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Spectral structure and linear mechanisms in a rapidly distorted boundary layer

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ABSTRACT

The aim of the present work is to investigate the spectral structure of a rapidly distorted boundary layer that develops on a flat plate in presence of a localised patch of roughness or/and grid-generated freestream turbulence. We observe that, at a certain distance downstream of the roughness patch the boundary layer exhibits a bimodal shape in the energy spectrum of the streamwise velocity fluctuations, similar to that found in a fully-turbulent boundary layer at relatively high Reynolds numbers. The physical mechanism that gives rise to the low-wavenumber peak in the spectrum, which represents long streamwise motions or "superstructures", is identified to be the interaction of the broadband disturbances with the region of high shear near the wall in the boundary layer. We next show that the flat-plate boundary layer combined with surface roughness and grid turbulence can serve as building-block elements towards synthesising the wall-normal structure of a canonical turbulent boundary layer, in the context of large-scale streamwise motions. The rapidly distorted (or "synthetic") boundary layer presents a simpler environment in which the coherent motions can evolve and therefore can enable a better characterisation of these motions. To further illustrate the utility of the present approach we compare results from our measurements with the predictions of the Rapid Distortion Theory (RDT). We show that the streamwise turbulence energy in the near-wall region of the rapidly distorted boundary layer grows linearly with time consistent with the RDT results on the effect of pure shear on an initially isotropic turbulence. Moreover close to the edge of the boundary layer the large-scale fluctuations experience an enhancement in the streamwise turbulence energy in accordance with the linear blocking model in the RDT framework. The present work thus highlights the importance of linear processes in wall turbulence and can help us identify aspects of it to which the linear theories can be meaningfully applied.

1. Introduction

One of the main themes of research on wall turbulence has been the structure of the wall-bounded flows, in both physical and spectral spaces. Since the work of Kim and Adrian (1999) it has been well recognised that a wall-bounded turbulent flow is primarily populated by two types of large coherent motion: the "Large Scale Motion" (LSM) and the "Very Large Scale Motion" (VLSM) in pipes and channels or "superstructures" in the boundary layer. The streamwise extent of the LSMs is of the order of $2-3\delta$ whereas that of VLSMs/superstructures is about $6-10\delta$ (Smits et al., 2011), where δ is the boundary-layer thickness, pipe radius or channel half-height. These motions appear in the pre-multiplied spectrum of the streamwise velocity fluctuations in the form of distinct humps in appropriate wavenumber ranges (see Kim and Adrian, 1999; Hutchins and Marusic, 2007). As the Reynolds number increases, the turbulence energy contained in VLSMs/superstructures is seen to progressively increase, and therefore these long streamwise structures are expected to play a prominent role at very high Reynolds numbers typical of those found in technological applications. As a result, a considerable effort has been invested in developing laboratory facilities that can achieve very high Reynolds numbers (see, for example, Hultmark et al., 2012; Mathis et al., 2009). Such efforts have provided important insights into the scaling and structure of wall turbulence and hold promising prospects for the future. However such facilities are highly specialised, and therefore alternative approaches for studying certain aspects of the coherent motion in high Reynolds number wall turbulence are worth pursuing. In this work we use such an approach and present findings from an experiment on a boundary layer developing over a flat plate in presence of a localised

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patch of surface roughness and/or grid-generated freestream turbulence. We show that the streamwise structures generated in such a boundary layer mimic those found in the fully-turbulent boundary layers, and therefore the present experimental design can help us better understand spectral properties of the large coherent motions in wall turbulence.

1.1. Effect of surface roughness and grid turbulence

Surface roughness has been used in the past to study the effect of change in the surface condition on the near-wall structure in wall-bounded turbulent flows. Extensive work has been done towards understanding the structure of a turbulent boundary layer (TBL) developing over a rough surface - see, for example, Townsend (1976), Krogstad and Antonia (1994) and Jiménez (2004) among others. Experiments have also been carried out for the case of an abrupt transition in surface condition in the form of either rough-to-smooth (R-S) or smooth-to-rough (S-R) or smooth-rough-smooth (S-R-S) transition. Some of the early investigations on the response of a TBL subjected to such changes in surface condition have been summarised in Smits and Wood (1985). It was realised that the effect of a surface perturbation on the boundary layer structure could be effectively described in terms of a new internal boundary layer which develops downstream of the perturbation. Furthermore, it was observed that the local-equilibrium hypothesis (Townsend, 1976) was no longer valid within the internal layer, wherein the effects of advection and diffusion of turbulence energy could not be neglected (Smits and Wood, 1985). In this context, Morrison et al. (1992) investigated the non-equilibrium effects of an R-S surface transition on the bursting mechanisms associated with the near-wall streaks in a TBL.

