# Inner-outer interaction in a rapidly sheared boundary layer

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## ABSTRACT

In the present work we study the inner-outer interaction in wall turbulence using a novel experimental arrangement of first generating a shearless boundary layer over a moving ground plane in the presence of grid turbulence, which is then passed over a stationary floor downstream resulting in a rapidly sheared boundary layer. The velocity spectra in such a boundary layer are shown to mimic the spectral features typical of a canonical turbulent boundary layer over a range of Reynolds numbers. This suggests that the rapidly sheared boundary layer consists of coherent structures that are qualitatively similar to the large-scale motions and superstructures observed in a canonical turbulent boundary layer. Static pressure fluctuations measured using a specially-made "needle" probe reveal the variation of the pressure field inside the rapidly sheared boundary layer. The pressure fluctuations in the free stream are seen to be highly correlated with wall pressure, especially when the boundary layer is sufficiently thin, supporting the view that the pressure fluctuations can play an important role in coupling turbulent eddies in the inner and outer regions. Further, we show that the present experimental arrangement is well-suited to studying the relative importance of the "top-down" and "bottom-up" mechanisms in wall turbulence in a systematic manner. The results obtained so far suggest that the top-down mechanism is dominant near the leading edge of the stationary surface with the bottom-up mechanism becoming progressively important as the boundary layer grows downstream.

### INTRODUCTION

The interaction between the inner and outer layer motions in a turbulent boundary layer (TBL) has been an area of investigation for several decades. It has long been realised that the different components of the Reynolds-stress tensor scale differently in the near-wall region - for example the Reynolds shear stress scales on inner variables whereas the streamwise normal-stress does not simply scale on inner variables but also depends on motion that scales on the boundary layer thickness (Townsend, 1976). These considerations led Townsend (1961) to propose the concept of 'inactive' motion associated with large-scale eddies which does not contribute to the shear-stress-bearing motion but appears as a linearly-superposed low-frequency modulation of the streamwise and spanwise components of velocity in the inner layer (Bradshaw, 1967). The strong dependence of the inner-scaled streamwise turbulence energy on Reynolds number observed in a TBL supports the presence of inactive motion (Fernholz & Finley, 1996). However some of the recent measurements on wall turbulence at very high Reynolds numbers (Morrison et al., 2004) have revealed that the large-scale eddies in the inner layer are not inactive but in fact contribute to the production of turbulence energy in this region. This suggests that the interaction of the outer-layer motion with the near-wall stress-producing motion should really be considered as nonlinear (Morrison, 2007).

In a related development, Kim & Adrian (1999) showed that a turbulent channel flow at high Reynolds numbers (Re) is populated by two types of large coherent motion - the "large-scale motions"(LSMs) and "very-large-scale motions" (VLSMs). Hutchins

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& Marusic (2007) investigated a TBL at high Re and found long streamwise motions akin to VLSMs, which they termed as "superstructures". The typical streamwise extents of the LSMs and superstructures in a TBL are  $2 - 3\delta$  and  $6 - 10\delta$  respectively, where  $\delta$ is boundary-layer thickness (Smits et al., 2011). As Re increases the VLSMs/superstrucutres are seen to become increasingly dominant and can account for a substantial fraction (up to 50%) of the total turbulence energy and Reynolds stress generated in the inner layer (Smits et al., 2011). Moreover although the superstructures primarily reside in the logarithmic and outer regions of the boundary layer, they exert considerable influence on the near-wall motion in the form of amplitude modulation (Mathis et al., 2009), resulting in a strong inner-outer interaction. The implication of these findings is that, at high Reynolds numbers, the "top-down" mechanism can become dynamically important in addition to the "bottom-up" mechanism which dominates at low Reynolds numbers (Morrison, 2007). The bottom-up (top-down) mechanism essentially implies that the *source* of turbulence energy is primarily in the inner (outer) region of the boundary layer, which is then diffused/transported into the outer (inner) region. In other words, in the case of a bottom-up (top-down) mechanism, the eddies which generate the turbulence energy scale on inner (outer) variables. In this connection, Hunt & Carlotti (2001) argue that the increasing top-down influence can result in "bursting" of the near-wall structures on the time scale of the outer motion in contrast to a low-Re TBL in which the bursting times scale on inner variables.

