circuitry. The circuitry ensures that each cycle of the signal exceeds a preset hysteresis level on either side of the zero level in the proper sequence before a count series is validated. This ensures against signals with low SNR being accepted. In addition, the signals are subjected to a single-cycle period check whereby the period of each cycle is compared with that of the adjacent cycle, and only those signals which pass this test are validated. The result of these precautions is that the eight-cycle period which constitutes the measurement have as good an SNR as possible given any flow situation. In the present set-up the arrangement of the optical systems is suitably modified as explained in § 2.

At the lower Mach number, measurements are also carried out using a DISA 5501 constant-temperature anemometer coupled to a DISA 55D10 linearizer. The probe is a single-wire type and is made from 5 $\mu$m tungsten wire. The DC level of the linearized anemometer output is measured with a Hewlett–Packard Digital Voltmeter and the r.m.s. level with a Bruel and Kjaer 2416 electronic voltmeter.

## 4. Results

### 4.1. *LV and hot-wire comparisons*

Figure 3 shows radial distributions of the turbulence intensity ($\tilde{u}/U_J$) obtained at $x/D = 2$ in the jet, using an LV and a hot-wire. Since the normalizing factor is the jet efflux velocity ($U_J$), this figure shows essentially the distribution of the turbulence

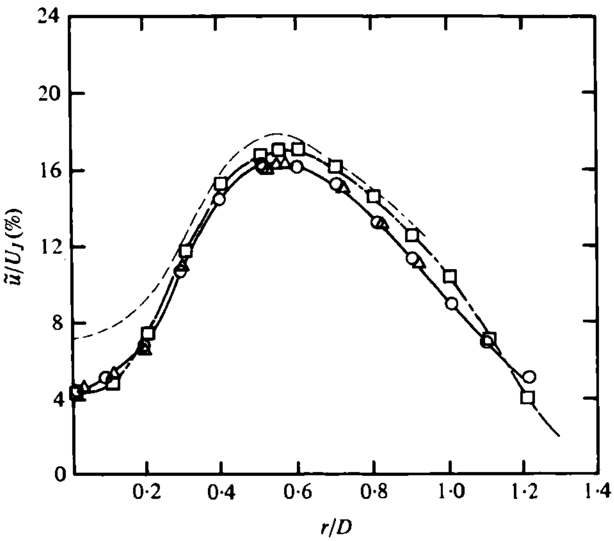


FIGURE 4. Radial distributions of turbulence intensity ($M_J = 0{\cdot}28$, $x/D = 4{\cdot}0$). LV data: ---, by the conventional method; △, by the dual sampling method using two PM tubes; ○, using one PM tube. Hot-wire data: □, corrected.

level over that cross-section of the jet. The LV results are obtained both by (*a*) the conventional single sampling method, and (*b*) the dual sampling method outlined in § 2.2. The hot-wire data, on the other hand, are obtained by the conventional method and subsequently corrected for tangential insensitivities of the wire and possible rectification of the signals as derived by Tutu & Chevray (1975).

As in the earlier studies, the LV data from the single sampling method tend to be significantly and systematically higher than the uncorrected hot-wire data. The correction applied to the hot-wire data helps to reduce some of the discrepancy, but this is mainly in the outer part of the jet ($r/D > 0{\cdot}6$) and in the inner region there is hardly any change. The LV data obtained by the dual sampling method on the other hand follow the hot-wire data very closely and especially those hot-wire data which have been corrected. It appears therefore that the dual sampling method is performing adequately in eliminating the errors.

It may be observed in passing that the LV data obtained by the two methods differ by an almost constant magnitude except for the region $r/D < 0{\cdot}3$. A similar tendency is seen in the corresponding distributions at $x/D = 4$, which are shown in figure 4, but in this case the diverging discrepancy occurs between $r/D = 0$ and about $0{\cdot}2$ instead. In a high Mach number jet (figure 8) the discrepancy does not diverge close to the jet axis even though the turbulence intensity is at some locations lower than those measured here. It appears therefore that the behaviour is associated with the magnitude of turbulence ($\tilde{u}$) rather than the turbulence intensity ($\tilde{u}/U_J$) falling below a prescribed limit. The inconsistency in the error emphasizes the weaknesses of the conventional method of obtaining turbulence measurements and underscores the effectiveness of the dual sampling method to produce the correct results.