In the relatively recent studies, surface roughness has been used to better understand the inner/outer interaction in wall turbulence. For example Birch and Morrison (2011) performed measurements on an extended region of distributed surface roughness in a channel and showed that the type of roughness used can have a significant influence on the self-similar nature of the mean velocity profile. With regard to the change in surface condition, Morrison (2007) showed that the flow downstream of an R-S transition experiences a strong inner/outer interaction between the internal boundary layer and the turbulence induced by the roughness. In this connection, Hanson and Ganapathisubramani (2016) have further investigated the effect of roughness-generated disturbances on the R-S transition layer in a TBL and highlighted the importance of the outer region in determining the near-wall scaling of the streamwise turbulence intensity.

In the present work, we carry out measurements downstream of a localised patch of distributed grit roughness (akin to the S-R-S transition) with oncoming boundary layer in a *laminar* state. We observe that, at a certain distance from the roughness patch, the pre-multiplied power spectrum (or energy spectrum) of the streamwise velocity fluctuations exhibits a bimodal shape that resembles that found in a high-Reynolds number TBL. The new internal shear layer downstream of the roughness patch appears to be the key factor in generating the low-wavenumber spectral peak, which represents the long streamwise motions.

The interaction of a grid-generated freestream turbulence field with a TBL has been a topic of many investigations, especially to understand the effect of a modified outer layer on the structure of the near-wall turbulence (Hancock and Bradshaw, 1989; Sharp et al., 2009). Dogan et al. (2016) showed that the large outer-layer structures in such a boundary layer have a modulating effect on the small scales near the wall and that this effect increases with increase in the freestream turbulence intensity. “Bypass transition” has also been studied extensively, where the grid-generated turbulence interacts with a laminar boundary layer generating streamwise Klebanoff disturbances comprising streaks and vortices - see the review by Durbin and Wu (2007) and the references therein. The main thrust of the bypass-transition studies is to understand the penetration of the freestream disturbances into the boundary layer to form streamwise streaks, their subsequent amplification and final breakdown into turbulent spots (Zaki, 2013).

Here we study the interaction of grid-generated turbulence with a laminar boundary layer with or without the presence of a roughness patch. Over a certain distance close to the plate leading edge, the grid/roughness-generated turbulence is rapidly distorted (due to the effects of shear and blocking). We therefore term this boundary layer as a “rapidly distorted” boundary layer. Although the present arrangement is similar to that used in bypass-transition studies, our main focus here is to look at the spectral features of the rapidly distorted boundary layer as it evolves downstream, and which are relevant to a canonical TBL. We find that the most energetic streamwise wavenumber (scaled on δ) for the boundary layer subjected to grid turbulence alone is in close agreement with the low-wavenumber spectral peak seen in the boundary layer downstream of the roughness patch (in absence of grid turbulence). This suggests a possible physical mechanism, in the form of the interaction of broadband disturbances with the near-wall shear, for generating the long streamwise structures or superstructures observed in high Reynolds number turbulent boundary layers. We also investigate the wall-normal variation of the energy spectra in the rapidly distorted boundary layer and show that it compares favourably with that found in a canonical TBL. This suggests that it may be possible to synthesise the spectral structure of a canonical TBL using a combination of freestream turbulence and a localised patch of surface roughness along with a flat plate boundary layer.

1.2. Rapid Distortion Theory

The principal assumption of Rapid Distortion Theory (RDT) is that there should be sufficient separation between two timescales: one associated with the imposed mean-flow distortion (t_d) and the other a time interval over which the turbulence field evolves through non-linear interactions (t_n). When $t_d < < t_n$ the nonlinear terms in the governing equation for turbulent fluctuations can be neglected, and therefore the “rapid” distortion of turbulent eddies can be described by a set of linearised equations (Hunt and Carruthers, 1990). One of the first investigations on the RDT was due to Batchelor and Proudman (1954) who considered the problem of turbulence subjected to large irrotational strain rates such as grid-generated turbulence passing through a rapid contraction. Since their work, the RDT has been used in a variety of flow situations such as a wake subjected to a rapid change in pressure gradient (Narasimha and Prabhu, 1972) or a wind flow past buildings (Bearman, 1972), among others. In the context of boundary layers developing under zero pressure gradient, the distortions primarily take place in the form of “shearing” due to the large velocity gradients present in the near-wall region and “blocking” due to the no-penetration condition imposed by the wall. In the present case of a rapidly distorted boundary layer it is reasonable to expect that the action of shear and blocking would be sufficiently rapid in a region close to the leading edge of the plate, and we show here that the predictions of the RDT are indeed applicable to this region.

There have been many studies in the literature that have considered the effect of homogeneous shear on an initial disturbance field. One of the main outcomes of such studies is the evolution of statistical quantities, such as turbulence intensity, two-point correlations and power spectra, with time (t) scaled on the local shear rate, S. Moffatt (1967) showed that, for an initial isotropic disturbance field, the total disturbance kinetic energy under the action of uniform shear (in the absence of blocking) increases linearly with

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