INFLUENCE OF A STRUCTURED WAVY SURFACE ON A TURBULENT FLOW

Shinji Nakagawa and Thomas J Hanratty *
Department of Chemical Engineering
University of Illinois, Urbana, IL61801, USA
* hanratty@scs.uiuc.edu

ABSTRACT

The influence of a train of sinusoidal waves on turbulent flow of water was studied. The waves had a height, a, of 0.5 mm and a wavelength, λ, of 5mm. The flow was such that a fully rough condition was realized. A consideration of the DNS study by Cherukat et al. (1998) of flow over a wavy wall with $2a/\lambda = 0.1$ reveals that turbulence is sustained in a completely different way by a wavy wall than by a smooth wall. Experiments with LDV and PIV show some differences in the turbulence observed over smooth and wavy walls. However, the similarities are more striking. This is particularly evident in PIV measurements of the large scale flow structures associated with Reynolds shear stresses. These results support the notion that at a sufficient distance from the wall turbulent flows have universal structures, which depend only weakly on the structure of the wall.

1 INTRODUCTION

Considerable work has been done examining the structure of turbulence for flow over smooth surfaces. One of the important outcomes is the finding that turbulence is sustained by flow oriented vortices in the viscous wall region and in the inner part of the log layer. These vortices bring high momentum fluid to the wall, exchange momentum with the wall and eject low momentum fluid from the wall. Stress producing motions in the outer flow are associated with large scale plumes of fluid (called "superbursts") which originate in the viscous wall region and extend for large distances in the wall-normal and streamwise directions. (Hanratty et al., 1999)

The turbulence over a roughened or structured wall is created by a different mechanism. Questions arise as to whether the turbulences for smooth and structured walls are similar at a sufficient distance from the wall. This paper addresses this issue.

2 EXPERIMENTAL PROCEDURES

Measurements were made for water flow in a 5cm x 60 cm rectangular channel. The top wall was smooth and the bottom wall contained a train of sinusoidal waves with a height, a, of 0.5mm and a wavelength, λ, of 5mm. The mean velocity profile is, therefore, asymmetric. The length of the test section was 3m and the wavy bottom wall contained about six hundred sinusoidal waves.

Turbulence measurements were made with a three-beam two-component laser Doppler velocimeter (LDV). Detailed descriptions of the channel facility and the LDV system were given by Günther et al. (1998) and Warholic et al. (1999). The dimensions of the measurement volume are 45μm in the streamwise and wall-normal directions and 0.44mm in the spanwise direction. The number of samples taken at each measurement point was 153,600.

Measurements were made for Re=3200, 11000 and 46000, where the Reynolds number is defined with the bulk velocity and the half height of the channel. These provide results under conditions that the surface may be considered hydraulically smooth, intermediately rough and fully rough. Only results for Re=46000 are presented here.

Photographic particle image velocimetry (PIV) was used for Re=46000. The flow was seeded with 5 μm Al_2O_3 particles and illuminated by two pulses of a Ruby laser. Images were recorded on a large format (4inch x 5inch) photographic film. The double-exposed PIV photographs were analyzed using the interrogation system described by Christensen et al. (2000). A Videk Megaplus CCD camera with 1024 x 1024 pixels was employed. The local displacement of particles was determined by using a one-frame cross-correlation analysis. The size of the interrogation spot was 1.4mm x 1.3mm. This is too large to resolve fine scale turbulence structure. However, the results provide useful information about comparatively large structures with length scales comparable to the half channel height of the channel.

