12th International Symposium on Turbulence and Shear Flow Phenomena (TSFP12)
Osaka, Japan (Online), July 19-22, 2022

ON THE STRUCTURE OF A TURBULENT BOUNDARY LAYER PERTURBUED BY A LARGE-EDDY BREAK-UP DEVICE

Abhishek Tyagi
Department of Aerospace Engineering
Indian Institute of Science
Bengaluru, Karnataka,560012-India
tabhishek@iisc.ac.in

A. Chandan Kumar
Department of Aerospace Engineering
Indian Institute of Science
Bengaluru, Karnataka,560012-India
achandankuma@iisc.ac.in

Sourabh S. Diwan
Department of Aerospace Engineering
Indian Institute of Science
Bengaluru, Karnataka,560012-India
sdiwan@iisc.ac.in

ABSTRACT

Large-Eddy Break-Up (LEBU) devices have been used in the past as means to reduce the skin-friction drag associated with a turbulent boundary layer (TBL). In this work we report wind tunnel measurements on a flat-plate TBL perturbed by a LEBU located at the edge of the log layer of the oncoming TBL. We find that the presence of LEBU causes a reduction in the near-wall peak for the streamwise velocity fluctuations, thereby directly affecting the near-wall turbulence cycle. We show that, apart from breaking up the large-scale eddies, the LEBU introduces a significant energy at scales 2-3 (and larger) times the oncoming TBL thickness, through the "rapid shearing" of turbulent eddies by the new viscous layer generated over the LEBU surface. This shows that a LEBU can affect the structure of the oncoming TBL in a much more complex manner than what is previously understood. Over a certain distance downstream of the LEBU, the larger-scale eddies are seen to cause a significant amplitude modulation of smaller-scale fluctuations. An exercise in amplitude modulation calculation involving two cut-off wavelengths is also presented. These results could help us better understand the scale interactions effected by long structures in a high-Reynolds number TBL.

INTRODUCTION

Manipulating a turbulent boundary layer (TBL) continues to remain an area of active research for a variety of reasons such as reducing drag that can be helpful in improving the efficiency of energy converting devices/machines and in turn saving fuel, and more fundamentally understanding the structure of the TBL. The Large-Eddy Break-Up (LEBU) devices, in the form of a thin (and short) flat plate or an aerofoil section mounted in the outer region of a TBL, have been explored in the past for reducing the skin-friction drag over a surface. However, after the towing tank experiment of Shalin et al. (1988) done at KTH it was realised that there was no net drag reduction (and in fact a drag increase) associated with the LEBUs. As a result, the interest in the use of LEBU as a drag-control device gradually faded; see the recent review by Alfredsson and Orlu (2018) for a more details.

There has been a renewed interest in LEBUs more recently, primarily using numerical simulations, towards using LEBUs for manipulating a "canonical" TBL and investigating the changes they cause to the TBL structure. For example, Chin et al. (2017) carried out a large eddy simulation (LES) to quantify the change in the skin friction downstream of a LEBU mounted at $y/\delta_c = 0.8$, where y is the wall-normal distance and δ_c is the 99% boundary layer thickness of the canonical TBL at the location of the LEBU. They found that the presence of LEBU breaks down larger-scale structures near the TBL edge and increases the turbulence intermittency (i.e., the fraction of the time the velocity signal is turbulent) in that region. Chin et al. (2017) reported an attenuation of energy over the spanwise wavelengths $\lambda_z^+ < 200$ and $\lambda_z^+ > 500$ and an increase in energy from $200 < \lambda_z^+ < 500$ (where $^+$ indicates normalization on wall variables) at a streamwise distance of about $50\delta_c$ downstream of the LEBU. The range $200 < \lambda_z^+ < 500$ represents structures that are longer than those present in a canonical TBL for which the typical spanwise spacing of near-wall streaks is $\lambda_z^+ = 100$. The LES study of Chan et al. (2021) used three different locations ($y/\delta_c = 0.1, 0.5, 0.8$) for positioning the LEBU and explored mechanisms that contribute to the reduction in the wall shear stress. Their results showed that a maximum skin-friction reduction of 30% or higher can be realised for LEBUs located at $y/\delta_c > 0.2$. Chan et al. (2022) investigated the skin friction coefficient in a TBL perturbed by a LEBU and found the LEBU to significantly reduce the skin friction associated with large scales ($\lambda_x > 3\delta$). The above numerical studies confirm the primary role of LEBUs as devices that break up the large-scale eddies. However, the way a LEBU affects the wide range of scales present in the oncoming TBL is still not well understood; see Savill and Mumford (1988). A particularly pertinent question is whether a LEBU can introduce wavelengths downstream of it which are longer than those present in the oncoming TBL. Carrying out an input-output analysis of the effect of LEBU on a TBL can help us tackle this and similar such questions.

