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On the convection velocity of wall-bounded turbulence resolved by ZDES mode III at $Re_\theta = 13\,000$

Nicolas Renard and Sébastien Deck

Abstract WMLES simulations of a flat-plate zero-pressure-gradient boundary layer are done with the Zonal Detached Eddy Simulation Mode III technique over a wide range of Reynolds numbers $3\,150 \leq Re_\theta \leq 14\,000$. A WMLES field is compared with the WRLES interpolated onto the WMLES mesh. Two interface heights are considered, $y_{\text{interface}} = 0.1\delta$ and $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$. The prediction and resolved fraction of mean skin friction is discussed, as well as remaining issues, especially in the logarithmic layer. An excess of high-wavelength streamwise velocity fluctuations is observed below the RANS/LES interface with $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$, and studied by a spectral convection velocity analysis, leading to the suggestion that it may be a footprint of coherent structures located further away from the wall.

1 Short discussion of the need and options for Wall-Modelled Large Eddy Simulation in applied aerodynamics

In applied aerodynamics, the increasing demand for the prediction of phenomena such as mild flow separations, strongly out of equilibrium boundary layers, aeroacoustics or unsteady loading may require a more detailed and universal description than the mean values provided by Reynolds Averaged Navier-Stokes models, motivating turbulence-resolving approaches of wall-bounded flows. However, in high Reynolds number attached turbulent boundary layers in most aerospace applications ($Re_\tau \approx 10^4 - 10^5$), the numerical cost of Direct Numerical Simulation, and even of Wall-Resolved Large Eddy Simulation, is prohibitive because of the lack of scale separation in the near-wall region. Introducing wall models and resolving

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the outer layer dynamics, the number of grid points for Wall-Modelled Large Eddy Simulation is approximately proportional to the square root of the number of points for DNS (see [6]), making WMLES affordable in applied aerodynamics at high Reynolds numbers.

Examples of wall models ([24]) are a dynamic wall boundary condition, a near-wall mesh superimposed to the LES mesh ([23]), or a lower-resolution turbulence model near the wall. In the latter option, a RANS near-wall description may be coupled to an outer LES, which naturally lies within the hybrid RANS/LES framework where LES is performed in the regions of interest, *e.g.* massive separations, free shear layers or the outer regions of attached boundary layers where resolving turbulence is needed, while a RANS treatment of the rest of the flow, especially some thin boundary layers, reduces the overall numerical cost ([28]). The near-wall RANS may for instance be a constraint for LES ([2]) or blended with the outer LES ([12]).

In the case of Detached Eddy Simulation ([33], [32]), the same turbulence model is simply used as the RANS model near the wall and as the subgrid scale model for the outer LES by switching the characteristic length at the RANS/LES interface, but the first attempts resulted in a *log-layer mismatch* and significant underestimation of mean skin friction ([21]). Active solutions such as stochastic forcing ([14]) raise questions as to their calibration, universality, acoustic signature and numerical robustness. Alternatively, the passive interface treatment may be improved by *ad hoc* functions and length scale definitions, such as in IDDES ([30]). However, this mostly empirical formulation still deviates from the logarithmic law and highly depends on the mesh resolution [29]. Instead, the simple initial DES formulation may be retained for WMLES if the RANS/LES interface height is properly defined by the user to minimise the reported difficulties. This zonal WMLES strategy is adopted for Mode III of Zonal Detached Eddy Simulation [3] described in the next section.