Here our aim is to study the inner-outer interaction in wall turbulence by performing experiments on a rapidly sheared boundary layer (RSBL). The RSBL is obtained by passing a shearless boundary layer, generated on a moving ground plane in the presence of free-stream turbulence, over a stationary surface downstream, resulting in large values of local shear. A shearless boundary layer obtained on a moving ground plane in a wind tunnel has been a subject of past investigations (e.g. Uzkan & Reynolds, 1967; Thomas & Hancock, 1977) with the aim of studying the "blocking" of the turbulence field near an impermeable boundary in the absence of shear. Some of the numerical and theoretical studies have also been directed towards understanding the structure of such a flow (Hunt & Graham, 1978; Perot & Moin, 1995). However, this is the first investigation to study the response of a shearless boundary layer to the imposition of the no-slip condition at the surface of a stationary floor and its evolution downstream. The motivation for working with the RSBL is to have an independent control of the outerregion turbulent motion and the near-wall shear (which are coupled in a canonical TBL) in order to investigate the interaction between the two regions in detail. The velocity measurements carried out show that, for a certain streamwise extent, the pre-multiplied spectra of the streamwise velocity fluctuations in the RSBL display a bi-modal shape which resemble those found in an equilibrium TBL. Further upstream in the RSBL (towards the leading edge of the stationary floor) the spectral shapes are akin to those found in very high Reynolds number wall turbulence.

Another important aspect of the present work is to better under-

stand the role of turbulent pressure field in the inner-outer interaction. Since the pressure field in incompressible flows is non-local in character it can facilitate interaction among disparate length scales. One of the first studies to carry out a detailed investigation of pressure field in a turbulent channel at low Re is the simulations by Kim (1989). In the context of control for relaminarisation, Sharma et al. (2011) have shown the importance of pressure fluctuations in wall turbulence, and the particular role of the linear source term,  $U' \frac{\partial v}{\partial x}$ , in the Poisson equation for pressure fluctuations. With regard to the experimental work, there have been many studies involving wall pressure measurements beneath a TBL. Some of the early experimental results have been summarised in Bull (1996); see also Gravante et al. (1998). On the other hand, measurement of pressure fluctuations inside the boundary layer is challenging due to the problems associated with probe interference and calibration. The first in-flow pressure measurements in a TBL were performed by Tsuji et al. (2007) using a specially designed probe. Subsequently static pressure probes designed on the same principle have been used to study the amplitude modulation of small-scale pressure fluctuations near the wall (Tsuji et al., 2016) and to find the correlation between local pressure and velocity fields in a TBL (Naka et al., 2015). Here we use a similar "needle" probe to measure pressure fluctuations inside the RSBL, along with a wall-mounted probe to measure surface pressure fluctuations. The results show that the evolution of the turbulent pressure field in the streamwise direction in the RSBL can be understood in terms of the top-down and bottom-up mechanisms, with the latter becoming more dominant as the boundary layer grows downstream. Overall the measurements reported here show that the RSBL can serve as an effective physical model to better understand the inner-outer interaction in wall turbulence and especially the role of pressure fluctuations in effecting such an interaction. Most importantly, the bottom-up and top-down effects can be controlled independently.

# EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

The present experiments have been carried out in a wind tunnel facility equipped with a moving ground plane (rolling road). The wind tunnel test section is 2.3 m (width) x 1.8 m (height) and the rolling road dimensions are 1.7 m (width) x 3.6 m (length). The experiment (figure 1) first generates turbulence using a rectangular grid (solidity = 25%, grid spacing = 130 mm) mounted at the entry to the test section. The turbulence then passes over the rolling road with speed matched to that of the free-stream velocity to generate a shearless boundary layer. Boundary layer suction is employed upstream of the rolling road (figure 1) to remove any residual vorticity. The free-stream turbulence is blocked at the surface of the rolling road due to the impermeability constraint. The flow then passes over a stationary floor downstream of the rolling road where it is subjected to large shear generated in a new boundary layer that starts at the leading edge of the stationary floor. The free-stream turbulence entering such a boundary layer will be rapidly sheared (RSBL). As the boundary layer grows downstream, the magnitude of shear progressively weakens and therefore beyond a certain distance it no longer behaves as a "rapidly sheared" boundary layer. However in the following we use the term RSBL to denote the boundary layer at any streamwise location, mainly to distinguish it from a canonical TBL

The velocity measurements are carried out using a single hotwire probe consisting of a platinum-Wollaston wire 2.5 micron in diameter with an active length of approximately 0.5 mm. The probe is connected to the Streamline Pro constant temperature anemometer (Dantec Dynamics Ltd.). The hot-wire signals are sampled at 60 kHz and are low-pass filtered at 30kHz. Pressure measurements



Figure 1. Schematic of the experiment.



