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THIRD-AND FOURTH-ORDER VELOCITY STRUCTURE FUNCTIONS IN A PERTURBED TURBULENT BOUNDARY LAYER

O. M. Oyewola[1, 2]
[1]School of Mechanical Engineering, Fiji National University, Suva, Fiji
[2]Department of Mechanical Engineering, University of Ibadan, Ibadan, Nigeria
E-Mail: oooyewola001@gmail.com

ABSTRACT

The response of higher-order velocity structure functions in flat plate turbulent boundary layer subjected to the effect of concentrated suction, apply through a single narrow porous wall strip have been examined using hot-wire anemometry methods. The results indicate that, the higher-order functions shows a greater sensitivity to a change in boundary conditions than the second-order functions suggesting that small scale motion follows a similar trend with large scale motion. However, relative to undisturbed layer, third and fourth-order structure functions of wall-normal velocity shows a greater departure than their longitudinal counterpart, reflecting a lower contribution to intermittency.

Keywords: measurement, turbulence, boundary layer, structure function, small-scale.

1. INTRODUCTION

Turbulence appears to be entirely random motion without any possibility to predict the development of flow properties. However, Kline *et al.* [4] flow visualization revealed the existence of coherent structures in wall bounded turbulent flow. This is not surprising since in the viscous sublayer the near wall flow appears to be made of neighbouring regions of high and low velocity. These streaks were presumed to be the result of elongated streamwise vortices very near the wall. In that respect, interfering with these vortices would influence both the large and small scale motion. The study of the small-scale motion underlies the essence of turbulent theory; the understanding of the properties of the small-scale motion would definitely improve the turbulence models especially for the flows subjected to perturbation. This is worth studying, as noted by Sreenivasan and Antonia [10], a proper theory of turbulence, if one were to emerge, may well relate to the small scale, which has the best prospect of being universal or quasi-universal. The distributions of energy among various scales in the undisturbed turbulent flows are well known. It is well established that energy is transferred to the smallest scales structures from the large scales structures through the effect of the mean shear and this energy is dissipated by viscosity. In that respect, considerable effort has been devoted in understanding the small-scale motion especially when it is subjected to a perturbation in the form of roughness elements. For example Antonia and his co-workers [1, 2], had studied extensively the effect of roughness on the small-scale turbulent structure. They showed that the small-scale motion presents some dependence on the roughness. Poggi *et al.* [8] argued that the roughness breaks down the scaling regions at small scales through the imposition of its characteristic scales. The response of the small-scale motion to a perturbation in form of suction applied through a short narrow wall strip has not received much attention may be as a result of the complexity of the response. Moreover, Oyewola *et al.* [6, 7], carried out studies on some characteristics of the small-scale motion in a turbulent boundary layer subjected to suction, applied through a short narrow wall strip. The overall conclusion stemming from the above studies is that the small-scale motion responds to a change in large-scale motion. They also found out that the pseudo-equilibrium and the anisotropy of the small-scale motion are altered by suction. The present study which extends the work of Oyewola *et al.* [6, 7] investigates the response of higher-order velocity structure functions to suction applied through a short narrow wall strip over a range of R_λ and for several suction rates. This is necessary in quantifying the small-scale motion because the higher-order statistics of the structure functions should be more sensitive to a change in boundary conditions than the second-order structure functions.

2. EXPERIMENTAL METHOD

Measurements were made in a smooth flat plate turbulent boundary layer, which is subjected to concentrated suction, applied through a short porous strip. The turbulent boundary layer develops on the floor of the wind tunnel working section (Figure 1) after it is tripped at the exit from a two-dimensional 9.5:1 contraction using a 100 mm roughness strip (Norton Bear No. 40, very coarse). Tests showed that the boundary layer was fully developed at the suction strip location, which is about 1200 mm downstream of the roughness strip. The roof of the working section is adjusted to achieve the desire pressure gradient (zero for the present investigation). The free stream velocity U_∞ was approximately 7 ms^{-1}; corresponding values of the initial momentum thickness Reynolds numbers $R_{\theta o}$ are1400 and the Taylor microscale Reynolds number is in the range R_λ = 90 - 120. A 3.25 mm thick porous strip with a width of 40 mm and made of sintered bronze with pore sizes in the range 40 - 80 μm or (0.4 - 0.9)ν/U_τ was mounted flush with the test section floor. Allowing for the width of the mounting recess step, the effective width (=b) of the strip was 35 mm. Suction was applied through a plenum chamber located underneath

