AN ADDITIONAL LOOK IN TURBULENCE STATISTICS

by

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This paper reports three experiments, performed in the plain wake behind a cylinder, free round jet and zero-pressure-gradient boundary layer. An X hot-wire probe was used in the free flows and twelve-sensor probe in the case of boundary layer. The statistical relationships between higher-order velocity moments in the far-field of the wake, analogue to relations previously proved by other authors in turbulent boundary layer and round jet, are given for the first time. It is also verified that two classes of statistical relationships, linear and parabolic, are valid both in bounded and free shear turbulent flows.

Introduction

Turbulence represents a rare problem in fluid mechanics that still remains unresolved. It can be formally described as a complex statistical phenomenon, introducing the general practice in turbulence modelling to operate with equations for moments of turbulent fluctuations. Many experiments are concentrated on measuring moments of velocity fluctuation probability density distributions. In the boundary-layer flows, moments up to the 4^{th} order are measured mainly. The most of classical data are presented in monograph [1] and newer in [2]. Some authors, like [3], reported moments of the 18^{th} order. In the free round jet [4–8] (among others) reported moments of velocity fluctuations up to the 4^{th} order. Moments of the 6-th order are reported in [9].

Available experimental results show strong deviations of probability density distributions of turbulent velocity, from the normal. Early studies of these non-Gaussian variations of turbulence properties in the wall flows are performed by [10]. At the beginning, the most of researches believed that an adequate information on the turbulent velocity probability density distribution could be expressed only as the table of the amplitude of distribution. On their opinion, it should be functionally connected with the instantaneous deviation of the local velocity field from the mean velocity value, at the point of consideration. Fortunately, Durst *et al.* [11] succeeded in analytical describing the probability density distribution in a boundary layer by the "general distribution function of turbulence flow properties". Furthermore, following [12], Durst *et al.* [13] proved that the 4^{th} order truncated Gram-Charlier series expansions can be used to describe a distribution of turbulent velocity fluctuations in the boundary layer. Direct studding of the relationships between higher-order velocity moments also gave encouraging results. For example, Jovanović [14] verified interrelations of higher-order velocity moments in boundary layer. Following his conclusions, in [8] are evidenced adequate relationships between 3rd and 4th order moments and [9] proved corresponding relations for the moments up to the 6th order in the free round jet.

In present work is verified the expected existence of similar relationships in the turbulent wake behind a round cylinder. Also, the general form of relationships between higher-order moments is checked in two additional flows: round jet and boundary layer. The newest generation anemometer probe, with twelve hot-wires, is applied for verifying the relationships between moments in boundary layer. In general, we clearly followed the existing statistical theory of turbulence, founded in [10] and [12], and advanced in [15].

Experimental set-ups and numeric procedures

Experiments, presented in this work, are performed under stable ambient temperatures, with variations within ±0.1K. In these situations, temperature corrections for hot-wire anemometer readings were not necessary. Carefully chosen numeric algorithms for hot-wire exit signals interpretation enable the reproduction of fluid velocity components (induced during probe calibrations) with errors smaller than 1%.

The first experiment was performed at the Faculty of mechanical engineering in Belgrade. Turbulent velocity field was measured in the near field of free round jet. Its initial velocity was 10 m/s in the axis of cubic profiled round nozzle of exit diameter D_0 = 24 mm. The jet exit velocity profile was "top-hat" type and the longitudinal turbulence level was about 1.5% in the axis. An X hot-wire probe with sensors of L=1.25 mm length and d = 0.005 mm diameter was used at overheat ratio of 0.8. Output anemometer voltages were sampled at f = 6 kHz per measurement channel. The cosine-law, based on effective cooling angles, was applied for hot-wire output signals interpretation. Probe was calibrated in the jet potential core, against the Pitot tube. Since the calibration data showed expected non-linearity, especially at low fluid velocities, calibration curves were fitted following the procedure reported in [16] and the law proposed in [17].

Turbulent boundary layer data originates from the wind tunnel in Hydrodynamic laboratory at the University of Maryland. Free stream velocity of only U_0 = 3 m/s and suitable tunnel design provided large coherent structures and good spatial resolution of measurement. All signals of twelve-sensor probe WP–12+(G) were used and interpreted by special gradient procedure (12+G), described in [18]. Selective separated usage of the corresponding signals of three arrays (see Fig. 1) results in possibility to simulate probes with various numbers of sensors. Using four signals of any of three arrays a four-sensor probe (4+) can be simulated. If the signals of sensors no 1 and 3 are used, the "V" probe in the vertical plane is simulated (VV), and similarly a horizontal "V" probe (VH) with sensors 2 and 4. In the last two cases, a variant of generalised procedure used for twelve and four sensor probe is applied [19].