Figure 2. The wall and needle pressure probes.

are performed using a piezo-resistive transducer 2.3 mm in diameter (Model ENDEVCO 8507C-1, Meggitt Sensing Systems). For wall-pressure measurements, a flush-mounted plug is used which has a sensing diameter of 0.2 mm with the transducer housed in a cavity behind the pinhole. The needle probe (see figure 2) is essentially based on the design proposed in Tsuji et al. (2007) and has a tube with outer diameter of 1.1 mm on which are made pinholes of size 0.2 mm. The overall dimensions of the probe used here are close to those corresponding to probe 3 given in table 2 in Tsuji et al. (2007). Both the wall and needle probes are calibrated using a plane-wave tube against a reference transducer. The pressure signals from a given probe and the reference transducer are acquired simultaneously over a range of acoustic frequencies (generated by a loud speaker), and a transfer function is designed to convert the pressure signal measured in the wind-tunnel experiments into calibrated signals. The low frequency noise from the measured pressure signal, which is typically present in wind-tunnel measurements, is removed using an optimal filtering scheme due to Naguib et al. (1996). The pressure signals are sampled at 125 kHz and low-pass filtered at 20 kHz, since the pressure levels are seen to hit the noise floor above 14 kHz, approximately.

The origin of the co-ordinate system is located at the leading edge of the stationary floor with x denoting the streamwise coordinate (positive in the downstream direction) and y denoting the wall-normal direction. U and u respectively denote the mean and fluctuating components of the streamwise velocity.

### RESULTS

Figure 3 shows the profiles of mean velocity and streamwise turbulence intensity in the wall-normal direction at x = -0.3 m, i.e. on the rolling road upstream of the stationary floor leading edge, normalised with the corresponding values sufficiently far from the surface. It shows that a shearless boundary layer has been generated on the rolling road with any changes in  $U/U_{\infty}$  of less than  $\pm 0.6\%$ . The root-mean-square (rms) streamwise fluctuation velocity shows an increase of about 20% over its value in the free-stream as the



Figure 3. Mean and rms velocity profiles for the shearless boundary layer over the rolling road. x = -0.3 m.

surface is approached, before dropping rather abruptly to its freestream value and finally to zero at the surface (not shown in figure 3). The variation of the rms fluctuating velocity in figure 3 is qualitatively similar to that reported in Thomas & Hancock (1977); see also Aronson *et al.* (1997).

The mean velocity profiles, scaled on inner variables, at various streamwise stations on the stationary floor are plotted in figure 4. A typical Blasius profile and a typical TBL profile are also included for comparison. The figure shows that the mean velocity profile is close to the Blasius profile in the region close to the leading edge of the floor and evolves towards an equilibrium turbulence profile in the downstream direction (although such a state is not realised even at the most downstream location, x = 1.745 m). Here the wall friction velocity  $u_{\tau}$  is determined for the equilibrium TBL by the Clauser chart method, taking  $\kappa = 0.41$  and the additive constant, C = 5.0. For the RSBL, it is obtained by making use of the linearity of the profile close to the wall - a reasonable assumption for the present case.