In this work, we carry out an experimental investigation on the scale manipulation in a TBL perturbed by a LEBU located at $y/\delta_c = 0.2$, i.e., at the edge of the log layer. We particularly focus on the region immediately downstream of the LEBU (up to $x/\delta_c = 3.5$; where x is the streamwise coordinate measured from the location of the LEBU). We find that the LEBU not only breaks up existing large eddies but also introduces considerable energy at higher streamwise wavelengths, which can be traced back to the turbulence energy generated over the LEBU surface by "rapid-shearing" mechanism. Furthermore, the amplitude-modulation coefficient immediately downstream of LEBU shows a considerable departure from its behaviour in a canonical TBL. We also perform a two-scale decomposition of the velocity signal to calculate the amplitude modulation among different ranges of scales, to enable a better characterization the effect of LEBU on the scale interactions in a TBL.

EXPERIMENTAL ARRANGEMENT

The present experiments are conducted in a low-speed open-circuit wind tunnel at the Indian Institute of Science Bengaluru, which has a test section of size 0.5m x 0.5m x 3m and a freestream turbulence level of less than 0.08%. A flat plate of 2.5m length and 0.5m width mounted inside the test section forms the measurement surface. A canonical TBL was obtained at 1m downstream of the leading edge (by tripping the laminar boundary layer), at the free-stream velocity (U_∞) of 17.5m/s and with $\delta_c = 21$ mm. The corresponding $Re_\theta = U_\infty \theta / \nu$ =2600, where θ is the momentum thickness and ν is the kinematic viscosity. The relevant parameters of the canonical TBL are listed in Table 1. A LEBU in the form of a flat strip of $0.75\delta_c$ length, $0.015\delta_c$ thickness and $0.2\delta_c$ height above the plate is mounted at 1m downstream of plate leading edge (figure 1). The LEBU height of $0.2\delta_c$ is chosen so as to investigate the scale interaction within the log layer of the TBL. Single-component hotwire anemometry measurements are carried out using the Dantec Streamline CTA and using a 5μm tungsten wire probe. The velocity signals are sampled at 60 kHz for 30s duration each measurement point using NI data acquisition unit (USB 6363). The hotwire probe is calibrated against six different speeds using the King's law. The hotwire probe is traversed in streamwise and wall normal directions with the help of stepper motors controlled through a LabVIEW program.

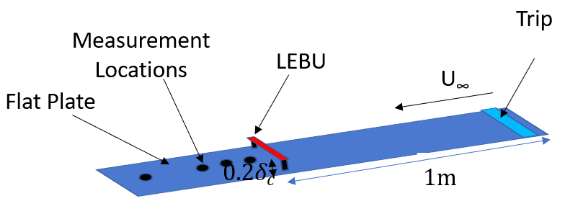


Figure 1. Schematic of the experimental setup (not to scale). Note that the flat plate is much longer than shown in the figure (total length = 2.5m)

Table 1. Parameters corresponding to the canonical TBL.

Parameters	Values
Boundary layer thickness $\delta_c (mm)$	21
Free stream velocity U_∞ (m/s)	17.5
Friction velocity u_τ (m/s)	0.68
Reynolds number Re_θ	2600
Karman number $Re_\tau = u_\tau \delta_c / \nu$	893
Shape factor H	1.39

RESULTS AND DISCUSSION

Figure 2a shows the evolution of the mean velocity profiles up to a distance of $3.5\,\delta_c$ downstream of the LEBU. Also included is the profile of the canonical TBL for comparison. The velocity defect representing the LEBU wake is apparent in the velocity profile (figure 2a); the maximum defect decreases in the streamwise direction as expected. Note that here δ represents the local 99% boundary layer thickness. The r.m.s. intensity of the streamwise velocity fluctuations, u_{rms}/U_∞, is plotted in figure 2b. One can see an enhancement of u_{rms} just above the position of the LEBU, i.e., $y/\delta \gtrsim 0.2$ and a decrease in the u_{rms} level below the LEBU position, for $y/\delta < 0.2$. Figure 2c shows the velocity-gradient defect of the perturbed TBL with respect to the canonical TBL. The changes observed in u_{rms} (figure 2b) can be attributed to the changes in the mean velocity gradient due to the presence of LEBU seen in figure 2c. The increase/decrease in the velocity gradient can result in a corresponding increase/decrease in the local turbulence production thereby affecting the local u_{rms} levels. This effect is clearly visible up to $x = 1.25\delta_c$, explaining the increase and decrease of r.m.s intensity just above and below the LEBU.