Figure 4 also shows a comparison between LV data obtained by the two schemes of the dual sampling method: the first using two photomultiplier tubes, and the other, one photomultiplier tube. The data from these two schemes fall on the same curve

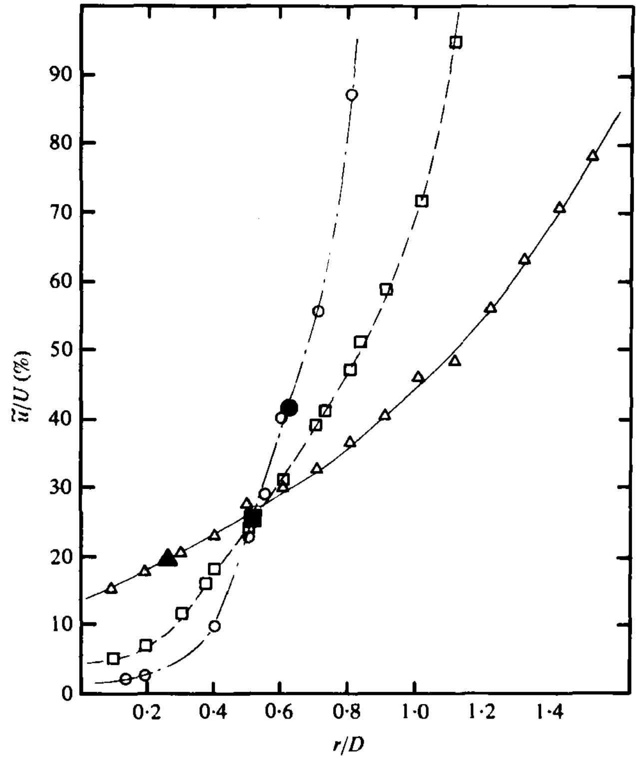


FIGURE 5. Radial distributions of local turbulence intensity. $x/D$: ○, 2; □, 4; △, 8. Solid symbols show approximate position where LV and hot-wire data begin to deviate significantly.

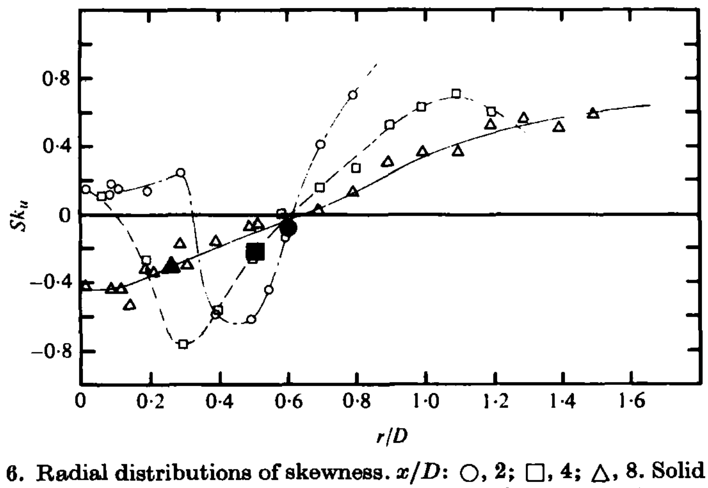


FIGURE 6. Radial distributions of skewness. $x/D$: ○, 2; □, 4; △, 8. Solid symbols show approximate position where LV and hot-wire data begin to deviate significantly.

and it is clear from these and measurements at other stations and in jets of different exit conditions that the two schemes produce identical results.