The mean-squared streamwise fluctuating velocity profiles in the RSBL, again scaled on wall variables, are shown in figure 5. The streamwise turbulence energy is seen to increase substantially from x = 0.275 m to x = 0.5 m, presumably because the boundary layer at x = 0.275 m is quasi-laminar, whereas that at x = 0.5 mm is transitional, as also evidenced by the mean profiles in figure 4. Downstream of x = 0.5 mm, the turbulence energy near the wall decreases monotonically and approaches the distribution found in the canonical TBL at  $Re_{\tau} = 2363$  (figure 5). Interestingly, the nearwall peak of the turbulence energy is seen to occur at  $yu_{\tau}/v \approx 12$ for all the locations both at, and downstream of x = 0.5 m in the RSBL. This matches well with the peak location typical of a canonical TBL (as clearly seen in figure 5), suggesting that the near-wall processes in the RSBL are likely to share some of the features of such processes in a canonical TBL. Note that since the RSBL is not fully turbulent, a strict inner-outer scale separation is not expected here. The wall scaling used in figures 4 and 5 is really meant as a convenient point of comparison between the RSBL and the canonical TBL.

Figure 6 shows the pre-multiplied spectra of the streamwise velocity fluctuations at five measurement locations at  $y/\delta \approx 0.2$ , where the streamwise wavenumber  $(k_x)$  is calculated from frequency (f) using Taylor's hypothesis,  $k_x = 2\pi f/U$ , where U is the local mean velocity. At x = 0.275 m, most of the energy appears at relatively low wavenumbers (around  $k_x y \approx 0.02$ ). At the two downstream locations (x = 0.5 m and 0.58 m) a new energy site emerges in the form of a broad hump at higher wavenumbers (around  $k_x y \approx 0.6$ ). Further downstream, the spectrum reverts back to a uni-modal distribution with the energy spectrum at x = 1 m and



Figure 4. Evolution of the mean velocity profile in the streamwise direction.



Figure 5. Evolution of the wall-normal profile of the streamwise turbulence energy in the streamwise direction.



Figure 6. Pre-multiplied spectra of the streamwise velocity fluctuations at different *x* locations and at  $y/\delta \approx 0.2$ .

1.75 m (figure 6) is qualitatively similar to that found in the wall layer of a canonical TBL at low Reynolds numbers ( $Re_{\tau} \approx 1000$ ). At x = 0.58 m, the spectral shape corresponds to that found in a moderate-Re TBL ( $Re_{\tau} \approx 3000$ ). Finally, the two upstream locations display a shape that is similar to that found in a TBL at very high Reynolds numbers ( $Re_{\tau} > 20,000$ ) (compare figure 6 here with figure 2 in Smits *et al.*, 2011). Thus as we move upstream in the RSBL, the shape of the spectra resemble those typical of a canonical TBL at higher and higher Reynolds numbers. This shows that the present experiment enables us to simulate the inner and outer spectral sites found in a TBL across a wide range of Reynolds numbers.

In a canonical TBL, the inner and outer spectral sites have been shown to correspond to the LSMs and superstructures respectively (Smits *et al.*, 2011). At low Reynolds numbers, LSMs are the prevalent coherent structures present in the buffer and log regions of a TBL. At higher Reynolds numbers, superstructures appear in the log and outer regions and become increasingly prominent as the Reynolds number increases. This implies that the coherent motions corresponding to the high-wavenumber spectral peak in the RSBL, which are dominant at the most downstream locations (x = 1 m and 1.75 m in figure 6) are analogous to the LSMs in the canonical TBL. On the other hand, the low-wavenumber spectral peak, which is dominant close to the leading edge of the floor (x = 0.275 m and 0.5 m), represents coherent motions that are analogous to the superstructures. Near the floor leading edge, the primary mechanism for the generation of turbulence energy inside the boundary layer is the interaction of the free-stream disturbances with the near-wall shear. In other words, the source of the energy is in the turbulent eddies in the free stream, which is then transported downward and appears in the form of elongated structures inside the boundary layer, suggestive of the top-down mechanism. As the boundary layer grows, the near-wall processes become progressively important and the turbulence energy produced near the wall diffuses outward, characteristic of the bottom-up mechanism. These considerations lead us to hypothesise that the superstructures in a canonical TBL could be formed as a result of a top-down process whereas the LSMs due to a bottom-up process. A perusal of the recent literature on largescale motions in wall turbulence shows that the exact cause of the superstructures (and VLSMs) is not yet entirely clear (Smits et al., 2011), although a few possibilities have been suggested. We believe the present work can help us better understand the origin of the LSMs and superstructures in a canonical TBL in a way indicated above.