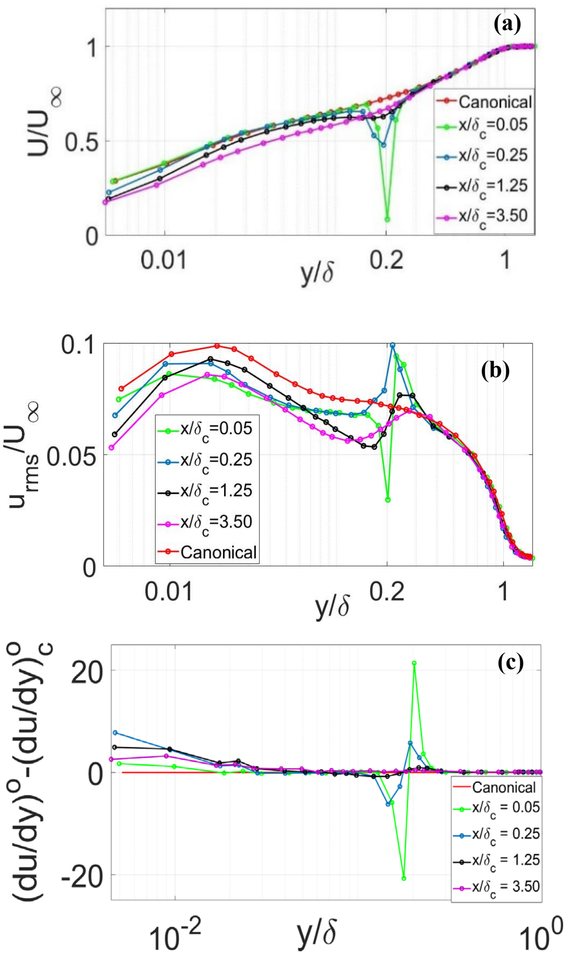


Figure 2 Profiles of (a) mean velocity and (b) r.m.s intensity (c) velocity-gradient difference between the perturbed TBL and the oncoming canonical TBL. Here δ is the local boundary layer thickness and δ_c that of canonical TBL

Interestingly the effect of LEBU is felt right down to the inner peak in u_{rms} located at about $y/\delta \approx 0.02$. While the position of the inner peak is not affected by the presence of LEBU, its magnitude is reduced by about 10-15% (figure 2b). This reduction cannot be attributed to the local velocity gradient which is seen to be higher for the perturbed TBL in comparison to the canonical TBL in the region $0.005 < \frac{y}{\delta} < 0.05$ (figure

2c), presumably due to the local acceleration caused by the presence of LEBU. This implies that, in presence of LEBU, the decrease in Reynolds shear stress in this region must be larger than the increase in the mean velocity gradient causing the energy production and therefore the u_{rms} levels to decrease. The exact mechanism by which the Reynolds stress near the wall decreases is not clear and is a topic of ongoing investigation. This exercise shows that by positioning the LEBU closer to the wall ($y/\delta_c = 0.2$) as done here, it is possible to directly affect the inner cycle of turbulence.