Although the LV data obtained by the dual sampling method and the corrected hot-wire data may be considered to be in reasonably good agreement over the jet cross-section, it may be seen in figure 4 that the hot-wire data tend to lie consistently a little above the LV data from $r/D = 0{\cdot}5$ to $1{\cdot}1$. This behaviour was not observed in the results at the upstream station (figure 3) when they were considered earlier. However, on closer scrutiny, it appears that even at this station, the same tendency may be observed from $r/D = 0{\cdot}6$ outward. The results at $x/D = 8$ show a similar tendency, deviating at about $r/D = 0{\cdot}3$ by amounts comparable to those shown in figure 4. The point at which the LV and hot-wire data deviate does not seem to bear any relation to the position of the peak turbulence level. Neither is the magnitude of the turbulence at this point related to the peak turbulence or any one fixed value of turbulence.

Figure 5 shows the radial distributions of the local turbulence intensity ($\tilde{u}/U$, $U$ being the local mean velocity) obtained with the LV at the three axial stations. The points at which the LV and hot-wire data begin to deviate are shown by the corresponding solid symbols. It is clear that the LV and hot-wire results disagree when the local turbulence intensity is high, but as with turbulence level, there appears to be no agreement on the exact magnitude of the local turbulence intensity at which the data would begin to deviate.

Figure 6 shows radial distributions of the skewness of fluctuating velocity signals. Once again the critical points are indicated on the respective curves by the solid symbols. The location of each point is apparently not decided by any specific magnitude or sign of the skewness either.

The problem of the deviation of LV and hot-wire data therefore cannot be linked with any particular characteristic of the velocity fluctuations. A check of the local mean velocities suggests that it is also not related to any special value of mean velocity. Since the deviation is not a function of any peculiarity of the velocity signal, the problem is probably not caused by an inadequacy of either the LV or the hot-wire anemometer processors.

The reason for the deviation is not altogether clear at present, although it appears more likely that the hot-wire data may be in error. Firstly, in a recent study of the response of the hot-wire to flow over it, and the methods of calibrating anemometers, Perry, Smits & Chong (1979) found that because of the high operating temperatures involved (*circa* 300 °C), hot wires tend to expand and buckle like columns between the restricted span formed by the tips of the two supporting prongs. The bow which forms along the wire produces nonuniformities in the wire characteristics and causes hot spots to appear on the wire. Perry *et al.*'s analysis has shown that if the temperature distribution along the wire is not symmetrical about the middle of the wire there could be an incorrect weighting or biasing of the high frequency components ($> 200$ Hz) of the velocity fluctuations which would significantly contribute to a higher *measured* overall turbulence level. Depending on the degree of asymmetry, the differences in the response could be as large as 10 % or more. Therefore, depending on the orientation of the bow and the position of the hot spot on the wire, the hot-wire results could be substantially in error. As Perry *et al.* have suggested, because these quantities cannot be controlled or monitored, the problem becomes 'intractable'.

Figure 7 shows the physical plane of the top half of the jet and the positions of the critical points are indicated. The trajectory of the vortex street in the jet is also indicated (Kwan & Ko 1976; Lau 1979*b*) and on the basis of the size of the vortex cores determined by Lau (1979*b*), it would appear that the problem is associated with the particular region of the jet outside the outer edge of the path of the vortex cores. In this region the flow is characteristically very erratic and instantaneous reversals of

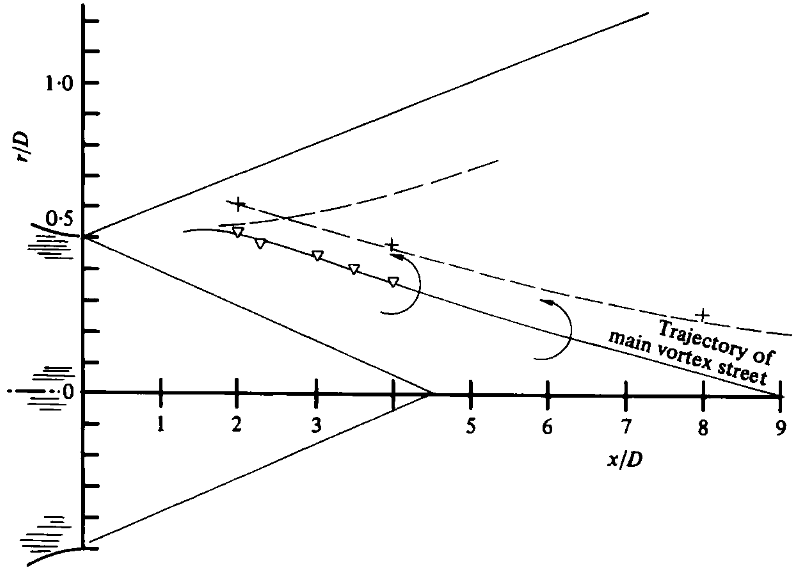


FIGURE 7. Physical plane of jet. ▽—▽, Vortex trajectory (Lau 1979*b*); +, approximate positions where LV and hot-wire data begin to deviate significantly.