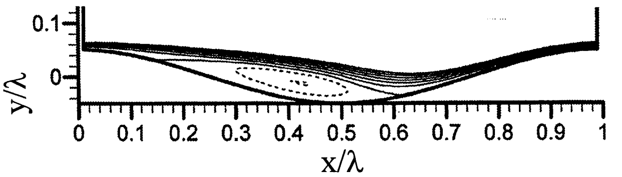

Fig.1 DNS calculations of streamline

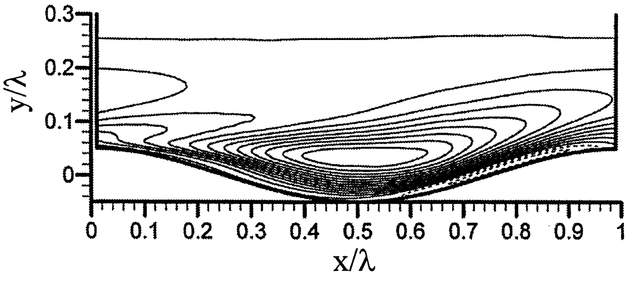

Fig.2 Contours of Reynolds stress from DNS

3 RESULTS AND DISCUSSIONS

3.1 Results from DNS

LDV measurements by Hudson et al. (1996) and DNS studies by Cherukat et al. (1998) have been made for a wave with the same steepness, or the same amplitude-to-wavelength ratio ($2a/\lambda=0.1$). The wavelength was ten times larger in the DNS calculation. However, the Reynolds number was smaller, so that both studies used the same non-dimensional wavelength, λ^+, where the "+" superscript denotes that the variable was normalized with the friction velocity and the kinematic viscosity. Furthermore, the velocity profiles for the DNS and the experiment at $Re=46000$ are characterized by approximately the same roughness functions, ΔU^+, defined as the downward displacement of the logarithmic regions of the velocity profiles from what is observed over a smooth boundary. This suggests that results from the DNS may provide insights regarding flow close to the structured surface under conditions that a completely rough condition exists.

The mean streamlines calculated in the DNS are shown in figure 1. They indicate separation at $x/\lambda=0.16$ and reattachment just downstream of the trough, $x/\lambda=0.61$. Figure 2 shows a plot of contours of the Reynolds shear stress calculated with the DNS. The ridge line may be looked upon as a shear layer (in the time-averaged sense). It is the loci of large productions of turbulence. The reattachment point is the start of a thin boundary layer which extends from $x/\lambda=0.61$ to the crest. The downstream end of this boundary layer is also a locus of large turbulence production.

Figure 3 shows the vectors in a y-z plane, at $x/\lambda=0.767$, in the center of the boundary layer region. Large vortical structures are noted close to the wall. These are different from the wall vortices seen close to a flat surface. They are larger and do not extend over as long a distance in the flow direction. They are observed to form in the region between the trough and crest. They are convected downstream and disappear rapidly after they pass over the crest. They, therefore, appear to be associated with a centrifugal instability in a region where the streamlines have a concave shape.

3.2 Similarity between flows over smooth and wavy surfaces

It is concluded from the above results that the sustenance of a turbulent flow by a structured wavy surface is quite different from what is observed at a flat surface. Therefore, it is of interest to note in figure 4 the similarities that exist between measurements of the root-mean square of the streamwise, u', and wall-normal, v', velocity fluctuations. The ordinates are normalized with the friction velocity. The abscissa is the distance from the average location of the wavy surface, y, normalized with the distance to the maxima in the velocity profile y_{max}. The friction velocity for the structured surface was 10.9cm/s. This is to be compared with the value of 7.62cm/s calculated from the Blasius equation. Data for a smooth wall were measured by Warholic (1999). Good agreement is noted between measurements of u' for rough and smooth surfaces if normalized with the respective friction velocities characterizing the two surfaces. Similar agreement is observed for the root-mean squares of velocity fluctuations in a direction normal to the surface, v'.

Previous studies (Raupach et al., 1990) of the boundary layer developed over rough surfaces also have shown similarity in the Reynolds stresses. However, it is noted that measurements with other types of roughened surfaces in boundary layers (Krogstad and Antonia, 1999) give different results from those cited above.

These results, initially, suggested to us that the turbulence, at a sufficient distance from the wall, could be universal. However, this need not be the case since the similarity is a reflection of the observation that the Reynolds stress coefficients, $R_{uv} = -\overline{uv}/u'v'$, are approximately equal for smooth and structured wavy surfaces.

For a location in the channel where the effects of viscosity or of wave-induced variations of mean velocity are small,