Note that in the above we have restricted ourselves to a qualitative comparison of spectral shapes in the RSBL with those in the canonical TBL. For a more quantitative comparison, e.g. with regard to the streamwise length or the energy content of the coherent motions, it would presumably be necessary to come up with a length scale in the RSBL which could be related to a relevant near-wall region in the canonical TBL. This will be addressed elsewhere. Furthermore, although the spectral shape near the RSBL leading edge corresponds to that in a high-Re TBL (figure 6), the wall-normal profile of turbulence energy does not (figure 5). This is clearly due to localness in Fourier space corresponding to an infinite spatial domain (and vice versa) and emphasises the fact that the RSBL emulates only one aspect of the canonical TBL in that, for instance, a large eddy with spatial coherence comprises a range of scales or wavenumbers.

Next we look at the behaviour of pressure fluctuations inside the RSBL with a focus on the region close to the leading edge of the stationary surface. Figure 7 shows the spectra of wall pressure fluctuations at x = 0.179 m and x = 0.5 m, with outer scaling, compared to that in a canonical TBL at a slightly different Reynolds number ( $Re_{\tau} = 2532$ ) than that presented above. In order to avoid any ambiguity associated with convection velocities, here frequencies are used instead of wavenumbers. Note that the spectrum at x = 0.179 m is not as smooth as the other spectra, even after optimal noise removal, as the pressure levels at this position are quite low (as shown in figure 7). The spectrum for the canonical TBL, over a range of intermediate frequencies, displays a slope close to  $f^{-0.7}$ . This is consistent with the observation in Tsuji et al. (2007) and supports the suggestion made by Bradshaw (1967) that for the wall pressure field, the  $k_x^{-1}$  dependence in the wavenumber spectrum is equivalent to an  $f^{-0.7}$  dependence in the frequency spectrum due to variations in the convection velocity of wall pressure. In comparison, the spectrum for the RSBL at x = 0.5 m shows a weaker slope at intermediate frequencies. Furthermore, Figure 7 shows that the RSBL contains higher energy at much lower frequencies, in terms of  $u_{\tau}$  and  $\delta$ , compared to the moderate-Re canonical TBL. This could possibly be interpreted as the wall signature of the very long



Figure 7. Comparison of the wall pressure spectra in outer variables.

superstructure-type motions which are generated by rapid shearing of turbulence in the RSBL (see figure 6).

Figure 8 shows the variation of rms static pressure fluctuations across the RSBL at three x locations (left panel). Also included for comparison are the measured pressure intensities from the present experiment in which the boundary layer is subject to free-stream turbulence with a stationary ground plane throughout. The canonical-TBL data of Tsuji et al. (2007) are also shown. The TBL with free-stream turbulence shows a good agreement with the canonical TBL close to the wall but has higher pressure intensities outside the edge of the boundary layer due to the presence of turbulence in the free stream. Similar behaviour is also seen, as expected, for the RSBLs for  $y/\delta > 1$  (figure 8, left panel). Within the RSBL, the pressure intensity increases with the streamwise distance up to x = 0.5m and decreases thereafter. This is consistent with the increase in the streamwise turbulence intensity initially (up to x = 0.5 m) followed by its decay further downstream as seen above (figure 5). For x = 0.179 m the data inside the boundary layer are not available (figure 8) since the boundary layer thickness is quite small at this location ( $\approx 2$  mm): the closest the needle probe can get to the wall is 1.9 mm, approximately.

The wall-normal variation of the correlation coefficient between the fluctuating wall pressure  $(p_w)$  and the static in-flow pressure  $(p_s)$  is shown in the right panel in figure 8. The correlation coefficient is defined as  $R_{p_w p_s} = (\overline{p_w p_s}) / \sqrt{\overline{p_w^2 p_s^2}}$ , where the overbar indicates time averaging. Values for  $R_{p_w p_s}$  in the TBL subject to free-stream turbulence are generally higher than the canonical TBL, especially in the outer region of the boundary layer. Interestingly, the values in the RSBL at both the locations show even higher values compared to those in the canonical TBL. Moreover  $R_{p_w p_s}$  in the RSBL is seen to increase moving upstream towards the floor leading edge (figure 8, right panel). This shows that the pressure fluctuations in the free stream are strongly coupled with the wall pressure when the shear rates inside the boundary layer are high, and the coupling gets weaker as the boundary layer grows downstream towards an equilibrium state. Since the RSBL contains (as discussed above) coherent motions that are qualitatively similar to those in a canonical TBL, the weakening of the correlation between wall and in-flow pressure in an equilibrium TBL as compared to that in the RSBL (figure 8) could be attributed to the incoherent motion present in the equilibrium boundary layers.