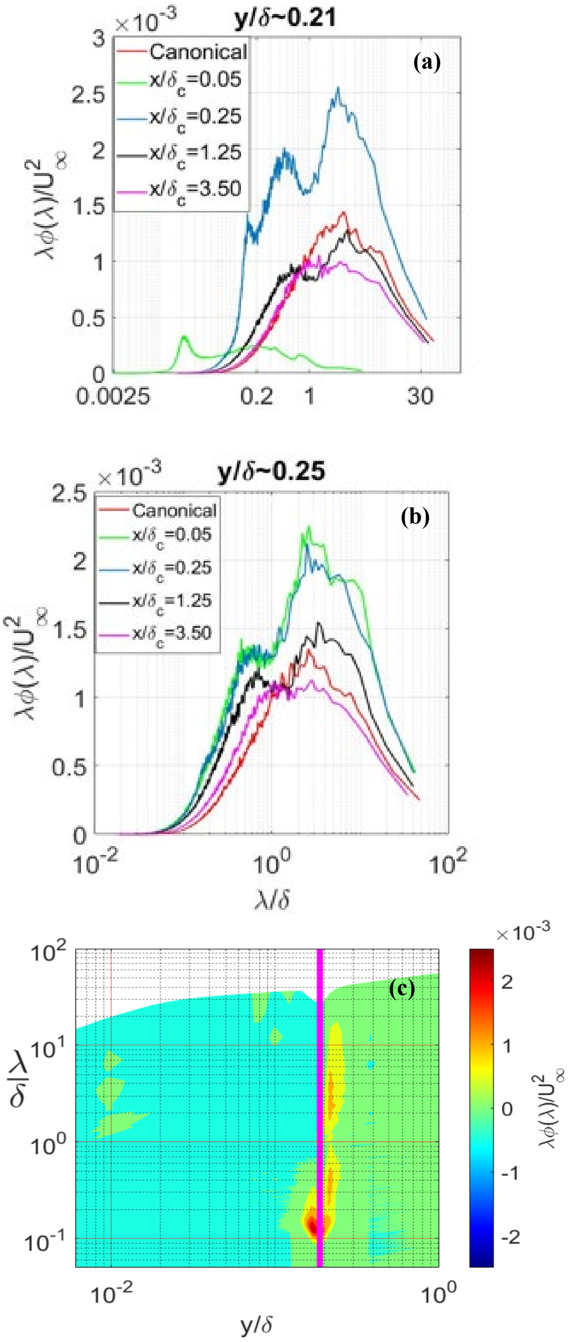


Figure 3 Pre-multiplied spectra of the perturbed TBL compared with the canonical TBL at (a) $y/\delta \approx 0.21$ and (b) $y/\delta \approx 0.25$ (c) Difference spectrogram at $x/\delta_c = 0.25$ where the magenta line shows the position of LEBU. The colour bar shows the difference in the pre-multiplied spectral energy.

Figure 3a shows the pre-multiplied spectral energy of streamwise velocity fluctuations, $\lambda\phi(\lambda)$, as a function of the streamwise wavelength, λ at $y/\delta \approx 0.21$. The wavelength is determined from the frequency using the Taylor's frozen-eddy hypothesis. Immediately downstream of the LEBU, i.e., at $x/\delta_c = 0.05$, there is a considerable reduction in the energy for $\lambda > 0.2\delta$ as compared to the oncoming canonical TBL and an enhancement of energy for smaller wavelengths. This represents the well-understood effect of LEBU in breaking up larger scales and promoting smaller scales. Interestingly a small distance downstream, at $x/\delta_c = 0.25$, there is a substantial increase in the spectral energy from $\lambda = 0.1\delta$ to about 20δ, with a dominant peak at $\lambda = 2 - 3\delta$. Further downstream $\lambda\phi(\lambda)$ decreases for all λs and at $x/\delta_c = 3.5$, it is smaller than that in the canonical TBL for $\lambda > \delta$ (figure 3a). From figure 3b we can see that at $y/\delta \sim 0.25$ the energy downstream of LEBU is enhanced at all the wavelengths even at $x/\delta_c = 0.05$ and again as with $y/\delta \sim 0.21$, the spectral energy gradually decreases as we move further downstream. Figure 3c shows the difference pre-multiplied spectrogram of the perturbed TBL with respect to canonical TBL at $x/\delta_c = 0.25$. Above the LEBU, there is an increase of spectral energy for nearly all the scales (with the highest enhancement happening just above the LEBU), whereas the spectral energy is reduced below the LEBU as compared to the canonical TBL.

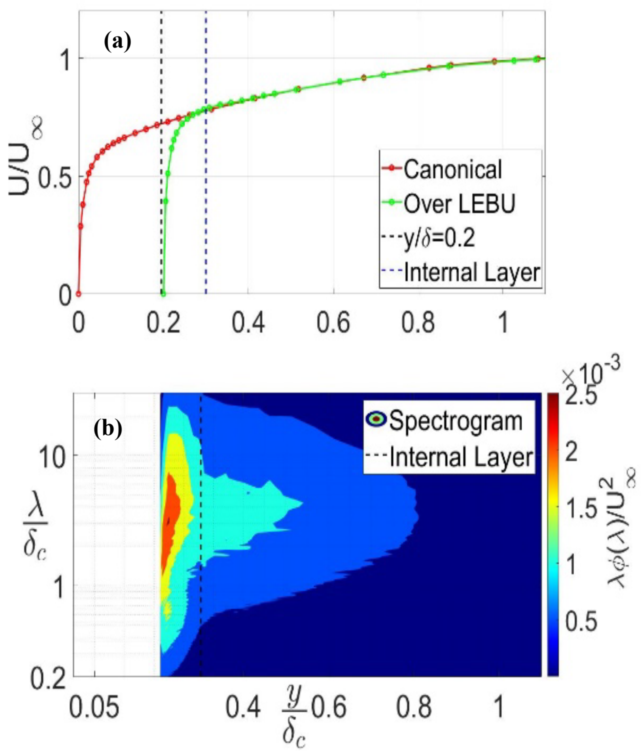


Figure 4. (a) Mean velocity profile measured over the LEBU surface compared with the canonical TBL. (b) Spectrogram of pre-multiplied energy measured over the LEBU surface.