flows are expected. It is conceivable therefore that when a hot-wire is placed in this region it could suffer distortions at frequent intervals which would give it an asymmetric distribution of the temperature at these instants and cause a bias in the total turbulence reading.

The second reason for questioning the hot-wire data concerns the correction applied to the hot-wire readings. As in most other hot-wire correction methods (see Tutu & Chevray 1975), the present approach relies on certain assumptions about the radial and azimuthal components of velocity fluctuations which cannot be fully verified.

On the other hand, a review of the likely difficulties with the LV suggests only one potential problem, and it is in connexion with how the flow is seeded. Conceivably, if the velocity at a point is composed of fluid which comes from both inside and outside the jet, an incorrect proportion of seeding from either side could affect the outcome of the velocity probability distribution. However, tests with different proportions of seeding from inside and outside of the jet show no significant effect on the magnitude of the turbulence level.

### 4.2. *Correction of previous LV data*

Figure 8 shows typically, radial distributions of LV data obtained by the conventional and dual sampling methods in a Mach 0·9 jet. Because of the high Mach number, no hot-wire data are obtained. The distributions are narrower than those of the Mach 0·28 jet at a corresponding axial station and this is indicative of the reduced spreading rate of the jet mixing layer due to an increased Mach number (Lau *et al.* 1979).

The discrepancy between the two sets of results is practically uniform over the whole cross-section, extending even to the jet centre-line. The size of the uniform difference is about the same as that measured in the lower speed jet (figure 3). This consistency suggests that the discrepancy is not Mach-number dependent and that it may be possible to correct previous LV data obtained by the conventional method.

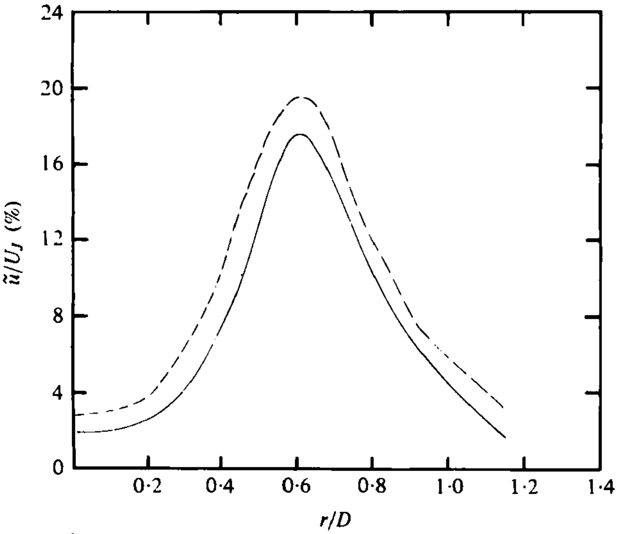


FIGURE 8. Radial distributions of turbulence intensity ($M_J = 0{\cdot}9$, $x/D = 4{\cdot}0$). LV data: ----, by the conventional method; ——, by the dual sampling method.