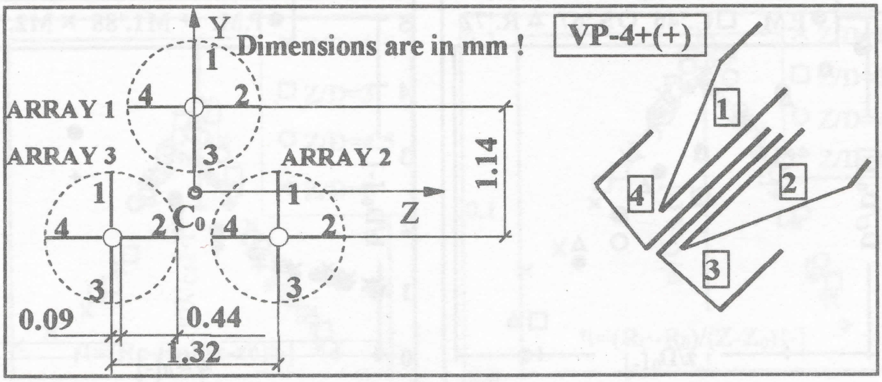


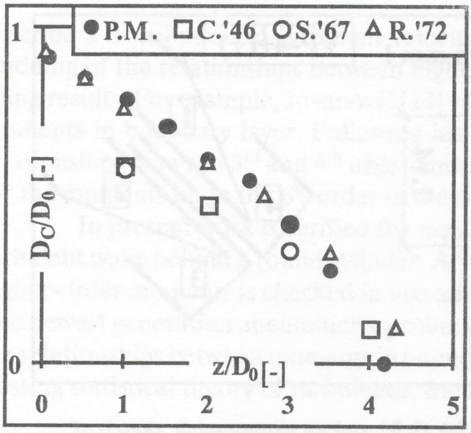
Figure 1. End view of the probe WP-12+ (left) and an axonometric sketch of its array (right)

The third experiment was performed in the turbulent plain wake behind a round D = 3 mm cylinder, mounted in the large square cross-section (2 × 1.4 m) wind tunnel in the Lehrstuhl fur Stromungsmechanik (LSTM) at the Friedrich-Alexander University of Erlangen-Nurnberg. Free-stream mean velocity was 6.44 m/s and turbulence level below 0.07%. Dantec X-probe (L = 1 mm and d = 0.005 mm) is used, with overheat ratio 0.8. Sampling rate was set to f = 1 kHz per channel. The cosine-law, based on effective cooling angles, was used to describe hot-wire cooling. Following cosine law [17], X probe was calibrated in the free-stream, against the Pitot tube. The experimental conditions were favourable: mean velocities were over critical limit of 5 m/s, their changes in the profiles under 0.5 m/s and turbulence levels under 2%.

Jet development in the near-field region

Boundaries of the jet potential core (P. M.) are presented in Fig. 2, together with experimental data reported in [20] (C.'46), [21] (R.'72) and [2] (S.'67). Although these data are in general agreement, some mutual differences still exist. They originate from different flow conditions. In the present case, linear regression gives the following equation for core boundaries: $R_C/R_0 = 0.165\,(Z/R) + 0.9967$. Here, R_C designates the core radius, R_0 nozzle exit radius and Z designates the axial distance from the virtual origin of the jet mixing layer (it is coincident with the nozzle lips in the present case: $Z_0 = 0$). Jet spreading is illustrated by Fig. 3, where jet half-width is designated with b and nozzle exit diameter by D_0. Present results (P.M.) agree well with corresponding data presented in [8] (M1. '88 and M2. '88).

Mean velocity profiles, presented toward non-dimensional width of the jet mixing layer $\eta = (R - R_C)/(Z - Z_0)$, are self-similar in region Z/D_0 = 1.5 – 4.5 (see Fig. 4). Normalized profiles of streamwise u' and cross-stream v' turbulence intensities are shown in Figs. 6 and 7 (respectively) and the radial profiles of shear-stress coefficient



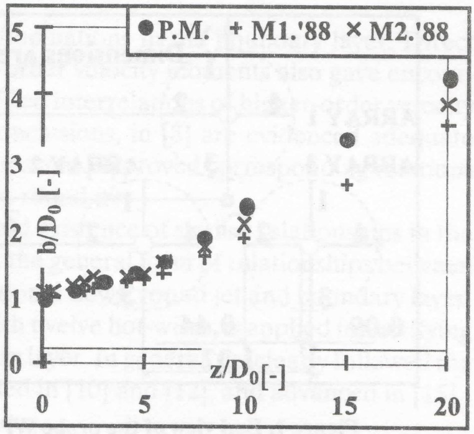
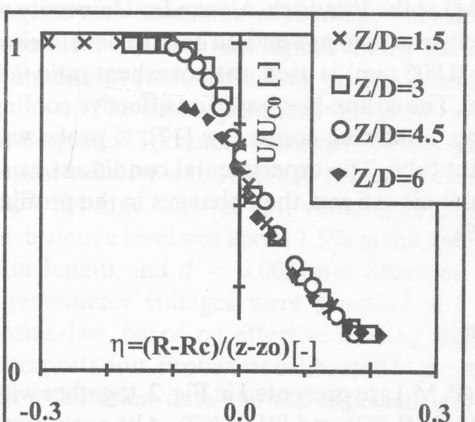


Fig. 2. **Fig. 3.**

Figures 2 and 3. Potential core diameter DC (left) and jet half-width b (right) in the nearfield



