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WALL FRICTION AND THE STRUCTURE OF NEAR-WALL TURBULENCE

Javier JIMENEZ

School of Aeronautics, U Politecnica, 28040 Madrid, SPAIN
(also Center for Turbulence Research, Stanford University
and NASA Ames Research Center, California, USA)

Abstract

We review briefly the present knowledge on the structure of vorticity in the near wall region of turbulent channels and boundary layers, with especial emphasis on the generation and amplification mechanisms for the near wall streamwise vortices, and on their relation to the generation of turbulent wall friction. The evidence is drawn from numerical experiments, using both natural and "unphysical" flow conditions. We show that the vortices are generated by the inviscid rotation of existing vorticity, and damped by the presence of the viscous wall. This leads to a new interpretation of existing drag control experiments, and to a (yet untested) prediction of a scaling parameter for drag reduction by riblets.

1. Introduction

In recent years, the structure of turbulence in the near wall region is starting to be clarified, mostly as the result of numerical experiments using full and "minimal unit" direct simulations (Jiménez and Moin, 1991). We present here a brief summary of the results obtained in this way. The wall region is dominated by unpaired streamwise vortices, in contrast to the the outer core, in which the dominant structures are horseshoe vortices inclined at roughly 45° from the free stream. The latter will not be discussed here, but a general view of the two regions, and of their dominant vortical structures, is given in figure 1.

From observations of flow fields such as that one, it appears that not all of the near wall streamwise vortices are related to outer structures. In fact, the near wall vortices scale in wall units, with an average spanwise separation $z^+ = 100$, while the outer flow structures scale with the thickness of the layer. As a consequence, a simple geometrical argument shows that the number density of both types of structures must be different, and that there can not be a one to one correspondence. While some of the near wall structures correspond to the legs of outer flow horseshoes, other are strictly near wall phenomena, with no outer region counterpart. Near the wall, there seems to be no essential difference between the two types, both of which are visible in figure 1. They only differ in whether they survive as they emerge into the outer flow, or whether they succumb to random processes of merging and annihilation.

The vertical velocities induced by the near wall streamwise vortices distort the mean profile and result in the formation of the alternate high and low velocity streaks, which are characteristic of the wall layer. Because the vortices are much longer than they are wide, this process is almost two dimensional (in the cross stream plane) and can be studied by two dimensional simulations, some of which will be discussed below. They show that the result of this interaction is not only a spanwise modulation of the wall stress, but an increase in the average friction.

In contrast, the vortex formation process is intrinsically three dimensional, since no vorticity amplification can take place in two dimensions. This process will be studied by manipulating the wall boundary conditions into "unnatural" control experiments. Finally, we will show that the results of these experiments lead to new insights into the behaviour of previous drag reduction schemes, and into the effect of riblets on skin friction.

2. The increase in skin friction

One of the most characteristic properties of turbulent boundary layers is that their friction drag is higher than that of laminar ones. The understanding of the origin of skin friction, and its control, are important technological goals in the study of wall turbulence.

It has been clear for some time that the streamwise vortices affect the distribution of longitudinal velocity and that, as a consequence, they influence the skin friction.

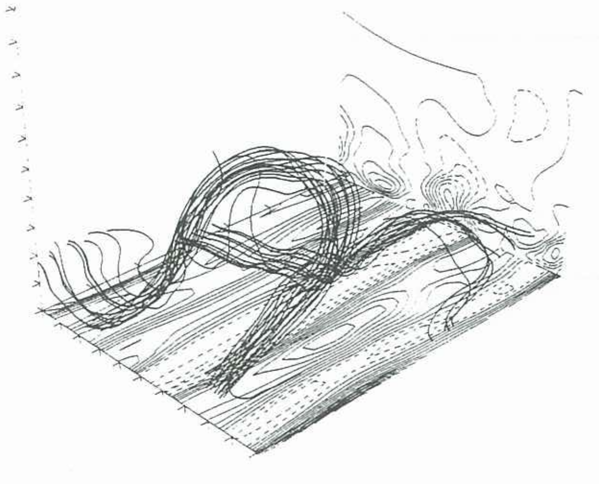

Figure 1.-Distribution of longitudinal perturbation velocity and selected vortex lines in a zero pressure gradient turbulent boundary layer. Flow is from lower left to upper right. $Re_\theta = 250$ (from Corral and Jiménez, 1992).