2 A WMLES strategy: Mode III of ZDES

In ZDES (Zonal Detached Eddy Simulation [3]) the user defines the zones of interest for LES. This technique has been extensively validated since 2003 in both academic and industrial problems ranging from the flat plate to a full airliner at flight Reynolds number [4]. Three modes may be assigned to each flow region depending on its nature and used simultaneously as demonstrated in [5]. Mode III results from the demonstration of the WMLES capacity of ZDES starting in 2007 ([9], [8]) and is also suitable for WRLES ([8],[7]). For WMLES, the RANS/LES interface height should not depend on the mesh resolution ([8]) and scale in outer units (*i.e.* be at a constant y/δ [6] or at the geometric centre of the logarithmic layer [25], [26]). The interface may typically be positioned from a pre-processing of the RANS flow field used as the initial condition for the ZDES simulation. ZDES mode III has been used on three-dimensional geometries representative of industrial problems (*e.g.* curved

duct for dynamic distortion predictions [15], high-lift three-element airfoil [5]). Because high-Reynolds-number attached boundary layers are ubiquitous in aerospace applications, the rest of the present study focuses on a flat plate boundary layer test case defined in the next section with as long a streamwise extent as possible.

3 Motivation, definition and visualisation of a high-Reynolds-number zero-pressure-gradient flat-plate turbulent boundary layer test case

A WMLES test case for external aerodynamics relevant to aerospace applications should at least feature spatial growth (thus excluding channel and pipe flows because of their different turbulent dynamics [18]) and high Reynolds numbers (because there are dominant physical phenomena such as superstructures at the Re_τ values typical of applications that are not visible at lower Reynolds numbers [31], [13]). A natural choice is the zero-pressure-gradient flat-plate boundary layer, an extensively documented test case representative of attached boundary layers without strong pressure gradients. Its geometrical simplicity puts great demands on turbulence modelling, whose validation on this test case may be seen as a mandatory first step before considering more complex flows where success or failure may be more geometry-dependent.

The ZPG TBL simulated here at $M_\infty = 0.21$ may be compared to incompressible data and covers a wide range of Reynolds numbers, $3\,150 \leq Re_\theta \leq 14\,000$ with the streamwise extent $L_x = 350\delta_0$ (δ_0 is the initial boundary layer thickness). Streamwise velocity spectra from a WRLES of the same test case (also performed with ZDES mode III [7]) reproduced in fig. 1 clearly indicate the presence of superstructures ($\lambda_x \sim 5 - 6\delta$) in the outer layer at $Re_\theta = 13\,000$ that are not visible at $Re_\theta = 5\,200$, confirming that a lower Reynolds number test case would not include superstructures despite their importance for applied aerodynamics (see *e.g.* their contribution to mean skin friction [7]).

Fig. 1 Reynolds number impact on the pre-multiplied spectra $k_x G_{uu}(k_x) / u_\tau^2$ reconstructed with a correlation-based convection velocity at $Re_\theta = 5\,200$ (left) and $Re_\theta = 13\,000$ (right). WRLES simulation using ZDES mode III (see [7] and [27]).

For WMLES by ZDES mode III, mesh spacings $\Delta x^+ = 200$ and $\Delta z^+ = 100$ in the streamwise and spanwise directions respectively ($\Delta x/\delta_0 = 0.212$ and $\Delta z/\delta_0 = 0.107$) are used here. The total number of grid points is $N_{xyz} = 30 \cdot 10^6$, much less than for the aforementioned WRLES ($N_{xyz} = 800 \cdot 10^6$ with $\Delta x^+ = 50$ and $\Delta z^+ = 12$). Because ZDES is developed with industrial applications in mind, the test case is simulated with the in-house FLU3M solver with robust second-order numerical schemes suited for complex geometries. This is not optimal for the present academic test case (where higher order schemes could help) but it represents how the method will be used in real geometries. The convective fluxes are discretized by a modified AUSM+(P) scheme with a wiggle detector reducing numerical dissipation [19] and the MUSCL state reconstruction. Time integration is second-order accurate implicit. The turbulent inflow is provided by a Synthetic Eddy Method ([22], [16]). The RANS/LES interface heights investigated here, $y_{\text{interface}} = 0.1\delta$ and $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$ (centre of the logarithmic layer), are illustrated in fig. 3.