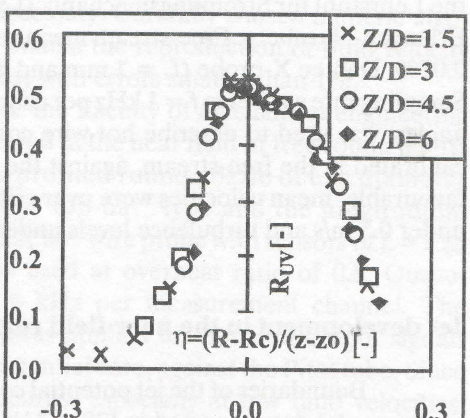


Fig. 4 **Fig. 5.**

Figures 4 and 5. Profiles of mean velocity *U*, normalized by nozzle centre value U_{C0} (left), and correlation coefficient R_{UV} (right) in the jet near field

Ruv in Fig. 5. Our results agree well with currently available data, reviewed in [7] among others.

Parameters of the jet transition region were measured at four cross-sections: $Z/D_0 = 4.5$, 6, 10, 20. Data are normalized by centreline mean velocity U_C in the current cross-section and plotted against non-dimensional radius R/b. Similarity of the mean

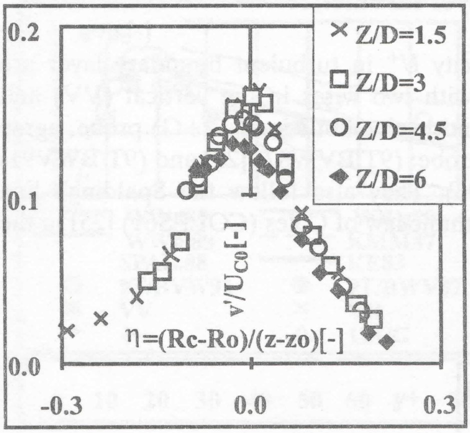


Fig. 6.

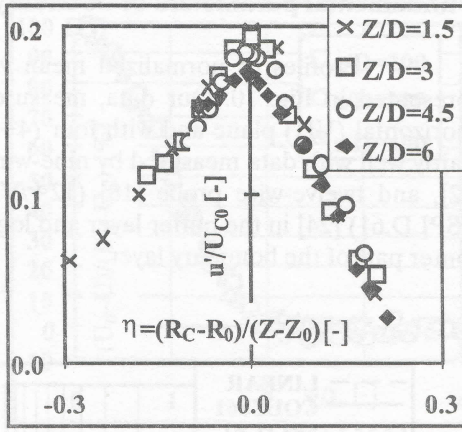


Fig. 7.

Figures 6 and 7. Streamwise *u'* (left) and cross-stream *v'* (right) rubulence intensity in the near field of turbulent free round jet

velocity profiles is achieved after $Z/D_0=6$, what is in agreement with [4] and [8]. However, that was not the case for turbulence intensity profiles, which need longer distances to achieve the self-similarity (see [4]). Profiles of streamwise mean velocity and turbulence intensity are presented in Figs. 8 and 9. In these figures, scales are changed: radius R is normalized by the jet half-width b.

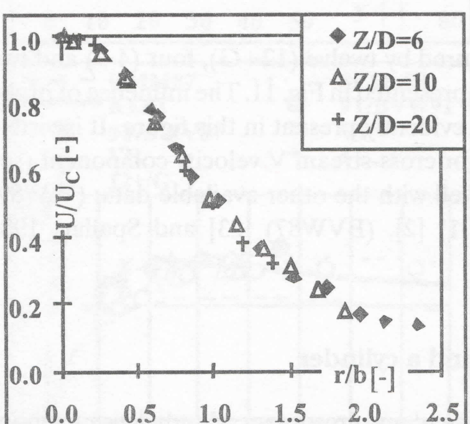


Fig. 8.

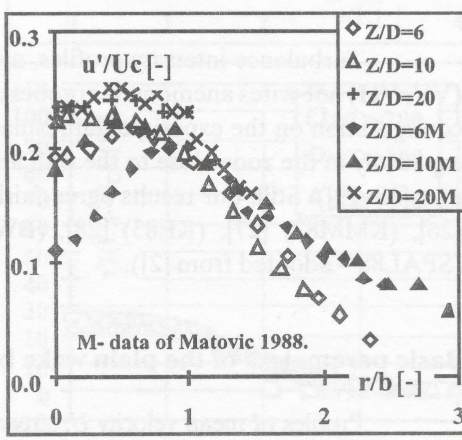


Fig. 9.

Figures 8 and 9. Mean velocity *U* (left) and streamwise turbulence intensity *u'* (right) in the jet transition region, both normalized by centreline mean velocity U_C

Fundamental parameters of boundary layer turbulence

Profiles of normalized mean velocity U^+ in turbulent boundary layer are presented in Fig. 10. Our data, measured with two wires in the vertical (VV) and horizontal (VH) plane and with four (4+) and twelve hot-wires (12+G) probe, agree fairly well with data measured by nine-wire probe: (9T/BVW87) [23] and (9T/BWV91) [2], and twelve-wire probe [18] (12+/VW96). They also follow the Spalding's line (SPLD.61) [24] in the buffer layer and logarithmic law of Coles (COLES61) [25] in the outer part of the boundary layer.