The vortices generate a transverse velocity field that carries high velocity fluid towards the wall at some places and low velocity fluid away from the wall at others. A high streamwise velocity gradient is thus established at the down-going locations, while a low gradient appears at the opposite sides of the vortices. This is the genesis of the alternate high and low velocity "streaks" that dominate the wall region (figure 2). What is not immediately clear is whether this process increases the *average* skin friction. In other words, whether the increase of the velocity gradient on the down going areas is enough to compensate the decrease in the up-going ones.

That this is indeed so was first demonstrated numerically in (Orlandi and Jiménez, 1991). Because the vortices are very elongated in the x direction, and because most of their induced velocity is confined to the transverse $y-z$ plane, the problem was approximated as being two dimensional in that plane, neglecting all the x variation. Different two dimensional vorticity configurations $\omega_x(y,z)$, modelling streamwise vortex pairs with varying degrees of asymmetry, were introduced in a flow with a vertical gradient of streamwise velocity $u(y)$, and their time evolution was computed. In the absence of x variation, the equations for u and ω_x decouple, and the streamwise velocity behaves as a passive scalar. The instantaneous skin friction can be computed from the averaged value of $\partial u/\partial y$ at the wall. It was found that, in all cases, the friction coefficient rose above that of the initial, uniform, "laminar" value. In fact, after a slow start, the averaged friction increased almost linearly with time, without any sign of saturation within the limits of the two dimensional approximation (and of an infinitely thick shear distribution).

The same question can be addressed analytically. In our context, the question is whether the spanwise average of the spanwise vorticity at the wall, $\bar{\Omega}(0) = < \partial_y u > |_{y=0}$, increases or decreases in time as a consequence of the action of a streamwise vorticity distribution ω_x, and of the associated transverse velocities v and w. The averaging operator is $< \cdot > = (1/L)\int(\cdot)\,dz$, and we will assume that the flow is spatially periodic in z.

The question does not have a unique answer, since the evolution of the average drag depends on the initial conditions. Those vertical motions carrying high speed fluid towards locations of the wall at which the vorticity is already high tend to reinforce the average, while those taking fluid away from the wall at those same locations weaken it. In addition, viscous diffusion induces an increase or a decrease in time of the averaged gradient, depending on whether $< \partial_y^2 \Omega >$ is positive or negative at the wall. The particular case of an initially uniform profile, for which u depends only on y at $t=0$, is free from most of those complicating factors, and can be analysed completely. It can easily be shown from the equations of motion that

$$\partial_t \bar{\Omega} = \partial_y^2 [\nu \bar{\Omega} - < uv >], \tag{1}$$

where ν is the kinematic viscosity. At the wall, since $u \sim y$, $v \sim y^2$, and $uv \sim y^3$, the second derivative of the Reynolds stress vanishes, and the only term left is the viscous one. This is true in general, and does not depend on the initial profile being independent of z. The only way that the Reynolds stresses may affect the average skin friction is through the viscous term, by changing the streamwise velocity profile away from the wall. Because of two-dimensionality, the vertical velocity v is due entirely to the streamwise vorticity ω_x, which is therefore responsible for all the Reynolds stress, and from any deviation of the skin friction from its laminar value.