Fig. 2 Flow visualisation near $Re_\theta = 13\,000$ with ZDES mode III in WRLES operation (left, [7]), WRLES interpolated onto the WMLES mesh (middle), and in WMLES operation (right, with $y_{\text{interface}} = 0.1\delta$). Isosurface $u = 0.8U_\infty$ coloured by wall distance; numerical Schlieren (density gradient magnitude).

A visual comparison of the flow resolved by ZDES near $Re_\theta = 13\,000$ in WRLES and in WMLES ($y_{\text{interface}} = 0.1\delta$) is provided in fig. 2. Some features of the WRLES, especially the inclined structures visible in the numerical Schlieren suggesting hairpin packets, may be recognised in the WMLES. An insight into the finest fluctuations that the WMLES mesh can support is obtained by interpolating the WRLES flow field onto the WMLES mesh. The comparison with the WMLES suggests that there is still room for improvement of the WMLES results, even regarding the largest-scale organisation of the flow field, as will be quantified in fig. 6.

4 WMLES prediction of mean skin friction by ZDES

The prediction of mean skin friction in attached boundary layers is mandatory for applied aerodynamics because of its relation to drag and to the spatial development of boundary layers. Hence a WMLES should ideally be as accurate as a RANS model with respect to this mean parameter, whose prediction by ZDES mode III is

detailed in §4.1 before a few issues related to the logarithmic layer are discussed in §4.2.

4.1 Accuracy, resolution and streamwise evolution of skin friction

In the present case, with both interface heights illustrated in fig. 3, mean skin friction predicted by ZDES is within 5 % of the Coles-Fernholz correlation (fitted to experimental data [20]) over the region of fully developed resolved turbulence (excluding the relaxation downstream the turbulent inflow), as shown in fig. 4. The resolved and modelled turbulent contributions are compared by plotting the resolved fraction of Reynolds shear stress $\langle u'v' \rangle_{\text{res}} / \langle u'v' \rangle_{\text{tot}}$ in fig. 3, equal to 0 in the case of a pure RANS behaviour and equal to 1 in the case of a DNS, thus quantifying the intermediate state between RANS and LES. The simulation is pure RANS only at the wall itself, with fluctuations resolved even in the RANS region. The resolved fraction is close to 1 in the outer layer and increases from the wall to the outer edge of the boundary layer. Its monotonicity is a satisfying property since the further away from the wall, the more resolution (rather than modelling) is expected. The resolved fraction is higher with the log layer centre definition of the interface at $Re_\theta = 13\,000$, which is not surprising since the interface is located much lower than the 0.1δ interface at this Reynolds number (fig. 3). Assessing the resolved fraction of turbulent mean skin friction by means of the FIK identity [11] [7] [6] shows that more than 90 % of the turbulent contribution is resolved at $Re_\theta = 13\,000$ with the log layer interface setting [26], a figure that increases with the Reynolds number.

Fig. 3 Present ZDES mode III interfaces for WMLES and profile of resolved fraction of $\langle u'v' \rangle$.

With the lower interface setting $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$ however, streamwise oscillations of mean skin friction are visible (fig. 4). This problem is strongly reduced by a smooth RANS/LES interface function f_δ [26] as illustrated in fig. 4, so that the formulation of the characteristic length scale of the SA turbulence model used for ZDES mode III becomes, as detailed in [26]:

$$\tilde{d}_{\text{DES}}^{\text{III}} = (1 - f_\delta) \cdot d_w + f_\delta \cdot \min(d_w, C_{\text{DES}} \Delta_{\text{vol}}); \quad \Delta_{\text{vol}} = (\Delta x \Delta y \Delta z)^{1/3} \quad (1)$$

$$f_\delta(\alpha) = \begin{cases} 0 & \text{if } \alpha \leq -1 \\ \frac{1}{1 + \exp\left(\frac{-6\alpha}{1-\alpha^2}\right)} & \text{if } -1 < \alpha < 1 \\ 1 & \text{if } \alpha \geq 1 \end{cases} \quad \left(\alpha = \frac{d_w - d_w^{\text{interface}}(x_{\text{center}})}{0.1 d_w^{\text{interface}}(x_{\text{center}})} \right) \quad (2)$$

Fig. 4 Smooth interface function f_δ and mean skin friction evolution.