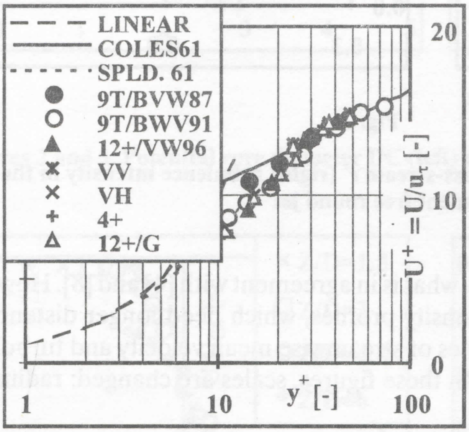


Figure 10. Non-dimensional mean velocity U^+, measured by two sensors in the vertical (VV) and horizontal (VH) plane, four sensor probe (4+) and twelve wire probe (12+G)

Turbulence intensity profiles, measured by twelve (12+G), four (4+) and two (VV, VH) hot-wires anemometer probes are presented in Fig. 11. The influence of probe configuration on the experimental results is evidently present in this figure. It is visible especially in the zone close to the wall and for cross-stream V velocity component (see also [18–19]). Still, our results agree fairly well with the other available data: (WW89) [26], (KMM87) [27], (KE83) [28], (BWV91) [2], (BVW87) [23] and Spallart 1988 (SPAL88 – adopted from [2]).

Basic parameters of the plain wake behind a cylinder

Profiles of mean velocity U, streamwise u' and crosstream v' turbulence intensity, measured at distances of 200, 300 and 400 diameters behind the round cylinder, are presented in Fig. 12. All parameters are normalized by the mean velocity deficit $(U_0 - U_C)$. Similarity of the mean velocity profiles is evident in all three measuring cross-sections. However, as usual, self-similarity of turbulence intensity profiles is achieved at larger