In the absence of vertical velocities, the evolution of the skin friction for short times is purely viscous, and can be expressed as a Taylor series

$$\bar{\Omega}_{0,\mathrm{visc}} = \sum_{n=0}^{\infty} \frac{(\nu t)^n}{n!} \partial_y^{2n} \bar{\Omega}|_{y=0} \tag{2}$$

The computation of the correction due to $< uv >$ is straightforward but tedious. The result, for a uniform profile, is

$$\bar{\Omega}_0(t) - \bar{\Omega}_{0,\mathrm{visc}}(t) = \nu t^3 < (\partial_z \omega_x)^2 > |_{y=0} \bar{\Omega}_0(0). \tag{3}$$

Because the expression in brackets is squared, the effect of the Reynolds stresses is always to increase the magnitude of the skin friction above its laminar evolution.

This suggests that the presence of the streamwise vortices is enough to explain the increase of wall friction in turbulent boundary layers, and that the drag increase would initially be proportional to the square of the streamwise vorticity fluctuations ω'^2. It also suggests that friction can be understood and controlled by acting on the location and strength of the vortices.

3. The origin of the vortices

Before we pursue this last idea, we have to understand how the streamwise vortices are generated and amplified. There are two processes by which new vorticity can be created. Pressure gradients can induce viscous diffusion from the wall, and into the flow, and velocity gradients within the flow can rotate and amplify existing vorticity into new directions.

The first process is generally referred to as the formation of secondary vorticity by the no-slip boundary condition. A positive vortex near a wall tries to generate a positive tangential velocity, which is counteracted by the viscous condition through the generation of a vortex layer of opposite sign.

This process is well known to occur when viscous vor-

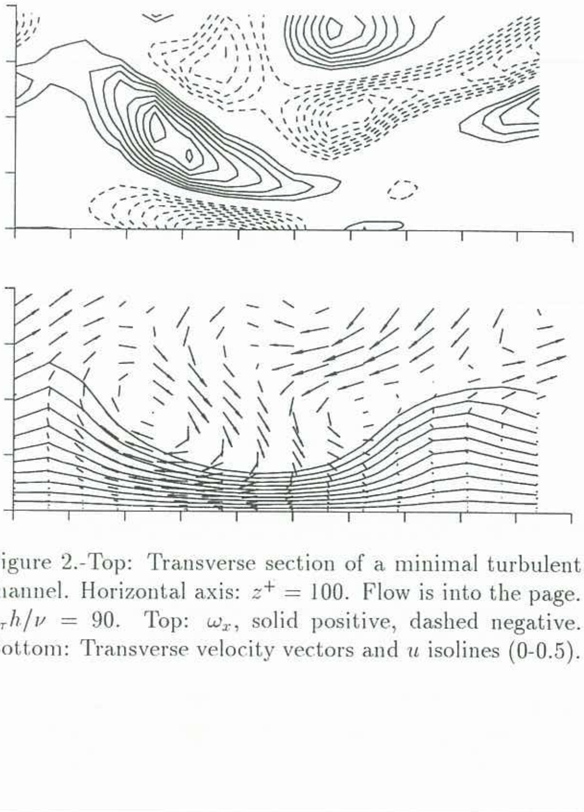

Figure 2.-Top: Transverse section of a minimal turbulent channel. Horizontal axis: $z^+ = 100$. Flow is into the page. $u_\tau h/\nu = 90$. Top: ω_x, solid positive, dashed negative. Bottom: Transverse velocity vectors and u isolines (0-0.5).

tices approach walls, and it has been shown to be responsible for the generation of substantial amounts of secondary circulation, which can organise itself into new compact vortices and which may lead to such phenomena as dipole rebound (Orlandi, 1991). Since rebound is a violent event in which the secondary vorticity couples to the original one to generate a vortex pair flying rapidly away from the wall, it has been proposed as a model for the formation of near wall vorticity, and for the bursting process in turbulent boundary layers (Ersoy and Walker, 1986). Strong layers of secondary streamwise vorticity are observed near the wall in turbulent channels, underneath the compact streamwise vortex cores (see figure 2).