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the suction strip and connected to a suction blower, driven by a controllable DC motor, through a circular pipe (internal diameter D = 130 mm and L/D ≈ 38, where, L, is the pipe length). The flow rate Q_r was estimated directly by radially traversing a Pitot tube located near the end of the pipe, for various values of the pipe centre-line velocity (U_c). A plot of Q_r vs U_c, allowed the suction velocity (V_w) to be inferred via the continuity equation ($Q_r = A_w V_w$, where, A_w is the cross-sectional area of the porous strip). The suction velocity was assumed to be uniform over the porous surface; this assumption seems reasonable if the variation in the permeability coefficient of the porous material is ±3%.

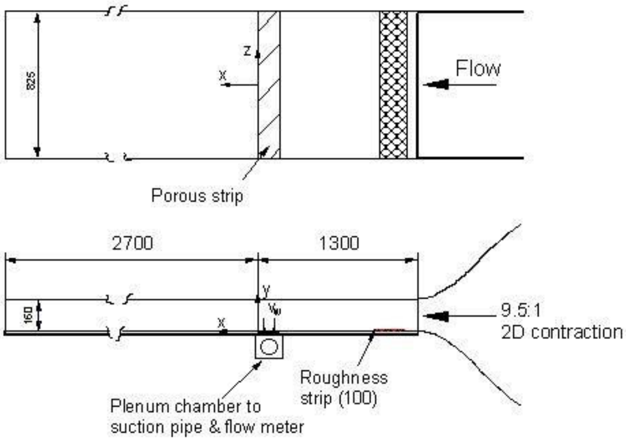


Figure-1. Schematic arrangement of the working section (Dimensions in mm).

Measurements were made for σ (= $V_w b/\theta_o U_\infty$, normalised suction rate or severity index as introduced by Antonia et al. [3] = 0, 0.8, 1.7, 3.3 and 5.5. The results for σ = 0 provided a reference against which the suction data could be appraised. The wall shear stress τ_w was measured with a Preston tube (0.72 mm outer diameter), and a static tube located approximately 35 mm above it at the same x position. The Preston tube was calibrated in a fully developed channel flow using a method similar to that described in Shah and Antonia, [9]. τ_w was determined from the relation $\tau_w = -h(dp/dx)$, where h is the channel half-width and p is the static pressure. Measurements of the velocity fluctuations in the streamwise and wall normal directions were made with cross wires, each inclined at 45° to the flow direction. The etched portion of each wire (Wollaston, Pt-10% Rh) had a diameter of 2.5 μm, and a length to diameter ratio of about 200. The separation between the inclined wires was about 0.6 mm. The velocity fluctuation in the spanwise direction was also measured by rotating the same X-probe through 90°. All hot wires were operated with in-house constant temperature anemometers at an overheat ratio of 1.5. The analog output signal of the hot wire was low pass filtered (the filter cut off frequency was typically between 5kHz and 8kHz), DC offset and amplified to within ±5 V.

3. RESULTS

The previous results of normalised mean energy dissipation rate and spectra of Oyewola *et al.* [6, 7] revealed that the pseudo-equilibrium of the small-scale motion has been altered as a result of the modification of the structures in the near-wall region of the boundary layer, this is confirmed in the distributions of the third-order velocity structure functions of u and v shown in Figures 2 and 3, for y / δ = 0.065 and 0.125, and for several suction rates. The velocity structure functions for the streamwise velocity component, u, are defined as

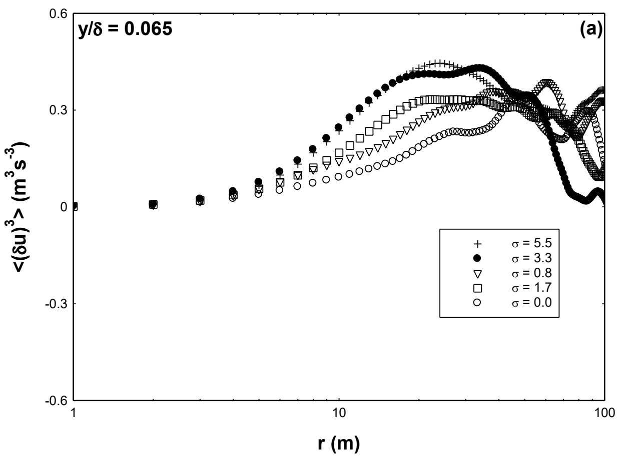
$S_{u,n}(r) = (\langle \delta u(r)^n \rangle)$,

Where $\langle \delta u(r) \rangle$ is the difference of the velocity along the longitudinal direction x over the distance r, namely

$\langle \delta u(r) \rangle = u(x + r) - u(x)$.