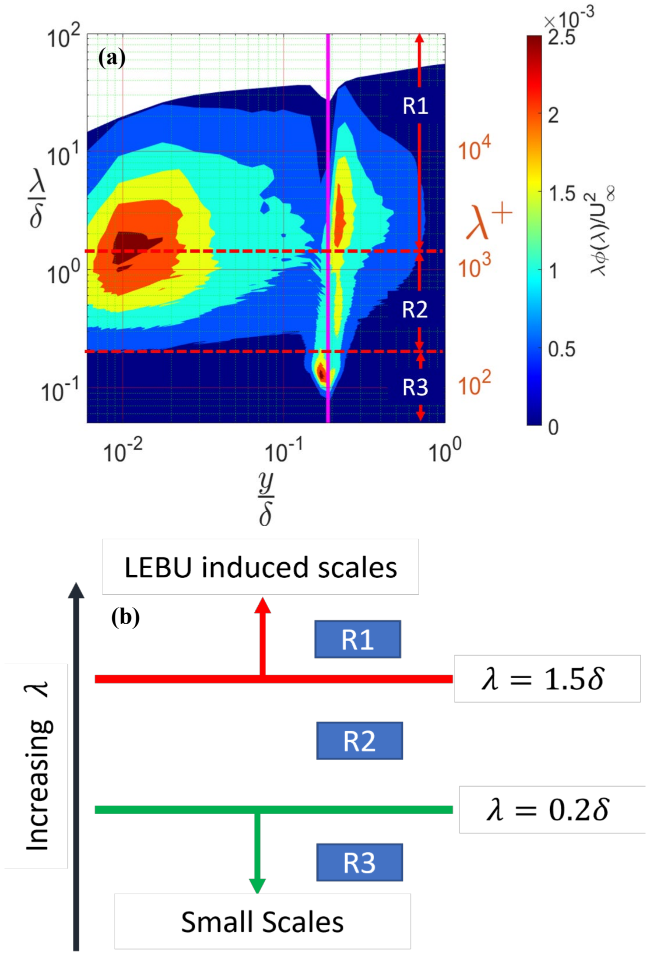


Figure 5 (a) Pre-multiplied spectrogram at $x = 0.25\delta_c$ downstream of the LEBU. The LEBU is represented by the magenta line. λ^+ is the wavelength scaled on wall variables using u_τ for the canonical TBL. (b) Schemetic of the ranges of scales (R1, R2 and R3) obtained by setting two cut-off wavelengths used for calculating the amplitude modulation coefficient. See the text for more details.

To understand the large amplification of energy observed at $x/\delta_c = 0.25$, we have carried out velocity measurements "over" the LEBU (i.e., on the LEBU surface), at the mid-location along its length. The mean velocity profile compared with the canonical TBL is shown in figure 4a. As expected, a new viscous layer is seen to be formed over the LEBU, which is responsible for breaking up the large eddies. However, there is another important consequence of the presence of such an "internal" shear layer within a TBL. The large velocity gradients within this layer can cause a "rapid shearing" of the turbulent eddies in the oncoming TBL, giving rise to relatively long streamwise structures. This is evident from the pre-multiplied spectrogram in figure 4b which shows that a significant energy is generated in wavelengths $\lambda > \delta_c$, with the peak energy at $\lambda \approx 3\delta_c$. In fact, the spectral energies in figure 4b near the LEBU surface are comparable or higher than those present around $y/\delta \approx 0.2$ in the canonical TBL (figure 3a). The wavelength of $3\delta_c$ represents a streamwise structure which is about 30 times the thickness of the internal layer formed over the LEBU (which is $\approx 0.1\delta_c$; figure 4). This is comparable to the streamwise structures of $20 - 30\delta$ obtained in the experiments of Diwan and Morrison (2017) who subjected a laminar boundary layer to broadband grid turbulence. They further showed that their results could be interpreted in terms of the "rapid-distortion theory". This provides a support to the present conjecture that the energy generated within the new layer over the LEBU is due to the rapid-shearing mechanism. These newly generated energetic eddies are swept downstream which is reflected in the pre-multiplied spectrum in the wake of the LEBU at $x/\delta_c = 0.25$, displaying a prominent peak at $\lambda = 3\delta$ (figure 3a). The elevated spectral energy for large λ, in comparison with the canonical TBL, is also evident in the spectra at $y/\delta \approx 0.25$ up to $x/\delta_c = 1.25$ (figure 3b). This suggests that a LEBU can affect turbulent fluctuations over a wide range of scales (and not merely large scales); see also Savill and Mumford (1988).