4.2 A few open questions related to the logarithmic layer

Mean skin friction prediction by ZDES is quite satisfactory (fig. 4), but some undesirable features may still be seen in the turbulent profiles (fig. 5). The inner-scaled mean velocity profile deviates from the logarithmic law to an extent depending on the interface setting. Among the three heights considered in fig. 5, $y_{\text{interface}} = 0.1\delta$ provides the best results. Associated with this deviation is a possible overestimation of the streamwise turbulent intensity near the RANS/LES interface (fig. 5). The spectral content of the excess of streamwise velocity fluctuations with $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$ is located right below the RANS/LES interface at large wavelengths (fig. 6), and is reminiscent of the stronger ‘superstreaks’ described in the early WMLES use of DES (*e.g.* [14]). The better experimental agreement of the spectrum with $y_{\text{interface}} = 0.1\delta$ has already been emphasized in [6] and [25], as well as some very-large-scale energy deficit in the outer layer [25] which remains unexplained to date. In order to better understand the nature of the excessive high-wavelength fluctuations, their convection velocity is evaluated in §5. Indeed, if these fluctuations were quite unphysical, their convection velocity could even be totally different from the expected turbulent dynamics, which would be visible in the spectral convection velocity.

Fig. 5 Velocity and normal Reynolds stresses profiles at $Re_\theta = 13\,000$

Fig. 6 Premultiplied streamwise velocity spectra at $Re_\theta = 13\,000$ with $y_{\text{interface}}^+ = 0.1\delta$ (left) and $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$ (right), reconstructed with the mean velocity as convection velocity. Solid lines: exp. data from [17] at $Re_\tau = 3\,900$.

5 Resolved spectral convection velocity at $Re_\theta = 13\,000$

The high-wavelength excess of power spectral density below the $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$ RANS/LES interface (fig. 6) is further investigated here by evaluating the wavelength-dependent convection velocity of the resolved fluctuations of streamwise velocity in this region of the spectrum. The method for the spectral assessment and the associated reconstruction of the spatial spectrum from time signals in the spatially developing boundary layer is detailed in [27] (inspired by a dual method [1]). The frequency-dependent convection velocity $U_c(f)$ and the correlation coefficient $\gamma_u(f)$ describing the degree of validity of Taylor's frozen turbulence hypothesis are given by:

$$U_c(f) = -\frac{2\pi f S_{uu}(f)}{\text{Im}(S_{u\partial_x u}(f))} \quad \text{and} \quad \gamma_u(f) = \frac{|\text{Im}(S_{u\partial_x u}(f))|}{\sqrt{S_{uu}(f)}\sqrt{S_{\partial_x u \partial_x u}(f)}} \quad (3)$$

The convection velocity $U_c(f)$ is presented for both interface settings in fig. 7. The relevancy of this information is confirmed by the correlation coefficient plotted in fig. 7, which is close to 1 for small scales ($\gamma_u(f) = 1$ would be encountered in pure constant convection of perfectly frozen turbulence), and has sufficiently high values even at large wavelengths. The convection velocity increases with wall distance, as expected, and no grossly unphysical value can be seen including in the high-wavelength energy site below the RANS/LES interface. This implies that the reported excessive streamwise velocity fluctuations are not travelling at a velocity much different from what is expected for this energy site, discarding the possibility that they could be spurious fluctuations travelling at a quite unphysical velocity.