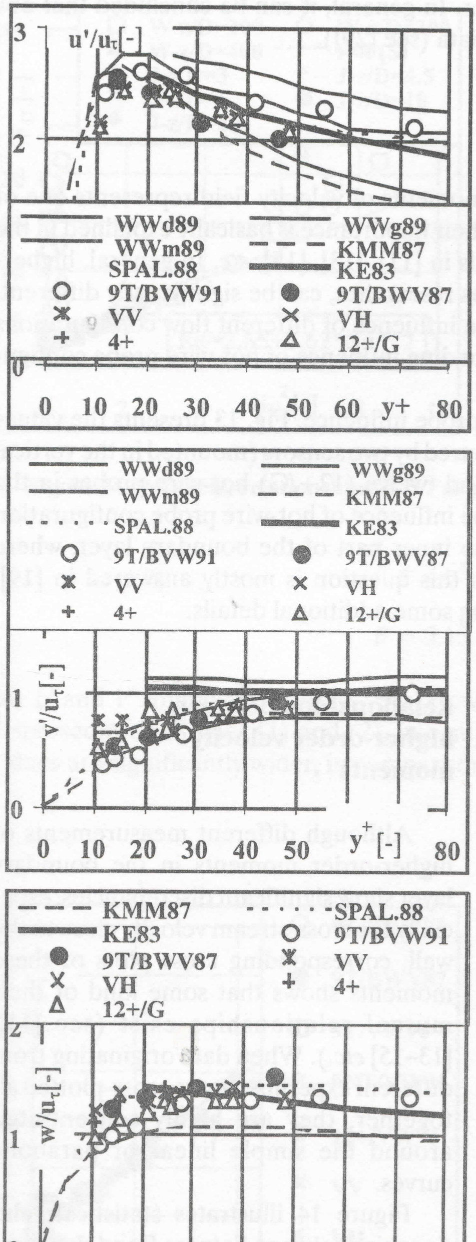


Figure 11. Turbulence intensities *u'*, *v'*, *w'*, in the boundary layer

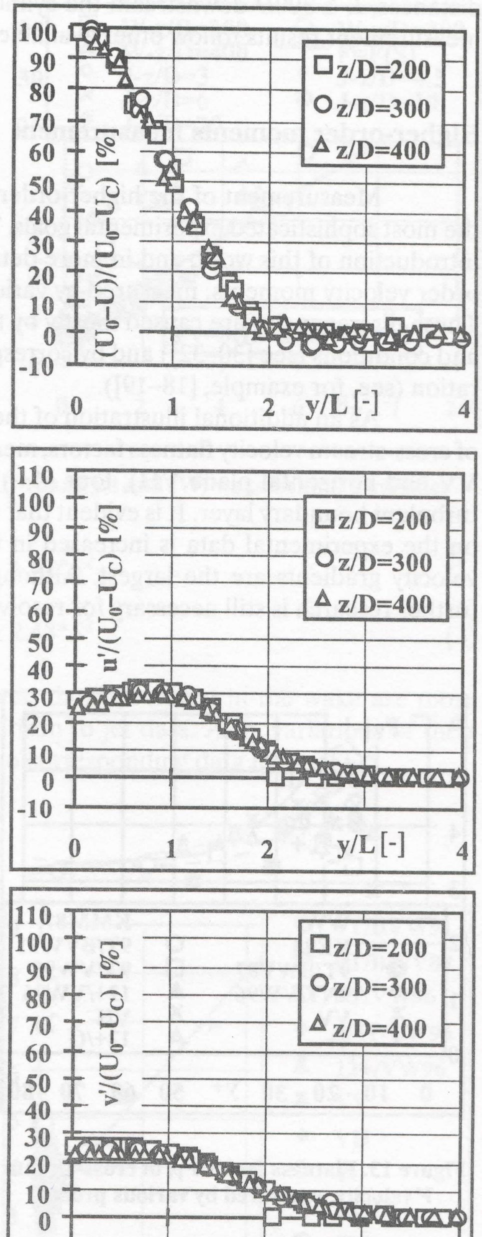


Figure 12. Profiles of mean velocity and turbulence intensities in the wake

distances, $L \geq 300D$ downstream the cylinder. In general, it can be concluded that our measurement results follow other available data (see [29]).

Higher-order moments measurement

Measurement of the higher-order moments of velocity field represents one of the most sophisticated experimental goals. Their importance is basically explained in the introduction of this work, and in more details in [11], [13], [15], *etc.* In general, higher-order velocity moments, measured by various researches, can be significantly different. These discrepancies are caused mostly by the influence of different flow configurations and conditions (see [30–32]) and by corresponding influence of hot-wire probe configuration (see, for example, [18–19]).

As an additional illustration of the probe influence, Fig. 13 presents the values of cross-stream velocity flatness factors, measured by two sensors (mounted in the vertical VV and horizontal plane VH), four (4+) and twelve (12+/G) hot-wire probes in the turbulent boundary layer. It is evident that the influence of hot-wire probe configuration on the experimental data is increased in the inner part of the boundary layer, where velocity gradients are the largest. Although this question is mostly answered in [19], further research is still necessary for resolving some additional details.

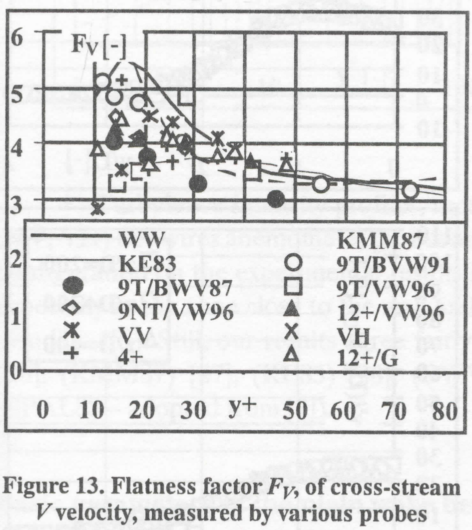


Figure 13. Flatness factor F_V, of cross-stream V velocity, measured by various probes

Relationships between higher-order velocity moments

Although different measurements of higher-order moments in the boundary layer show significant discrepancies, especially for cross-stream velocity close to the wall, corresponding cross plots of these moments shows that some kind of their mutual relationships exist (see [11], [13–15] *etc.*). When data originating from different experiments are cross-plotted all together, they are highly concentrated around the simple linear or parabolic curves.

Figure 14 illustrates statistical relationships between flatness F and skewness S factors of the streamwise U and cross-stream V velocity components. Our data, measured in the round jet (J) at Z/D_0=3, 4.5, 6, 10 and 20 and in the wake (W) at distances Z/D=200, 300 and 400 downstream a cylinder, fairly well follow trend lines:

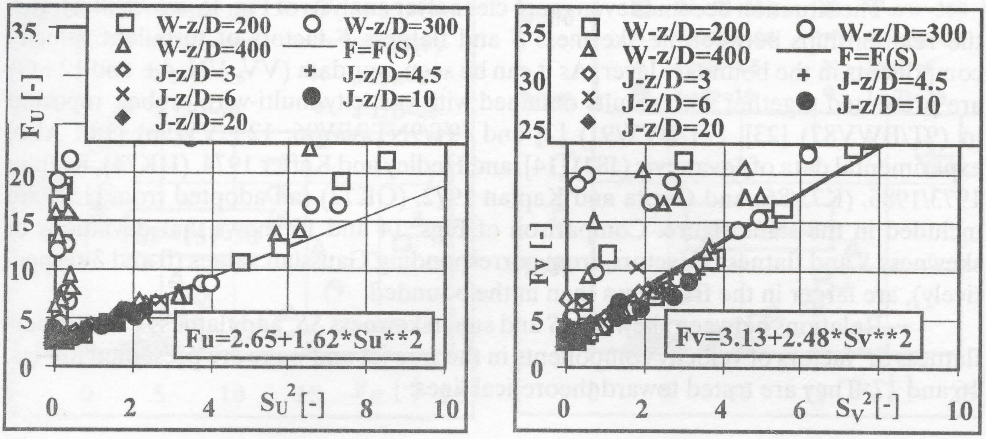


Figure 14. Parabolic relationships $F = F(S)$: (J) round jet and (W) wake behind a cylinder

$$F = 2.65 + 1.62*S^2 \tag{1}$$

$$F = 3.13 + 2.48*S^2 \tag{2}$$

for U and V component respectively. However, data measured in the wake are more dispersed around lines (1) and (2), in comparison to jet data. Also, variations of their values are significantly wider, in comparison to corresponding data in the jet.