Figure 5(a) shows the pre-multiplied spectrogram at $x = 0.25\delta_c$ downstream of the LEBU. Apart from the elevated energies appearing at small wavelengths of the order $\lambda = 0.1\delta$, the spectral energy is primarily focussed at two energy sites – one near the wall at $y/\delta \approx 0.01$ and the other near the LEBU location at $y/\delta \approx 0.2$. The shape of the spectrogram in figure 5(a) resembles that observed in a high-Reynolds number TBL (Hutchins and Marusic 2007) where the spectral energy is focussed into an inner peak and an outer peak. The scale separation between these two energy sites in the present experiment is not as large as that observed for the high-Re TBL, since our Reynolds numbers are much lower. Nevertheless, perturbing a TBL with the help of a LEBU can be useful in mimicking the spectral structure of the high-Re TBL in a low-Reynolds-number wind-tunnel facility to understand the inner-outer interaction among different turbulence scales.

Figure 6 (a) presents the amplitude-modulation coefficient, R, between the filtered envelope of small scales and the filtered large scales as defined by Mathis et al. (2009); a cut-off wavelength of $\lambda = 1.5\ \delta$ is used for this purpose. Note that the standard practice is to use $\lambda = \delta$ as the cut-off wavelength for decoupling of large and small scales in high Reynolds number TBLs (Mathis et al. 2009). The larger cut-off wavelength used here is because the near-wall spectral peak appears around this value of λ (figure 5a) in the present experiment, which we would like to consider as part of the "small scale" range as per the standard practice. We have confirmed that using $\lambda = 1.5\ \delta$ as the cut-off wavelength produces almost the same result as obtained using a cut-off of $\lambda = \delta$ (see also Mathis et al. 2009). It is evident that the presence of LEBU affects the variation of R over the region $0.4 > y/\delta > 0.02$, beyond which R for the perturbed TBL is close to that for the canonical TBL (figure 6a). There is a significant increase in amplitude modulation around $y/\delta \approx 0.2$, with R exhibiting large positive values, comparable to or higher than those seen for the canonical TBL near the wall. Above the LEBU, there exists a small region of decreased scale correlation relative to the canonical TBL. It is clear from figure 6a that larger scales introduced by the LEBU significantly modulate the smaller scales near its vicinity, thereby altering the structure of the oncoming TBL.

To better characterize the effect of presence of LEBU on the scale interactions within the TBL, we carry out an exercise of calculating amplitude modulation coefficients using two cut-off wavelengths – $\lambda = 1.5\delta$ and $\lambda = 0.2\delta$. This is shown schematically in figure 5(b). The use of two cut-off wavelengths results in three different ranges of scales (figure 5b) – (a) R1, representing scales predominantly induced by LEBU at $\lambda > 1.5\delta$, (b) R2, involving the range of scales between $\lambda = 1.5\delta$

and $\lambda = 0.2\delta$, and (c) R3, representing scales smaller than 0.2δ that are typically present in the wall layer. These ranges are also marked on the spectrogram at $x = 0.25\delta_c$ shown in figure 5a. The modulating effect of R1 on the combined ranges of R2 and R3 has already been shown in figure 6a – which we term as the "conventional" (single cut-off) exercise.

In the following, we compare the amplitude modulation coefficients obtained by considering different ranges of scales with those corresponding to the conventional single cut-off. First, we list out the features for the modulation of R3 by R2 (figure 6b):