On the other hand, Jiménez and Moin (1991) studied the evolution of individual flow fields in a minimal turbulent channel, and computed the different terms in the budget of streamwise vorticity. Their conclusion was that new streamwise vorticity was predominantly created away from the wall ($y^+ \approx 15$) by the inviscid rotation of existing spanwise and normal vorticity into the streamwise direction. Later Sendstad (1991) observed streamwise vortices being generated at that approximate location as thin vortex sheets, parallel to the wall. The sheets increase later their intensity, presumably through stretching by the background shear, and roll at one of their edges into compact circular streamwise cores. The rolling process was studied, in the two dimensional transverse approximation, by Jiménez and Orlandi (1992). It involves the interaction of the sheet with its virtual image across the wall, due to the impermeability condition. The interaction pushes the vorticity in the sheet laterally, until it accumulates in one of its edges creating the compact core. Because of the presence of the wall image, the newly created core behaves like a vortex dipole, slowly moving laterally along the wall.

Since both generation mechanisms are plausible, and since both have been observed in individual flow fields, a new experiment seems necessary to distinguish which one is dominant in real turbulent flows. We present now such an experiment.

The first mechanism (viscous diffusion) depends on the non-slip transverse condition

$$w(z,\, y=0) = 0, \tag{4}$$

while the second one is independent of it, and depends presumably only on the interaction of rotated vorticity with the mean shear, which is controlled by the presence of the *longitudinal* no-slip condition

$$u(z,\, y=0) = 0. \tag{5}$$

In physical flows both conditions are satisfied together at the wall, but there is no reason why that should be true in numerically simulated fields. In fact, it is possible to set up a numerically experiment in which either condition (4-5) is substituted by a free slip. Consider a turbulent flow in which (4) is substituted by

$$dw/dy|_{y=0} = 0. \tag{6}$$

If the streamwise vortices were generated by the viscous mechanism, their formation would be inhibited by the absence of the transverse no-slip condition, their intensity would be weakened, and the skin friction would drop with respect to that of a "natural" flow. Conversely, if the inviscid mechanism were predominant, the main effect of (4) would only be to weaken the streamwise vortices through viscous friction at the wall. In this scenario, as the transverse no-slip condition is removed, the streamwise vortex formation mechanism would not be affected, but the lateral dissipation would decrease. The vortices would tend to become stronger, increasing the Reynolds stresses and the skin friction.

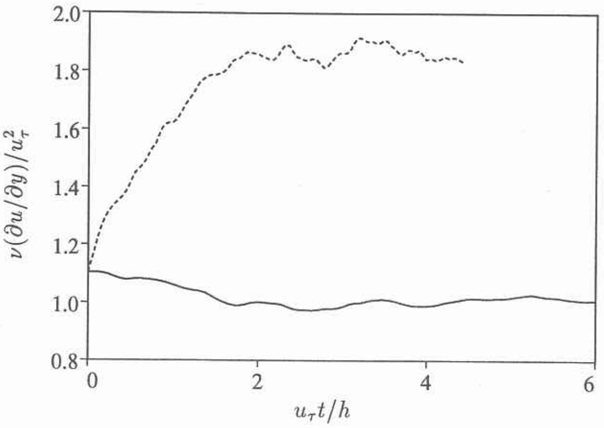

Figure 3.-Time evolution of skin friction for a natural turbulent channel (solid line), and for one in which $\partial w/\partial y \approx 0$ at the wall, [actually $w(0) = w(y^+ = 5)$]. Initial condition, fully developed channel. u_τ: friction velocity for the natural channel. h: half height. $u_\tau h/\nu = 120$.

The result of such a numerical experiment is shown in figure 3, which compares the time evolution of a natural turbulent channel with that of an anisotropic one satisfying (5-6) at the wall. In agreement with the inviscid model of vortex formation, the skin friction increases by a factor of about 1.8 in the anisotropic case. A similar experiment, using a different numerical code, higher Reynolds number ($u_\tau h/\nu = 180$) and a somewhat higher resolution, was carried out recently by Orlandi (private communication) with similar results (the drag increase was somewhat lower, 1.65).