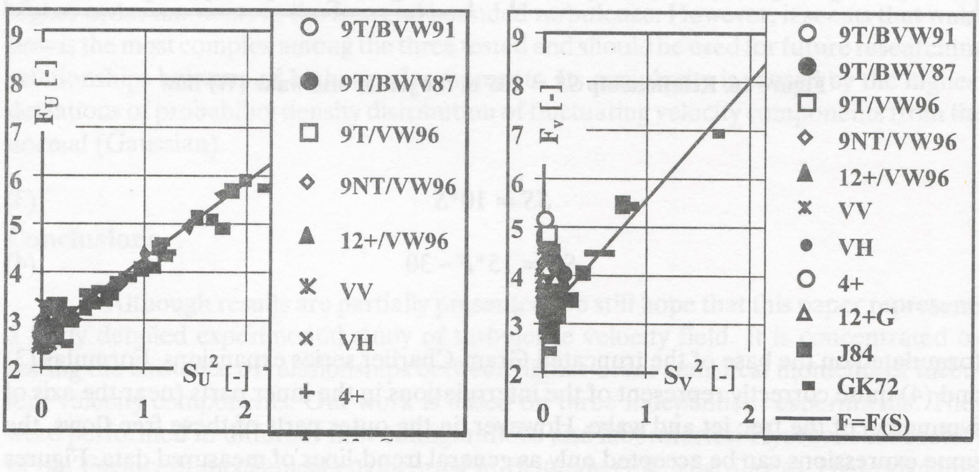


Figure 15. Parabolic relationships $F = F(S)$ in the turbulent boundary layer

The situation becomes even more clear after analysis of Fig. 15, which illustrates the relationships between he skewness S and flatness F factors of turbulent velocity components in the boundary layer. As it can be seen, our data (VV, VH, 4+ and 12+G) are presented together with results obtained with vorticity multi-wire probes, reported in (9T/BWV87) [23], (9T/BVW91) [2] and (9T/9NT/VW96, 12+/VW96) [18]. Also, experimental data of Jovanovic (J84) [14], and Hedley and Keffer 1974. (HK74), Kreplin 1973/1986. (K73/86) and Gupta and Kaplan 1972. (GK72) (all adopted from [15]) are included in the same figure. Comparison of Figs. 14 and 15 shows that deviations of skewness S and flatness F factors, from corresponding Gaussian values (0 and 3 respectively), are larger in the free flows than in the bounded.

Relations between skewness S and superskewness SS, and flatness F and superflatness SF factors of velocity components in the free jet and wake are presented in Figs. 16 and 17. They are tested toward theoretical lines:

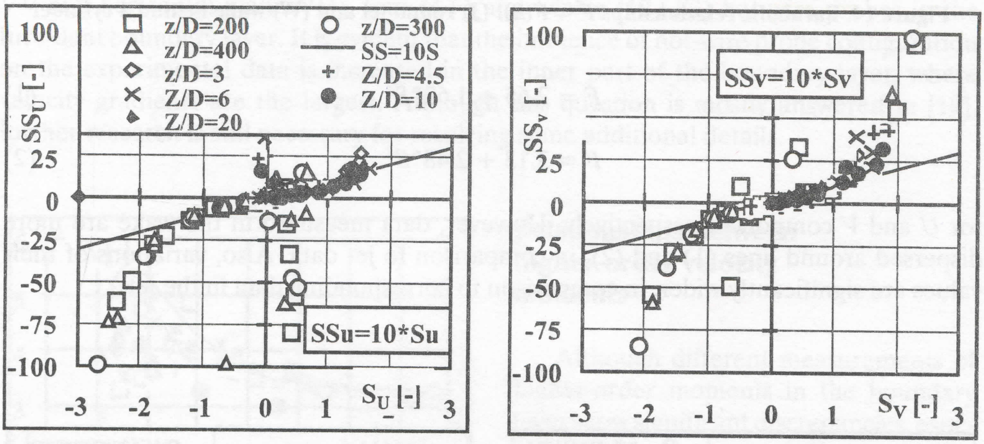


Figure 16. Relationship $SS = 10S$ in the jet (J) and wake (W) flow

$$SS = 10^{*}S \tag{3}$$

$$SF = 15^{*}F - 30 \tag{4}$$

formulated on the base of the truncated Gram-Charlier series expansions. Formulas (3) and (4) quite correctly represent of the interrelations in the inner parts (near the axis of symmetry) of the free jet and wake. However, in the outer parts of these free flows, the same expressions can be accepted only as general trend-lines of measured data. Figures 14–17 show that deviations of experimental data from theoretical line (3) and (4) are