The velocity structure functions, $S_{v,n}(r)$, for the wall-normal velocity component, v, are defined similarly.

There is fairly good collapse in all the distributions for r < 10, suggesting that when normalised with Kolmogorov constants, Kolmogorov similarity hypothesis should be reasonably satisfied for suction and non-suction at higher-order small scale statistics. However, third-order velocity structure functions of u and v for r > 10 departs from those for σ = 0, reflecting a manipulation in the structure of the boundary layer which invariably alter the pseudo energy contents of the layer. The effect increases as the suction rate is increased. The departure is significant in v than u distributions. This is in agreement with the skewness distributions, where skewness of v departs significantly as compared with skewness of u.



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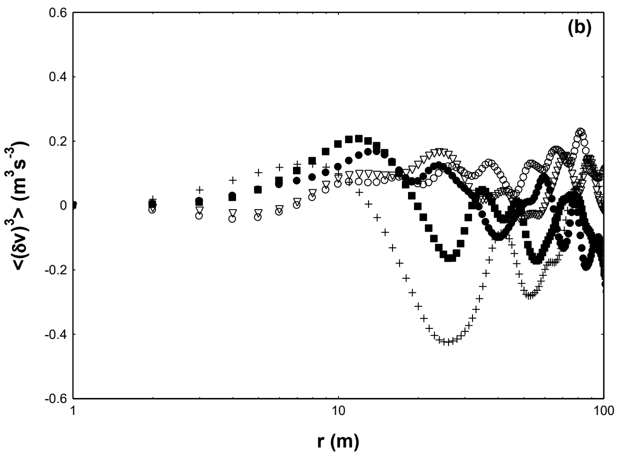


Figure-2. Distributions of third-order velocity structure functions in linear-log scale for several σ at y/δ=0.065 (a) $<(\delta u)^3>$; (b) $<(\delta v)^3>$.

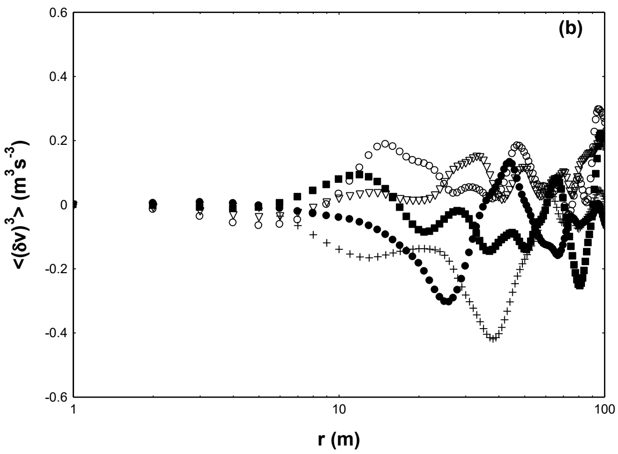
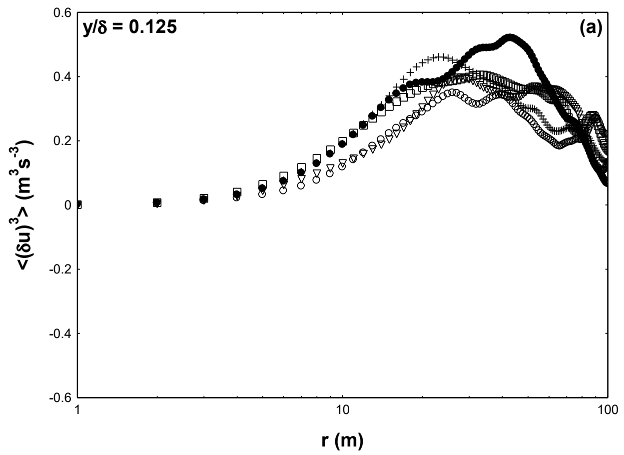