$$-\overline{uv} = \frac{y}{y_o} u^{*2}, \tag{1}$$

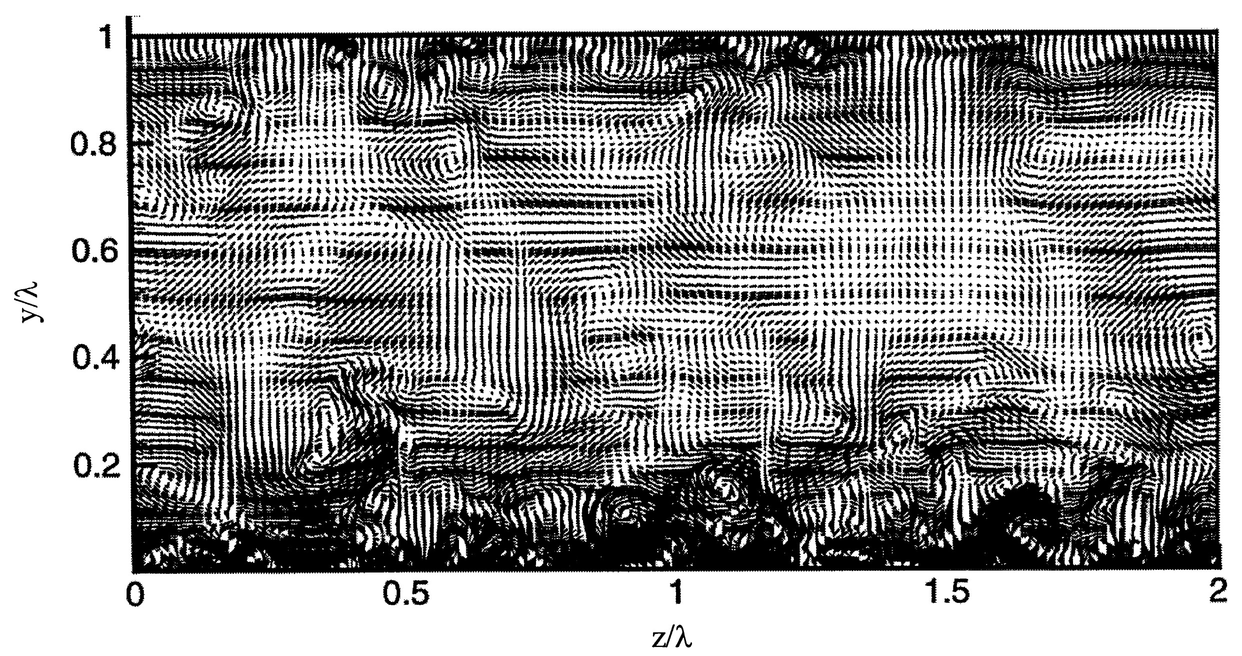

Fig. 3 Vectors in x-z plane at x/λ = 0.767

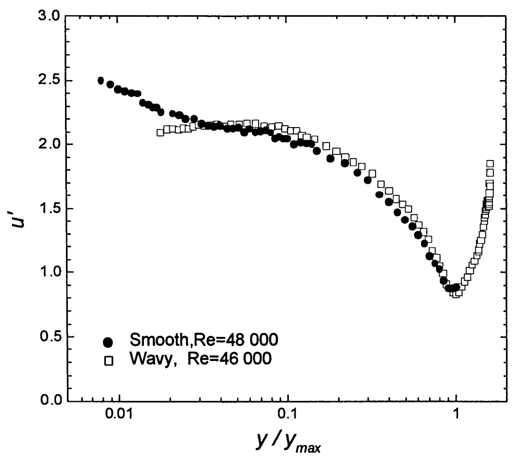

Fig. 4 (a) Measured values of the dimensionless root-mean square of the velocity fluctuations in the x-direction

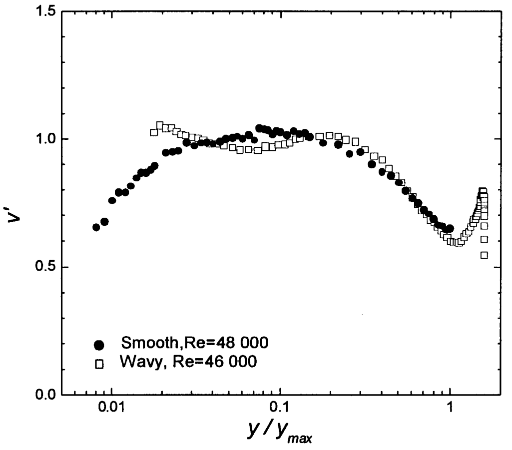

Fig. 4 (b) Measured values of the dimensionless root-mean square of the velocity fluctuations in the x-direction

where y_o is the location where the Reynolds stress is zero. Substituting for $-\overline{uv}$,

$$R_{uv}\, u'v' = \frac{y}{y_o} u^{*2}, \qquad (2)$$

$$u'^{+}\, v'^{+} = \frac{1}{R_{uv}} \frac{y}{y_o}. \qquad (3)$$

If R_{uv} is the same function of y/y_o for smooth and rough surfaces, the product $u'^{+}v'^{+}$ would also be the same. If the ratio v'^{+}/u'^{+} are roughly equal then u'^{+} and v'^{+}, as well as the product, would show similarity.