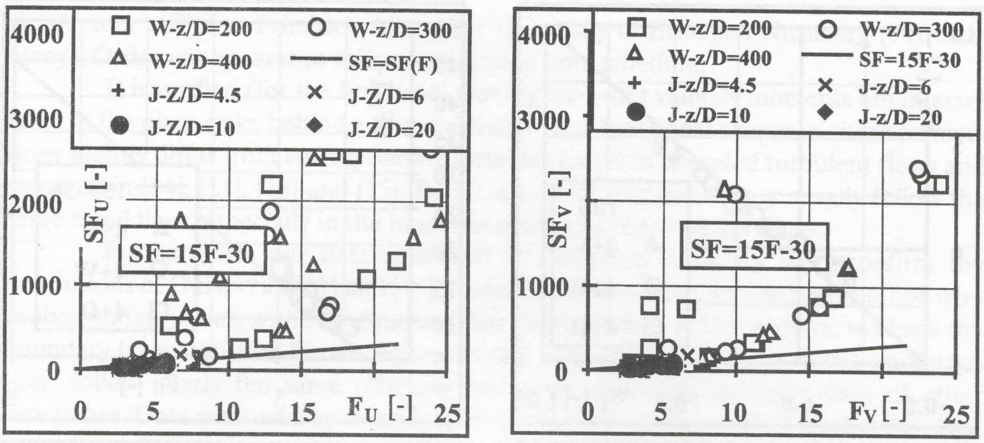


Figure 17. Testing the trend-line $SF = 15F\text{-}30$ in the jet (J) and wake (W)

larger in the wake in comparison to free jet. In addition, the interval ranges of moments are larger in the wake, when compared to their values in the round jet.

As it can be seen in Figs. 18 and 19, our high-precision measurements with four wires 4+ probe confirm relationships (3) and (4) in bounded flows. In order to additionally check the moments interrelations, output signals were interpreted by three algorithms: special generalised procedure (4+V) [18] and it's modified variants (4+W) and (4+D) [32]. Although various procedures give different values of S, SS, F and SF factors, their crossplots $SS = SS(S)$ and $SF = SF(F)$ follow the same trend lines (3) and (4). In such a way, it is verified that these interrelations are practically independent on the signal interpretation procedure.

Data presented in Figs. 14–19 confirm the existence of similar interrelations of higher order moments in the free and bounded turbulence. However, it seems that wake flow is the most complex among the three tested and should be used for future researching relationships between of higher-order moments. Its complexity is caused by the highest deviations of probability density distribution of fluctuating velocity components from the normal (Gaussian).

Conclusions

Although results are partially presented, we still hope that this paper represents a fairly detailed experimental study of turbulence velocity field. It is concentrated on testing the existence of relationships between higher-order statistical moments of turbulent velocity components. Our work is based on three independent experiments. They were performed in different flow configurations and laboratories: Hydraulic laboratory of the Faculty of mechanical engineering in Belgrade (FR Yugoslavia), Hydrodynamic laboratory of the Department of mechanical engineering at the University of Maryland