Fig. 7 Spectral convection velocity $U_c(f)$ (3) and associated correlation coefficient $\gamma_u(f)$ (3) at $Re_\theta = 13\,000$ with $y_{\text{interface}} = 0.1\delta$ (left) and $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$ (right). Isolines of $k_x G_{III}(k_x)/u_\tau^2$ in white solid lines.

The locus where the $U_c(f)$ convection velocity matches the local mean velocity, $U_c(f) = \langle U \rangle$, represented in solid line on top of the streamwise velocity spectra in fig. 8, may be called the 'critical layer' because of the analogy with stability analysis (where the maximum amplitude of the perturbation can be close to the locus where its phase speed coincides with the mean velocity). In fig. 8, the 'critical layer' coincides with the $\lambda_x \approx \delta$ energy site with both interface settings. In the case of a WRLES, this is even true for all three energy sites (hairpin packets, inner site and superstructures [27]). As for the high wavelengths below the RANS/LES interface in both WMLES simulations of fig. 8, the 'critical layer' is on the contrary located above the energy sites themselves. This suggests that the high-wavelength energy site of u' with excessive levels for $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$ may be a footprint of coherent structures dynamically rooted higher in the boundary layer, near the 'critical layer'. Indeed, if the high wavelength energy site had its own dynamics, one would expect

its convection velocity to be close to the mean velocity at its own wall distance rather than higher. Although explicit proof is still needed, fig. 8 strongly suggests that the observed excess of large-scale streamwise velocity fluctuations with $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$ actually is the footprint of a more physical dynamics located higher in the boundary layer. Whether this footprint may be removed without an active forcing is still an open question, probably related to the reduction of the logarithmic law deviation and to the resolved very-large-scale energy deficit in the outer layer.

Fig. 8 Premultiplied streamwise velocity spectra at $Re_\theta = 13\,000$ with $y_{\text{interface}}^+ = 0.1\delta$ (left) and $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$ (right). The solid line represents the $U_c(f) = \langle U \rangle$ locus ('critical layer').

6 Outlook

ZDES Mode III has been analysed for WMLES of a ZPG flat-plate boundary layer over a wide Reynolds number range $3\,150 \leq Re_\theta \leq 14\,000$. In the fully developed region, mean skin friction is predicted within 5 % of the experiments, using only $30 \cdot 10^6$ points ($800 \cdot 10^6$ are required for a WRLES of the same test case also using ZDES mode III). The resolved fraction of Reynolds shear stress, which indicates whether the simulation is RANS or LES, is a monotonous function of wall distance close to 1 in the outer layer (both are satisfying properties). With the RANS/LES interface set at the centre of the logarithmic layer, the resolved fraction of turbulent mean skin friction increases with the Reynolds number and is greater than 90 % at $Re_\theta = 13\,000$. A smooth RANS/LES interface function successfully reduces the streamwise friction oscillations with the lower interface setting. Several issues still arise in the logarithmic layer, with a deviation of the mean velocity profile, a very-large-scale turbulence deficit in the outer layer and an excess of high-wavelength streamwise velocity fluctuations below the RANS/LES interface with $y_{\text{interface}}^+ = 3.9\sqrt{Re_\tau}$. The latter problem has been analysed in more detail by assessing the wavelength-dependent convection velocity of the streamwise velocity fluctuations. The results suggest that the observed excessive energy is a footprint of a physical mechanism located higher in the boundary layer, rather than an autonomous artifact. This demonstrates the interest of using spectral analysis to get a better insight into the resolved field and its physical nature. To limit the high-

wavelength footprint, properly setting the RANS/LES interface height is required, but the possibility to reduce it further without resorting to an active forcing is still an open question, probably related to the reduction of the log law deviation and of the very-large-scale energy deficit in the outer layer. Solving these issues on the generic high Reynolds number flat plate test case appears as a mandatory step before the WMLES technique is adapted to curvilinear complex geometries, since they affect very large wavelengths associated to key turbulent phenomena (*e.g.* superstructures) specific to the high Reynolds numbers characterising aerospace applications.

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