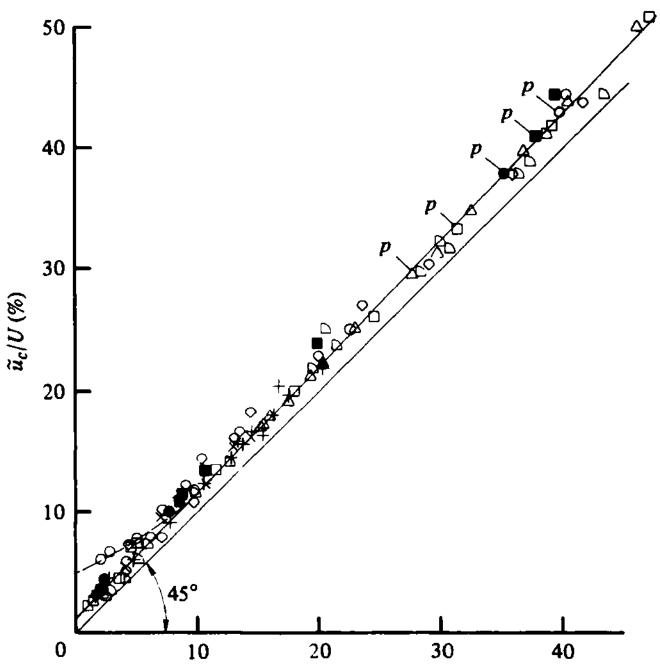


FIGURE 9. Local turbulence intensity: Conventional method versus dual sampling method. Single jet: $x/D =$ ○, 2; □, 4; △, 8. (Open symbols: $M_J = 0{\cdot}28$. Solid symbols: $M_J = 0{\cdot}9$.) Co-annular jets: +, ×, inverted velocity profile; ▽, ◺, normal velocity profile.

Figure 9 shows a plot of the local turbulence intensity obtained by the conventional method ($\tilde{u}_c/U$) versus the local turbulence intensity obtained by the dual sampling method ($\tilde{u}_d/U$). Data are taken from single jet results presented earlier and results obtained in heated and unheated coannular jets (with inverted and normal velocity profiles). The points associated with the turbulence level ($\tilde{u}$) being a maximum are flagged and annotated with a *p*.

Except for the systematic trend in the Mach 0·28 results at $\tilde{u}_d/U < 8\,\%$, the data points fall on one straight line. Since the results are for diverse flow conditions, it would seem that the straight line is fairly universal and may be used to correct data obtained previously with the same LV system.

A 45° line is also drawn, and it shows that the discrepancy in the LV data is not exactly uniform but increases linearly with the local turbulence intensity. The increase however is at a very slow rate.

## 5. Conclusion

Turbulence measurements with the laser velocimeter obtained by the conventional method of analysis, using single sample statistics, are contaminated with noise-induced errors. The error originates from imprecise triggering of the data acquisition process, caused by noise within the photomultiplier tube signal.

This paper describes a method of making turbulence measurements which removes the effect of the noise-induced component that is inherent in the velocity samples. The outcome of this method is the same as that achieved by measuring and extrapolating correlograms as suggested earlier by Whiffen *et al.* (1978). But the process does not involve the computation of the full correlogram and is therefore less lengthy and less time consuming.

Two approaches to the method are suggested. In the first case, simultaneous velocity samples obtained from two photomultiplier tubes, focussed on a single set of interference fringes at the measurement volume, are recorded and a covariance formed with them. By this means, the uncorrelated noise-induced components of the velocity average out to zero leaving the unbiased turbulence reading. In the second approach, the two corresponding velocity samples are determined from two eight-cycle periods taken from the signal of a single photomultiplier tube. The two periods are staggered so that four cycles of the signal separate their starting points. The sample pairs are then cross-correlated in the same way as in the first approach.

The two schemes yield identical results which in general compare favourably with corrected hot-wire data. A small but consistent deviation is however noticed between the LV and hot-wire results in the outer part of the mixing region. It is speculated that the buckled form of the hot-wire caused by thermal expansion of the wire, coupled with the buffeting which the hot-wire must no doubt be subjected to in this region, may be the cause of the slightly higher reading obtained with the hot-wire. The correction applied to the hot-wire data is also open to suspicion.

Measurements are also carried out in heated and high Mach jets of various configurations. They indicate a universal variation of the discrepancy in LV results obtained by conventional means using a single sampling technique. From a plot of all the data from the various jets, it appears that there is a straight line relationship between the results of local turbulence intensity obtained by the conventional method and those by the dual sampling method presented here. The existence of such a universal relationship suggests that it would be possible to make corrections to past and future turbulence data obtained by the conventional single sampling technique.

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