We concluded that the observed similarity of measurements of u'^{+} and v'^{+} are a consequence of the method of scaling. Therefore, similarity could be observed if turbulence structures are quite different.

Statistical quantities that might reflect differences in structure are presented in figure 5, which shows a plot of the ratio, α, of the quadrant 2 (Q2) and

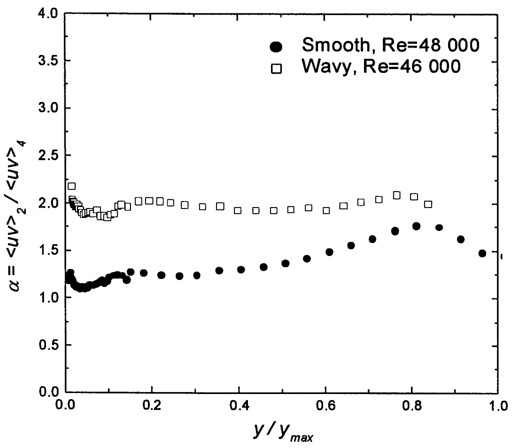

Fig.5 Measurements of the relative contributions Q and Q4 events to the Reynolds stress

quadrant 4 (Q4) contributions to the Reynolds shear stress. Large differences are noted in the results obtained for smooth and structured surfaces. Similar differences are found when skewnesses of the streamwise and wall-normal velocity fluctuations are compared.

3.3 PIV measurements

Samples of our PIV results are shown in figures 6 and 7. The fluctuating velocities, which are obtained by subtracting the time-averaged velocity measured with LDV from the instantaneous velocities, are presented as vector plots. Figure 6 gives an example of strong Q2 events. Figure 7 shows an example of strong Q4 events. The region where the Q2 or Q4 contribution to the Reynolds shear stress exceeds a value that is twice wall friction, u^{*2}, are highlighted. The Q2 event in figure 6 is observed to cover a large portion of the channel. Similar Q2 events are observed in a channel with smooth walls. No obvious imprint of the wavy wall on the turbulence is observed in the PIV data.

We tentatively presume from our PIV studies that stress producing events over smooth and wavy surfaces are, to a first order approximation, the same at a sufficient distance from the surface. However, it is expected that these structures will show differences between the flows if detailed statistics are compared, as shown in a quadrant analysis of LDV measurements.

References

Cherukat, P., Na, Y., Hanratty, T. J., and McLaughlin, J. B., 1998, "direct numerical simulation of a fully developed turbulent flow over a wavy wall", Theoret. Comput. Fluid Dynamics, vol. 11, pp. 109-134.

Christensen, K. T., Soloff, S. M. and Adrian, R. J., 2000, "PIV Sleuth: Integrated particle image velocimetry interrogation / validation software", TAM Report No.943, UILU-ENG-2000-6018, ISSN 0073-5264.

Günther, A., Papavassilious, D. V., Warholic, M. D., and Hanratty, T.J., 1998, "turbulent flow in a channel at a low Reynolds number", Exp. Fluids, vol. 25, pp. 503-511.

Hanratty, T. J., Liu, Z. C. and Na, Y., 1999, "structure of wall turbulence", Proceedings of Ha Minh Hieu Commemoration Conference, Institute de Mecanique des Fluides, 18 November, Toulouse, France.

Hudson, J. D., Dykhno, L. and Hanratty, T. J., 1996, "turbulence production in flow over a wavy wall", Exp. Fluids, vol. 20, pp. 257-265.

Krogstad, P. A. and Antonia, R. A., 1999, "surface roughness effects in turbulent boundary layers", Exp. Fluids, vol. 27, pp. 450-460.

Liu, Z. C., Adrian, R. J. and Hanratty, T. J., 2000, "large-scale modes of turbulent channel flow: transport and structure", TAM Report No.929, UILU-ENG-2000-6004, ISSN 0073 5264

Raupach, M. R., Antonia, R. A. and Rajagopalan, S., 1991, "rough-wall turbulent boundary layers", Appl. Mech. Rev., vol. 44, pp. 1-25.

