Vortex ring/viscous wall layer interaction model of the turbulence production process near walls*

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Abstract. An experimental simulation of the interaction of vortex ring-like eddies with the sublayer of a turbulent boundary layer is investigated. An artificially generated vortex ring interacting with a Stokes' layer enables investigation of the interaction with reproducible initial conditions and in the absence of background turbulence. All of the observed features in the turbulent boundary layer production process such as the streaky structure, the pockets, the hairpin vortices, streak lift-up, oscillation, and breakup, have been observed to form. The model shows us that hairpin vortices can pinch off and reconnect forming new vortex ring-like eddies. Interestingly, the model includes interactions that occur with low probability in the turbulent boundary layer, but which contribute significantly to transport, and may be the events most readily controllable.

List of symbols

- \( D \) the diameter of a vortex ring
- \( R_e \) Reynolds number based on momentum thickness
- \( T \) time to instability
- \( T_p \) average time between pockets
- \( U_c \) convection velocity
- \( U_r \) velocity of a vortex ring
- \( U_{TE} \) convection velocity of a Typical eddy
- \( U_w \) velocity of the moving belt
- \( u_r \) friction velocity
- \( U_{\infty} \) freestream velocity
- \( x \) coordinate in the main flow direction
- \( y \) coordinate normal to the surface
- \( z \) spanwise coordinate
- \( \delta \) the Stokes' layer thickness
- \( \theta \) momentum thickness of the shear layer
- \( v \) kinematic viscosity
- \( \lambda \) streamwise wavelength
- \( \tau \) shear stress
- \( \omega_z \) spanwise vorticity

Superscripts

- \(^*\) non-dimensionalized by \( v/u_r \)

1 Introduction

There is a need to construct both experimental and numerical simulations of the turbulence production process near walls, because of the difficulty of isolating mechanisms when experiments are conducted in the boundary layer flows. A good simulation must embody the essential features of the production process. In this paper we report a new observation in turbulent boundary layers that helps complete the picture of structural feature interactions, and then present an experimental simulation that models all of the important properties.

Turbulent boundary layer structure that should be modeled includes the long streaks (Runstadler et al. 1963), the pockets (Falco 1980a, 1980b), the hairpins (Falco 1982, Acarlar and Smith 1984), the Typical eddies (Falco 1977, 1983), and coherent regions of streamwise vorticity and/or streamwise vortices. Basically, these structural features have been shown to be associated with the production process, but the formation of the structures and the interactions are not completely understood. A number of investigators have studied the formation of low speed streaks. Oldaker and Tiederman (1977) observed that a pair of low speed streaks formed as a result of the response to what appeared to be a sequence of local high speed outer region eddies interacting with the wall and aligned along a streamwise direction. The path left by the outer region disturbances clearly formed a high speed streak. Falco (1980a) observed the formation of low speed streaks in pairs by a similar mechanism. Although low speed streaks are often observed to exist singly, care must be taken when interpreting low speed streak formation, because once formed the low speed streaks can persist for very long times (Smith and Metzler 1983), and have simply convected into the observation zone.

Since the mid fifties, it has been suggested that long counter rotating streamwise vortices exist in the wall region and that pairs of these vortices produce a gathering of wall layer dye between them that we see as the low speed streaks. A high speed streak would be the result of high speed fluid being induced towards the wall between a pair of these streamwise vortices rotating the other way. A number of authors have suggested causes for these streamwise vortices. The currently most popular sug-
gestion is that they are the ‘legs’ of hairpin vortices that are also observed in the wall region. However, as Acarlar and Smith (1984) have pointed out, it is very hard to understand how the hairpin legs could extend upstream as far as would be necessary to produce streaks of length $x^* = O(1000)$. Thus, there is still no experimental evidence supporting the various rational physical hypotheses describing the formation of long streaks.

Another feature of the wall region structure is the frequent rearrangement of marker that moves it away from a local region, leaving a scoured ‘pocket’ of low marker concentration. Figure 1 shows two pockets as seen in a layer of smoke marked sublayer fluid. Pockets are footprints of outer region motions that interact with the wall. Falco (1980a) showed that they start out as a movement of wall layer fluid away from a location as a high speed outer region eddy (a Typical eddy, discussed below), nears the wall. The interaction results in the footprint opening up into a developed pocket shape. Fluid is seen to lift-up from the downstream end of the pocket, and take on the characteristics of a hairpin vortex (Falco 1982).

We have also observed hairpins appearing to form over individual streaks. The streak is seen to become lumpy, and one of the lumps grows and a hairpin emerges from it. Acarlar and Smith (1984) have also observed hairpins growing over simulated streaks, and it appears, in a turbulent boundary layer.

The microscale coherent motions observed across a turbulent boundary layer, which are similar to laminar vortex rings embedded in a shear flow, are called Typical eddies. They have been studied by Falco (1974, 1977, 1982, 1983), who showed that they contribute significantly to the Reynolds stress in the outer part of the boundary layer, and that they are the excitation eddies that create the pockets. Experiments using two mutually orthogonal sheets of laser light enabled Falco (1980b) to determine, as far as the smoke marking allows, that the coherent feature was a ring, as opposed to a portion of a hairpin vortex, as suggested by Head and Bandyopadhyay (1981).

Both types of hairpin creation mechanisms described above can produce hairpins that can pinch-off and form new vortex rings. Falco (1983) showed visual evidence of a hairpin lifting from the downstream end of a pocket, contorting and pinching off to form a new vortex ring-like Typical eddy. This pinch-off mechanism has also been clearly shown to occur in the calculations of Moin et al. (1986) mentioned above.

Many investigators have noted the presence of streamwise vortices in the wall region. Almost without exception, the vortices have been of short extent (Praturi and Brodkey 1978, Falco 1980b, Smith 1982). A number of investigators have suggested that streamwise vortices of much greater extent exist in the wall region, essentially laying just above the wall in pairs, which are responsible for the creation of both low and high speed streaks. This evidence is of a statistical nature, usually from correlation measure-ments. However, no one has ever observed them, and recent calculations of turbulent channel flow using the full Navier-Stokes equations (Kim 1986), have shown that the eddies which have streamwise vorticity are not elongated in the stream direction.

We will present new boundary layer observations on the formation of streamwise streaks, show that the vortex ring/wall layer simulation can exhibit all of the structural features discussed above, and help us understand their formation and interactions.

2 Experimental techniques

The boundary layer motions were made visible by seeding the flow with 0.5–5 micron oil droplets, and illuminating the oil fog with laser light spread into sheets that could be placed parallel to the wall in the wall region, or perpendicular to the wall and parallel to the flow, or both. The technique has been described by Falco (1980c), so we will not repeat the details here. A new twist, used in these new experiments, which was of particular value in finding the long streaks and their correspondence with the coherent motions above the wall, was the capability to observe the washout of smoke in a laser sheet parallel to the wall while we could simultaneously observe the motion above the wall in a laser sheet perpendicular to the wall and parallel to the flow.

2.1 Vortex ring/moving wall simulations

We can simulate the interaction of a Typical eddy with the viscous wall region of a turbulent boundary layer by creating a vortex ring and having it convect towards or away from a moving wall. For convenience, we have used an impulsively started wall. It has the advantages of being