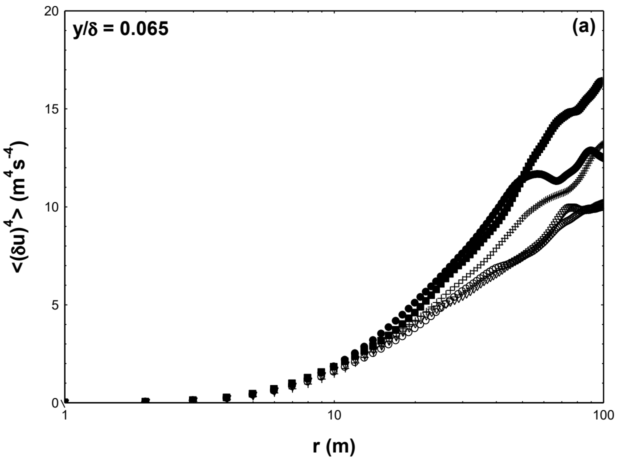
Figure-3. Distributions of third-order velocity structure functions in linear-log scale for several σ at y/δ=0.125 (a) $<(\delta u)^3>$; (b) $<(\delta v)^3>$. Symbols are as in Figure-2.

The present result corroborates the argument that the effect at the large scale is felt to the smaller scale. However, the changes between the suction and no suction of $<(\delta u)^3>$ and $<(\delta v)^3>$ implies a change in the anisotropy of the layer. This is not surprising since the velocity shear imposes a strong anisotropy and this anisotropy is increased when suction is applied. Meanwhile as y / δ increases, the effect of suction is reduced especially for $<(\delta u)^3>$.

In comparison with the second-order structure functions (not shown), the third-order structure functions show a greater departure, corroborating the support that higher-order turbulent statistics are more sensitive to a change in boundary conditions than the second-order functions. This argument is well observed in the present distributions and would suggest that small-scale motion follows a similar trend as their large-scale counterpart. The overall result indicates that the energy contents of the layer have been modified by suction at the large scale and the effect is transmitted to the smaller scales in order to maintain the interaction between the large-scale motion and the small-scale motion.



In Figures 4 and 5, the forth-order velocity structure functions are plotted against r in linear-log scale for y / δ = 0.065 and 0.125, and for several suction rates. While there is fairly good collapse for r < 10 (over the dissipative range), there is clearly discernible $<(\delta u)^4>$ and $<(\delta v)^4>$ dependence on σ for r > 10, the dependence is stronger for $<(\delta v)^4>$. This is not surprising, in the large-scale measurements, the changes observed in the flatness of v is stronger than those of u when suction is applied. This effect is scaled down to the smaller scales as observed in the distributions, suggesting that the smaller scales response similarly to some certain degree to change in the boundary conditions as the large scale.



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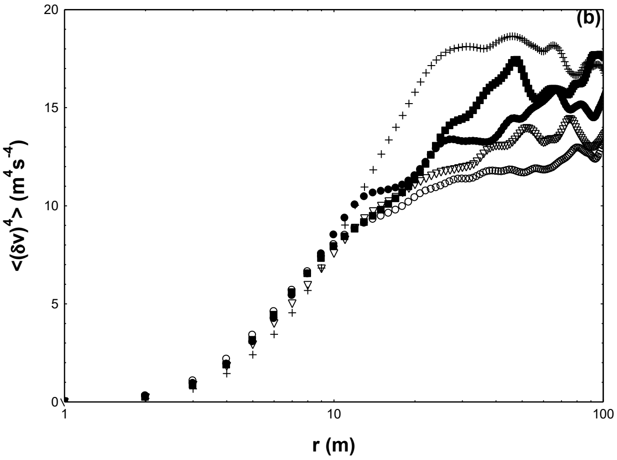

Figure-4. Distributions of forth-order velocity structure functions in linear-log scale for several σ at y / δ=0.065 (a) $<(\delta u)^4>$; (b) $<(\delta v)^4>$. Symbols are as in Figure-2.