Warholic, M. D., 1997, "modification of turbulent channel flow by passive and additive devices", Ph.D. thesis, University of Illinois, Urbana.

Warholic, M. D., Schmidt, G. M. and Hanratty, T. J., 1999, "The influence of a drag-reducing surfactant on a turbulent velocity field", J. Fluid Mech., vol. 388, pp. 1-20.

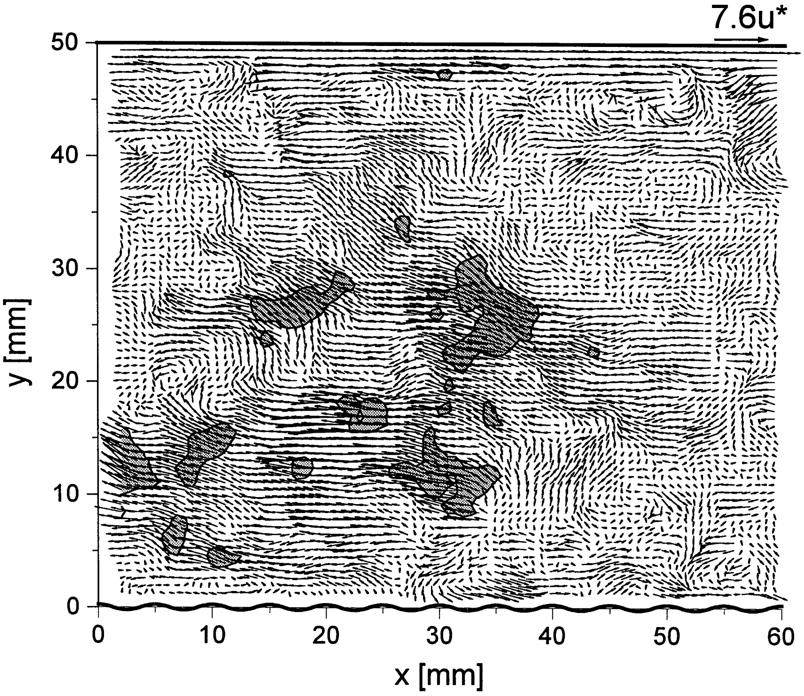

Fig.6 Fluctuating velocity vector plot. Regions of high Q2 contribution to Reynolds shear stress (-*uv*>2*u***u**) are highlighted.

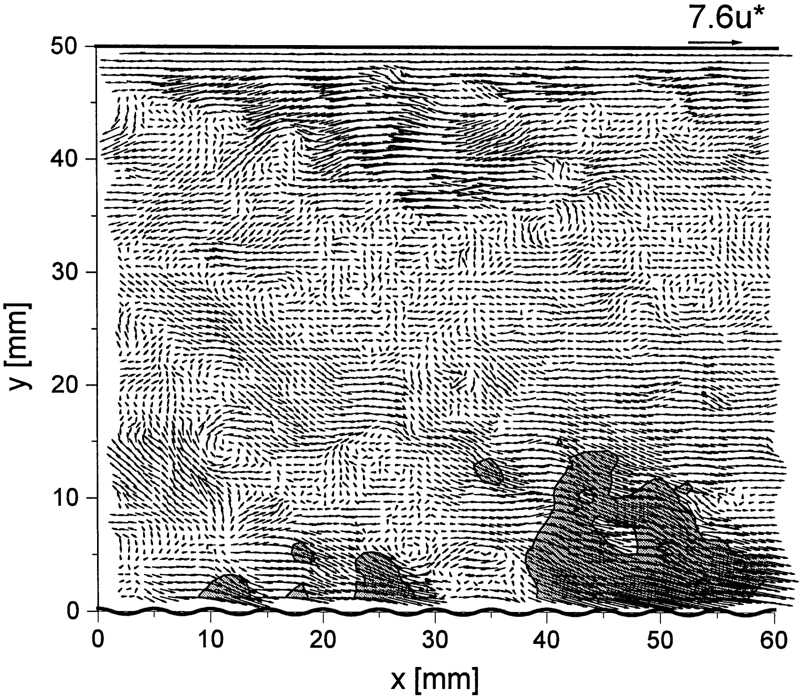

Fig.7 Fluctuating velocity vector plot. Regions of high Q4 contribution to Reynolds shear stress (-*uv*>2*u***u**) are highlighted.