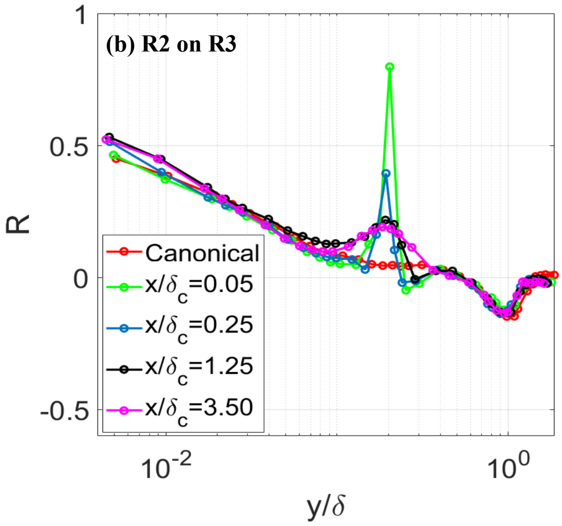
i. The modulating effect is localized close to the LEBU location ($0.1 < \frac{y}{\delta} < 0.25$).
ii. The peak positive correlation around $\frac{y}{\delta} = 0.2$ decreases more rapidly as we move downstream than in figure 6a.
iii. The negative correlation from $\frac{y}{\delta} = 0.5$ to the edge of the boundary layer is reduced drastically. Interestingly this effect is observed also for the canonical TBL.
iv. The local minima in R above and below the LEBU are decreased in magnitude and shifted closer to the LEBU.

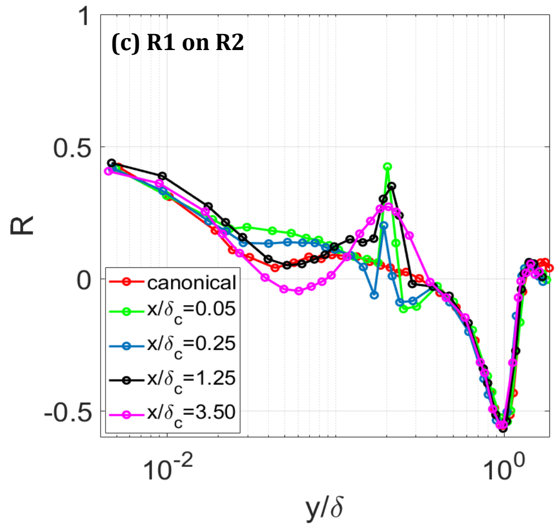
Next, we consider the effect of R1 on R2 (figure 6c):

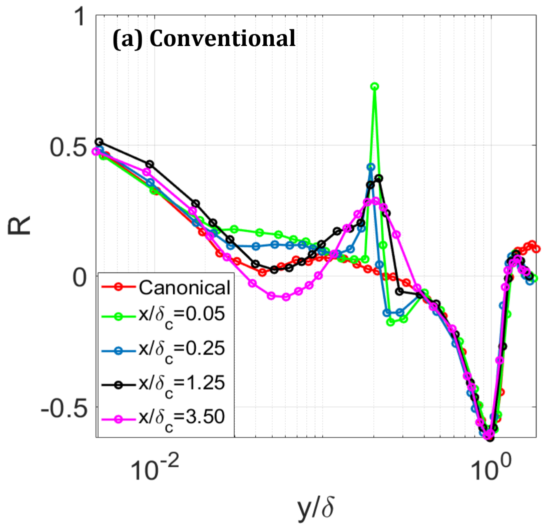
i. The peak positive correlation is reduced for $\frac{x}{\delta_c} = 0.05$ whereas that for other x locations is not much affected.
ii. Overall, the shape and the extent of modulation in wall normal direction remains similar to the conventional case (figure 6a).

Finally, we describe the modulating effect of scales R1 on scales R3 (figure 6d):

i. The peak positive correlation near the LEBU ($\frac{y}{\delta} \approx 0.2$) is large for all $\frac{x}{\delta_c} > 0.05$ compared with that for the case discussed above (figure 6c). It is nearly the same as for the conventional case (figure 6a).
ii. The positive correlation values near the wall are somewhat increased for the LEBU as well as for the canonical TBL.
iii. The extent of modulation in wall normal direction compared with that for the canonical TBL is similar to that observed for the conventional cut-off (figure 6a).







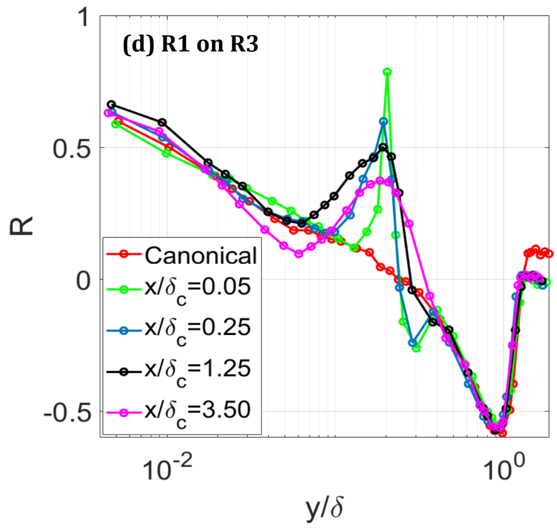


Figure 6 Profiles of the amplitude modulation coefficient for the perturbued TBL compared with those for the canonical TBL. (a) Conventional (single) cut-off case $\lambda = 1.5\delta$, (b) Range 2 on Range 3, (c) Range 1 on Range 2, (d) Range 1 on Range 3. See figure 5 for the definition of the three ranges.

