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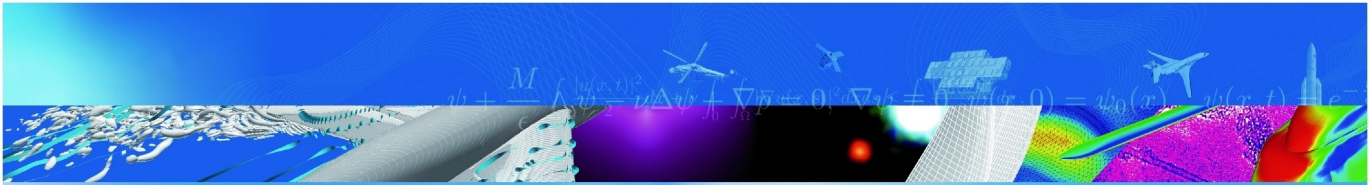
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Towards a physical scale decomposition of mean skin friction generation in the turbulent boundary layer

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Wall-bounded turbulence is ubiquitous in flows of engineering or environmental interest, where the high values of the Reynolds number result in phenomena such as very large scale motions ([8], [4]). This complex turbulent dynamics determines global parameters such as mean skin friction, contributing for instance to the overall drag and energy consumption of an aircraft.

Although many studies have been devoted to the fluctuations of skin friction, surprisingly less has been achieved towards the understanding of the generation of mean skin friction. It has been suggested that the buffer layer dynamics is involved ([5]), but a contribution from the outer layer at high Reynolds numbers may not be excluded. In the case of the incompressible zero-pressure-gradient flat-plate boundary layer, one may wish to quantify the contribution of turbulent fluctuations, as a function of their nature and distance from the wall, to the excess of mean skin friction in comparison with the laminar case. The FIK identity ([3]) was used in the past to spectrally decompose the turbulent contribution to the mean skin friction coefficient $C_f = \tau_w / (1/2\rho U_\infty^2)$ ([2]). However, the physical interpretation of the terms of this identity is not straightforward. To address this issue, a physical decomposition of mean skin friction generation was recently introduced ([7]):

$$C_f = \underbrace{\frac{2}{U_\infty^3} \int_0^\infty \nu \left(\frac{\partial \langle u \rangle}{\partial y} \right)^2 dy}_{C_{f,a}} + \underbrace{\frac{2}{U_\infty^3} \int_0^\infty -\langle u'v' \rangle \frac{\partial \langle u \rangle}{\partial y} dy}_{C_{f,b}} + \underbrace{\frac{2}{U_\infty^3} \int_0^\infty (\langle u \rangle - U_\infty) \frac{\partial}{\partial y} \left(\frac{\tau}{\rho} \right) dy}_{C_{f,c}} \quad (1)$$

where $\tau/\rho = \nu \partial \langle u \rangle / \partial y - \langle u'v' \rangle$. The discussion of this new decomposition suggests that at very high Reynolds number, the turbulence-induced excess friction may be essentially related to the production of turbulent kinetic energy (represented by $C_{f,b}$) in the logarithmic layer ([7]).

The present study investigates the resolved contribution of turbulence to mean skin friction in a spatially developing flat-plate boundary layer up to $Re_\theta = 13\,000$ described by a wall-resolved large-eddy-simulation database [2] (fig. 2, left) obtained with the Zonal Detached Eddy Simulation technique [1]. The friction decomposition (1) is assessed using this ZDES database and compared with DNS and RANS data in figure 1.

In order to assess the contribution of the resolved large scales of motion in the outer layer to mean skin friction, the velocity time signals from the database may be used to reconstruct turbulent spectra in the streamwise direction, using a suitable convection velocity ([6]). More specifically, the contribution of turbulence to the excess friction (compared with the laminar case) at high Reynolds numbers is related to the term $C_{f,b}$ (1), *i.e.* to the overall production of turbulent kinetic energy, as discussed in ref. [7]. The final paper will consequently present streamwise spectra of turbulent kinetic energy production. A preliminary result at $Re_\theta = 13\,000$ is given in figure 2 (right), suggesting the significant contribution of very large streamwise length scales in the outer layer to the overall TKE production contained within the boundary layer profile. The contribution of given wavelength bands at given wall distances will be quantified from the finalised spectra.