This result strongly suggests that the streamwise vortices are created through inviscid interaction of the mean streamwise flow with transverse vorticity perturbations, and that the only effect of the transverse no-slip condition at the wall is to limit their intensity through viscous dissipation.

The mechanism for the subsequent amplification of the vortices generated in this way is clearly the straining by the ambient shear. Consider a vortex element randomly generated, as ω_y, in a shear $\partial u/\partial y = \Omega$. At first, the perturbation vorticity is weak with respect to the mean shear, and behaves passively with respect to advection. Two points on the vortex line, separated by a vertical distance h, are displaced horizontally by an amount Sh, where the total strain $S = \Omega t$ increases linearly with time. The inclination of the vortex line decreases as $1/S$, until it becomes oriented almost parallel to the free stream. In the process its length increases almost proportional to S, and its vorticity increases by the same amount. Note that the lateral extent of the vortex element is not modified by the stretching, while its thickness normal to the shear decreases as $1/S$, so that the element quickly becomes a sheet parallel to the wall. This agrees with the observations by Sendstad (1991).

The process continues until either the vorticity in the perturbed element becomes comparable to Ω, or until viscous dissipation becomes important. In the first case, which is true in most cases with small shear, the vortex element eventually deforms the background flow, and the linear approximation cannot be applied any more. In the second, which applies near the wall, the vorticity increases for some time, and then begins to decay. In this latter case it can be shown that the maximum vorticity amplification is proportional to $(\Omega/\omega_o)^{1/3}$, where ω_o is the intensity of the initial perturbation. Thus,a stronger shear generates stronger vortices, in accordance with intuition. Because of the arguments in the previous section, it should also generate a stronger skin friction.

4. Skin friction control

The discussion in the previous section suggests that the intensity of the streamwise vortices could be controlled by changing the relation between the lateral and longitudinal non-slip conditions. In fact Choi, Moin and Kim (1992a) have shown that drag reduction can be achieved through manipulation of w at the wall. In their experiments $w(y=0) = -w(y=h)$, where $h^+ \approx 5-25$. If we assume that $w(y)$ is approximately linear near the wall, this is approximately equivalent to imposing a transverse no-slip condition $w=0$ at $y=h/2$. In the spirit of the model being discussed here, the drag reduction would come from this difference in the location of the two non-slip conditions, the one controlling the generation and stretching of the streamwise vortices, and the one controlling their dissipation. A consequence of this argument is that the results of different control strategies using $w(0)$ should be correlated by the location of "virtual origin" of the w profile above the location of $u=0$. Some preliminary experiments suggest that this is approximately true, and further ones are in progress.

It is an interesting possibility that this same mechanism might also explain the drag reduction obtained using riblets. It has been suggested that riblets work by impeding transverse motion near the wall (Bechert and Bartenwerfer, 1989, Choi, 1989). Jiménez and Orlandi (1992) suggest specifically that the reduction is due to the interference of the riblets with the formation of streamwise vortex sheets and cores. In both views, the effect of the riblets could be approximated by raising the effective distance of the viscous boundary condition for transverse motion ($w=0$) above that for the longitudinal velocity. The effect of the increased transverse dissipation would be to move the streamwise vortices away from the wall, into regions with lower mean shear, where they would be stretched less and would attain weaker maximum intensities. This upward shift of the streamwise structures above riblets has been observed in numerical experiments by Choi, Moin and Kim (1992b). Finally Luchini et al. (1991) pointed out that, for laminar viscous flow over a grooved surface, the virtual origin for flow along the grooves (u) is lower than that for transversal flow (w). This offset would correspond directly to the virtual origin interpretation discussed above for the w control experiments, and the results of different riblets should be correlated by it. This should be specially true for relatively small riblets which are seen by the structures as sub-scale roughness.

Acknowledgements

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