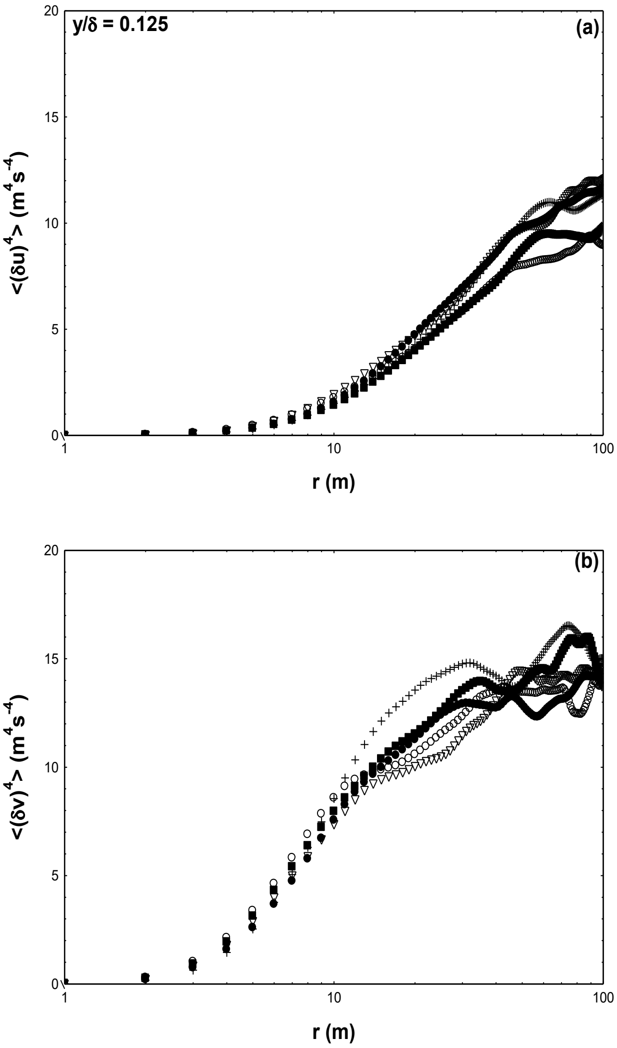

Figure-5. Distributions of forth-order velocity structure functions in linear-log scale for several σ at y / δ=0.125 (a) $<(\delta u)^4>$; (b) $<(\delta v)^4>$. Symbols are as in Figure-2.

Interestingly, when σ exceed 3.3, the departure from no suction case at r ≥ 10 is significant in all the distributions. The result implies that when σ exceed a certain critical value, the effect on the larger scales are significant, which, in turn, would have a non-negligible effect on the smaller scales. This collaborates the work of Oyewola *et al.* [5] which showed that σ has to exceed a certain critical value before it effect on the structures of the layer can be significant that is for relaminarisation to take place. This is clearly evidence even at the higher-order statistics of the velocity structure functions, highlighting that the effect of suction on the small-scale extends to a significant portion of the boundary layer. The changes in third- and fourth-order structure functions may probably suggest that the organization of the flow field in the near-wall region of smooth wall flows has been partially destructed. This implies that the contribution to intermittency becomes lower. The effect is stronger in wall-normal than longitudinal.

4. CONCLUSIONS

Analysis of the third-order and forth-order velocity structure functions has been carried out in a turbulent boundary layer subjected to the effect of concentrated suction, applied through a single narrow wall strip using hot-wire anemometry methods. The results indicate that, relative to no suction, both the third-order and forth-order velocity structure functions showed fairly good collapse for r < 10 especially in forth-order velocity structure functions suggesting that when normalised with Kolmogorov constants, Kolmogorov similarity hypothesis should be reasonably satisfied for suction and non-suction at higher-order small scale statistics. However, third-order and forth-order velocity structure functions for r > 10 depart from those for σ = 0, reflecting a manipulation in the structure of the boundary layer which invariably alter the pseudo energy contents of the layer. Both third-order and forth-order velocity structure functions shows a greater departure than the second-order functions (not shown), indicating that small-scale motion follows a similar trend with their large-scale counterpart. This imply that higher-order statistics are more sensitive to a change in boundary conditions that the second-order. While the organization of the flow field in the near-wall region was partially destructed, the contribution to intermittency is lower in wall-normal than longitudinal.

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Nomenclature

b	width (m)
D	diameter for pipe (m)
h	channel half width (m)
k	wave number
L	length (m)
p	pressure (kg/ms^2)
q	energy (kgm^2/s^2)
Q	flow rate (m^3/s)
U	velocity (m/s)
V	suction velocity (m/s)
x	streamwise location (m)
y	distance normal to the wall (m)

Greek Letters

λ	Taylor microscale (m)
η	Kolmogorov length scale (m)
δ	boundary layer thickness (m)
τ	shear stress (kg/ms^2)
θ	momentum thickness (m)
σ	severity index
ν	kinematic viscosity (Ns/m^2)

Subscripts

c	centre
β	u or v or w
r	radius (m)
u	streamwise velocity
v	wall normal velocity
w	spanwise velocity
w	wall
*	normalisation with Kolmogorov variables