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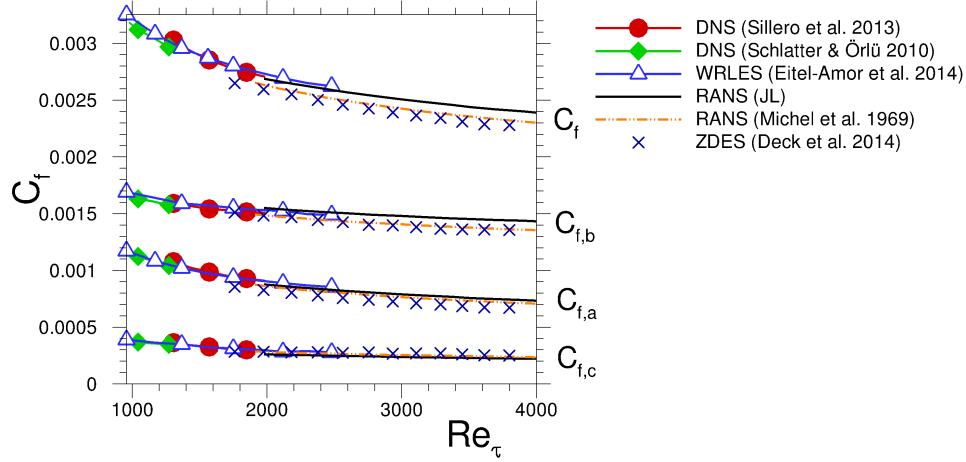


Figure 1: *Decomposition (1) of mean skin friction in the zero-pressure-gradient boundary layer.*

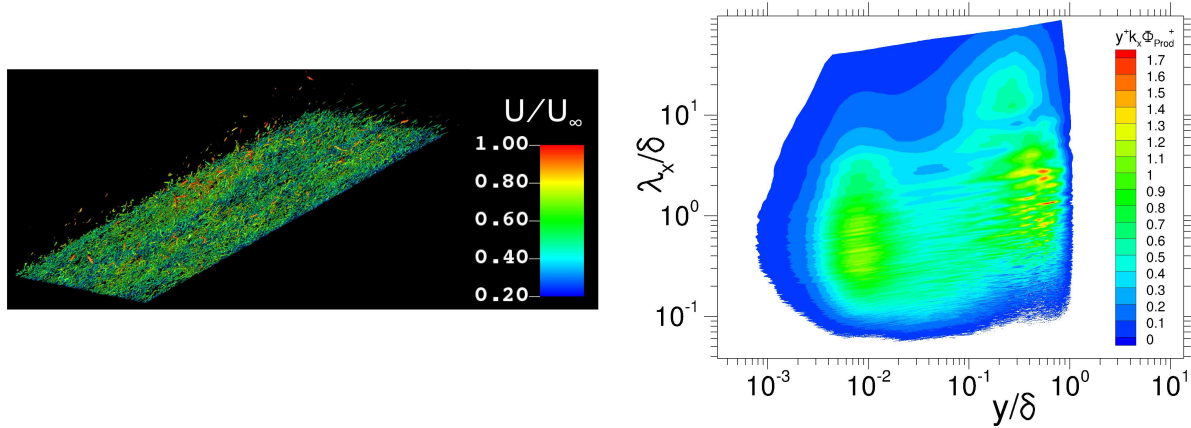


Figure 2: *Isosurface of the non-dimensionalised Q criterion $Q\delta_0^2/U_\infty^2 = 0.5$ coloured by the streamwise velocity near $Re_\theta = 13\,000$ in the database [2] (left); Premultiplied streamwise spectrum of turbulent kinetic energy production at $Re_\theta = 13\,000$ (right).*

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