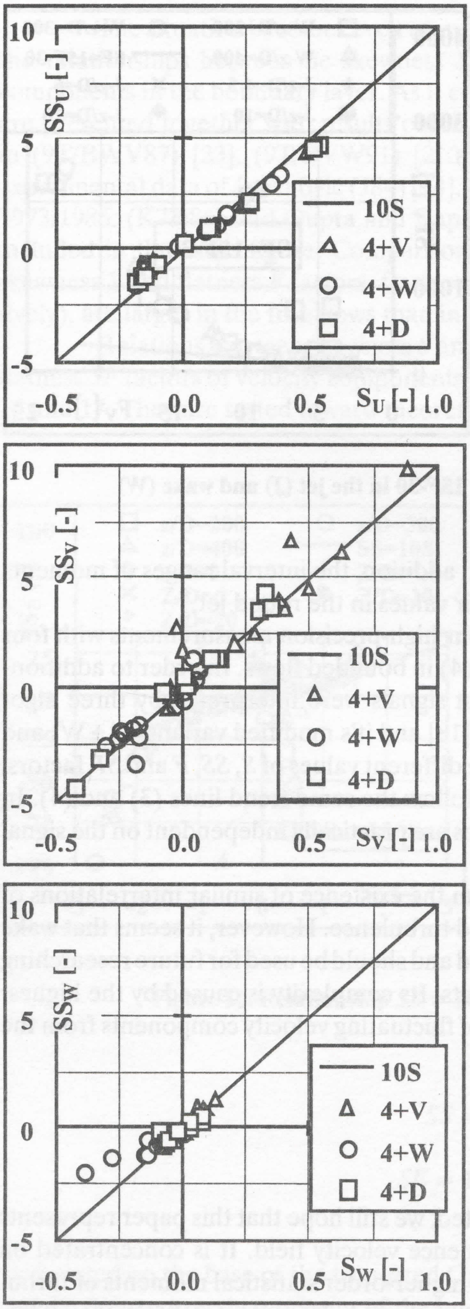


Figure 18. Relationship SS = 10S in the turbulent boundary layer

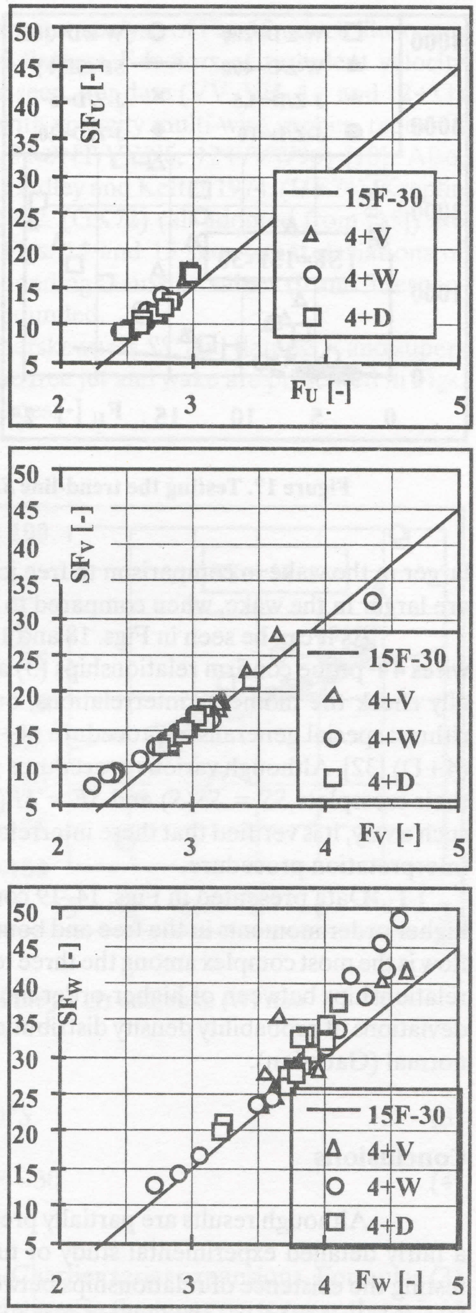


Figure 19. Relationship SF = 15F-30 in the turbulent boundary layer

(USA) and LSTM at Friedrich-Alexander University of Erlangen-Nurnberg (FR Germany). Order of appearance follows measuring time schedule.

It is verified (for the first time) that higher-order velocity moments are interrelated in the plain wake behind a round cylinder. The functional shapes of these connections slightly differ from corresponding formulas found in bounded turbulent flows and reported in [14], [11], [13] and [15]. But, it is evident that our data generally follow the same trend lines, especially in the inner (near the axis) parts of the wake.

Furthermore, our data measured in turbulent boundary layer confirm the conclusions of Durst *et al.* [11] and [13]. It should be noted that we used various hot-wire probe configurations, with two, four and (for the first time) twelve sensors, to check the boundary layer statistics. Presented results that correspond to various probe configurations follow nearly the same relations and agree well with available data of other researches. Data measured by different probes are highly concentrated around the same trend-lines. This is in a way surprising, because Vukoslavčević and Petrović [19] proved significant influence of probe configuration on the measured values of some higher-order velocity moments. It means that the influence of hot-wire probe configuration on measured values of higher-order velocity moments (reported in [19]) still does not influence significantly the shapes of their interrelationships.

However, some limited influence of the flow configuration on these relationships exists. Present measurements and available results of other researchers show this clearly. It seems that Gram-Charlier relationships, proved in bounded flows, represent only the linear model of the corresponding connections in the free flows. Probably, free turbulence (especially wake flow) is more general case from the statistical point of view, in comparison to bounded.

In the free flows, experimental data are more dispersed around Gram-Charlier theoretical lines SS = 10S and SF = 15F-30, in comparison to bounded flows. But still, these formulas are fairly acceptable approximations of corresponding relationships in the turbulent plane wake behind a cylinder and free round jet.

Further analysis of existing statistical theory of turbulent flows is necessary. It should follow results proposed in [11]. There, the applicability of "general distribution function" for describing the probability density distribution of turbulent velocity components through the whole boundary layer is reported. We believe that future trials, for describing relationships between higher-order velocity moments, should include this function.

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List of symbols

b – jet half-width
d – hot-wire diameter
D – cylinder diameter
D_0 – diameter of the nozzle lips
D_C – jet potential core diameter
D_{C0} – jet potential core exit diameter
f – sampling frequency
L – hot-wire length
R – jet radial coordinate
R_0 – jet exit radius
R_C – jet potential core radius
R_{UV} – shear stress correlation coefficient
S – skewness factors
F – flatness factors
SS – superskewness factors
SF – superflatness factors
u' – streamwise turbulence intensity
v' – cross-stream turbulence intensity
U – fluid mean velocity
U_C – jet/wake mean axis velocity
U_0 – free stream mean velocity
U_{C0} – mean velocity in the axis of the jet nozzle lips
y^+ – non-dimensional distance from the wall*
u_τ – friction velocity*
U^+ – non-dimensional mean fluid velocity in turbulent boundary layer*
Z – jet/wake streamwise coordinate

Z_0 – jet virtual origin coordinate
Δt – temperature difference
η – non-dimensional width of the jet mixing layer
ρ – fluid density
τ_w – wall shear stress

*

$y^+ = y^* u_\tau / \nu$
$u_\tau = (\tau_w/\rho)^{1/2}$
$U^+ = U/u_\tau$

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