To explore this aspect further, the change in the behaviour of pressure spectra measured using the needle probe at different wall-normal locations (figure 9) is examined at x = 0.179 m and at x = 0.5 m. At x = 0.179 m (top panel in figure 9), the wall pres-



Figure 8. Wall-normal profiles of rms pressure intensities (left) and correlation coefficient between the in-flow pressure and wall pressure (right).

sure spectrum (labelled as  $y/\delta = 0$ ) matches quite well with the free-stream pressure spectrum, except at low frequencies. The pressure fluctuations in the free stream appear to penetrate deep into the boundary layer and leave their footprint on the wall without much modification caused by the presence of the boundary layer shear. This observation supports our proposition (made in connection with figure 6) that the dominant mechanism in the region close to the floor leading edge is the top-down mechanism, in which the source of turbulence energy is from the outer part of the flow. Further downstream at x = 0.5 m (bottom panel in figure 9), the wall pressure spectrum is significantly different from that in the free stream. This could be attributed to the action of the bottom-up mechanism which involves generation of turbulence energy in the near-wall region, in addition to the energy transported towards the wall from the free stream. We therefore suggest that the pressure statistics and spectra are generally consistent with the behaviour of the streamwise velocity fluctuations.

### CONCLUDING REMARKS

In this paper we have reported results from an experiment performed on a rapidly sheared boundary layer, in which blocked free-stream turbulence is rapidly sheared. The shapes of the premultiplied spectra of the streamwise velocity fluctuations measured in the RSBL resemble those found in a canonical TBL. At the furthest downstream locations in the RSBL, the spectral shape is found to be uni-modal and similar to that seen in a low Reynolds number TBL. Further upstream near the leading edge of the stationary floor, the spectrum becomes bi-modal in shape, with the low-wavenumber peak becoming progressively more dominant, and similar to the spectra typical of high Reynolds number TBLs. This implies that the RSBL consists of coherent motions which are analogous to the LSMs and superstructures observed in a canonical TBL. These observations suggest that the superstructure-type motions could be formed as a result of the top-down mechanism (in the form of rapid shearing of free-stream disturbances) whereas the LSMs as a result of the bottom-up mechansim (due to the near-wall processes). Thus the present experimental arrangement can help us understand whether the origin of a particular type of coherent motion is in the inner layer or the outer layer of a TBL, which is an important aspect of the inner-outer interaction. This is possible mainly because in our experiment the inner region (which is a source of shear) and the outer region (which consists of free-stream turbulence) can be independently controlled, at least over a certain distance close to the leading edge of the stationary floor. In a canonical TBL on the other hand, the inner and the outer regions are inter-dependent, which



Figure 9. Variation of the pressure spectra in the wall-normal direction measured by the needle probe and compared with wallpressure spectrum ( $y/\delta = 0$ ) at x = 0.179 m (top) and x = 0.5 m (bottom).

makes it difficult to determine the exact origin of a given coherent motion.

We have also carried out measurement of pressure fluctuations inside the RSBL close to the floor leading edge. It is observed that the correlation coefficient between the in-flow static pressure and wall pressure is much higher in the RSBL, especially close to the edge of the boundary layer, as compared to a canonical TBL. This implies that the pressure fluctuations near the boundary-layer edge are strongly coupled with those in the near-wall region and could also have a role in the formation of the large-scale coherent structures, given the fact that the RSBL is primarily composed of coherent motion (with non-coherent part less prominent). Furthermore, the pressure spectra measured inside the RSBL are consistent with the presence of the top-down mechanism close to the floor leading edge, wherein long streamwise motions akin to superstructures are observed.

In summary, the present work shows that the rapidly sheared boundary layer serves as means to studying certain aspects of high-Re wall turbulence and can provide insights into the role of pressure in effecting the inner-outer interaction.

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