To summarize the above exercise, we find that the modulating effect of the large scales in R1 introduced by the LEBU on the small scales in R3 (figure 6d) is qualitatively similar to that observed with the conventional single cut-off (figure 6a). The presence of LEBU significantly affects the modulation of small scales immediately downstream of it, i.e., in its wake region. On the other hand, the effect of the intermediate scales in R2 on the scales in R3 (figure 6b) is much different from that for the conventional case (figure 6a). In particular, the effect of LEBU is much more localized and the negative correlation near the edge of the boundary layer is significantly suppressed, which is also the case for the canonical TBL (figure 6b). The implications of these results towards understanding scale interactions within the TBL perturbed by a LEBU are being explored. We believe the scale interaction between small scales and “synthetic” large scales could also help us better understand the amplitude modulation caused by the “superstructures” in a canonical TBL at high Reynolds numbers.

CONCLUSION

In this work we have characterized the structure of a TBL perturbed by a LEBU in its immediate vicinity. We find that the LEBU not only breaks up the large-scale eddies as understood conventionally but also introduces significant energy at larger scales (about 3δ), through the rapid shearing of oncoming disturbances by the new viscous layer formed over its surface. The presence of LEBU causes a suppression of the near wall turbulence peak which is an interesting observation. The amplitude modulation of small-scale eddies by the larger scales is significantly altered over a certain region above and below the LEBU. To better characterize the effect of the presence of LEBU on the scale interactions within the perturbed TBL, we have calculated the amplitude modulation coefficient using two cut-off wavenumbers and compared the results with the conventional analysis that uses a single cut-off for the wavenumber. The present work highlights the utility of LEBU as an effective manipulator of the structure of a canonical TBL.

ACKNOWEDGEMENT

A.T. thanks Mr Satyajit Dey for providing LabVIEW codes for carrying out the present measurements. S.S.D. acknowledges financial support from Science and Engineering Research Board (SERB), India through the grant ECR/2018/002417. We thank an anonymous referee for suggesting the amplitude modulation exercise with two cut-off wavelengths.

REFERENCES

Alfredsson, P.H, and Orlu, R. 2018, "Large eddy break-up device-a 40-year perspective from Stockholm horizon", *Flow Turbulence Combust.*, Vol. 100., pp. 877-888.

Chan, I.C., Orlu, R., Schlatter, P., and Chin, R.C 2021, "The Skin Friction Coefficient of Turbulent Boundary Layer Modified by Large Eddy Break-Up Device", *Phys. Fluids*, Vol. 33, (3) 035153.

Chan, I.C., Orlu, R., Schlatter, P., and Chin, R.C 2022, "Large-scale and small-scale contribution to skin friction reduction in a modified turbulent boundary layer by large -eddy break-up device", *Phys. Rev. Fluids*, Vol. 7, 034601.

Chin, C., Orlu, R., Monty, J., Hutchins, N., Ooi, A., and Schlatter, P., 2017, "Simulation of Large Eddy Break-Up Device (LEBU) in moderate Reynolds number turbulent boundary layer," *Flow Turbulence Combust.*, Vol. 98., pp. 445-460.

Diwan, S.S. and Morrison, JF., 2017, "Spectral Structure and Linear Mechanisms in a Rapidly Distorted Boundary Layer", *Int. J. Heat Fluid Flow*, Vol.67, pp. 63-73.

Hutchins, N., and Marusic, I., 2007 "Evidence of very long meandering features in the logarithmic region of turbulent boundary layer: ", *J. Fluid Mech.* Vol. 579, pp. 1-28.

Mathis, R., Hutchins, N., and Marusic, I., 2009 "Large-Scale Amplitude Modulation of Small-Scale Structures in Turbulent Boundary Layers: ", *J. Fluid Mech.* Vol. 628, pp. 311-337.

Savill, A.M. and Mumford, J.C ,1988, "Manipulation of Turbulent Boundary Layers by Outer -Layer Devices: Skin-Friction and Flow Visualization Results", *J. Fluid Mech* Vol. 191, pp. 389-418.

Shalin, A., Johansson, A.V. & Alfredsson, P.H. 1988, "The possibility of drag reduction by outer layer manipulators in turbulent boundary layers", *Phys. Fluids*, Vol. 31., pp. 2814-2820.