2nd European Fluid Dynamics Conference (EFDC2)
26 – 29 *August* 2025, *Dublin, Ireland*

Outer-layer self-similarity in spatially developing turbulent boundary layers

Jason Appelbaum[*], Tobias Gibis[*], Sergio Pirozzoli[†], Christoph Wenzel[*]

A direct numerical simulation (DNS) of a spatially developing flat-plate turbulent boundary layer in the low supersonic regime will be examined, with the goal of characterizing the changes to the mean flow field as the turbulent wake becomes self-similar. One challenge in acquiring cross-comparable turbulent boundary layer measurements, both numerically and experimentally, is the persistent influence of 'subjective' factors in the upstream flow, such as the method used to induce turbulent transition. Artifacts can propagate surprisingly far downstream, particularly in the wall-distant region of the boundary layer, making it difficult to draw canonical conclusions about the behavior of spatially developing boundary layers. The present DNS has used a digital filtering method at the domain inflow at a minimal *Re*, enabling e.g. >300 inflow boundary-layer thicknesses of streamwise relaxation space to be covered before $Re_{\theta_i} \approx 1200$, still squarely in the low *Re* regime, where Re_{θ_i} is the incompressible-equivalent Reynolds number based on the momentum thickness. Fig. 1(a) shows the progression of the skin-friction coefficient c_f. At low *Re*, c_f is often empirically approximated by a power law, i.e. $c_f \approx a \cdot Re_\theta^b$, for example in [1], where a and b are constants. Analytically derived formulations become more applicable at sufficiently high *Re*, such as the 'Coles-Fernholz 2' correlation $c_f \approx 2[\kappa^{-1} \ln(Re_\theta) + C]^{-2}$, discussed in [2], where κ and C are constants. In

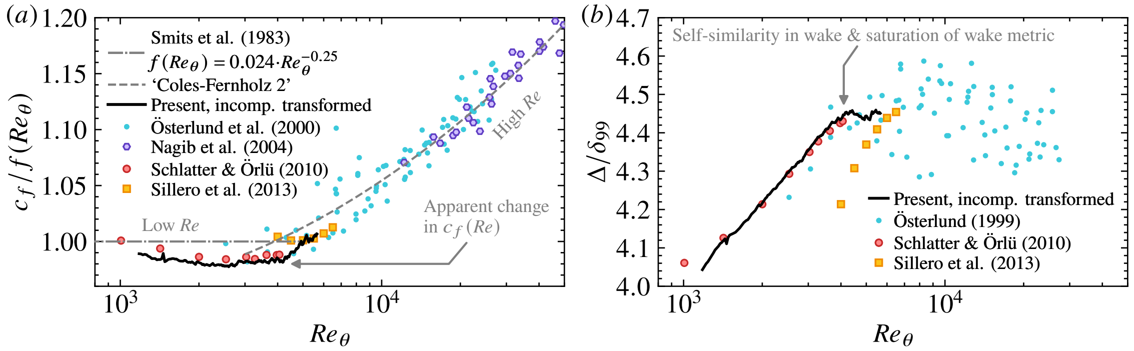

Figure 1: (a) Skin-friction coefficient c_f, normalized by the empirical fit for low *Re* from [1]. (b) Wake development metric Δ/δ_{99}, where Δ is the Rotta-Clauser length scale and δ_{99} is the 99% hydrodynamic boundary-layer thickness. Both quantities exhibit a distinct departure from their low-*Re* progression around $4000 \lessapprox Re_\theta \lessapprox 5000$.

the immediate vicinity of the crossing of the low- and high-*Re* correlations mentioned, there has been an effective 'blind spot' in the body of available data. DNS datasets were either limited in *Re* such that they did not capture the 'crossover' between the disparate c_f trends, or established inflow independence at *Re* in excess of the crossing. Experimental measurements which directly measure τ_w, for example [3] [4], have largely focused on the high-*Re* regime where the wake profile has already become self-similar, as is visible in Fig. 1(b). The present DNS, whose reliable range spans $1200 \lessapprox Re_{\theta i} \lessapprox 5600$, covers the establishment of outer-layer self-similarity, a fundamentally important stage in the intermediate development of a turbulent boundary layer. Results indicate a relatively abrupt change in the progression of c_f vs $\ln(Re)$, coincident with the end of steady relative wake growth in the low-*Re* regime and the onset of self-similarity in the outer layer. Detailed analysis regarding the *Re*-dependence the mean flow field will be presented.

[*]Institute of Aerodynamics and Gas Dynamics, University of Stuttgart, Germany
[†]Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Italy
[1]Smits et al., *Journal of Ship Research* **27**, 147-157 (1983)
[2]Nagib et al., *Philosophical Transactions of the Royal Society A* **365**, 755-770 (2007)
[3]Österlund, *Physics of Fluids* **12**, 1-4 (2000)
[4]Nagib et al., *IUTAM Symposium on One Hundred Years of Boundary Layer Research*, 383-394 (2004)
[5]Sillero et al., *Physics of Fluids* **25**, 105102 (2013)
[6]Schlatter et al., *Journal of Fluid Mechanics* **659**, 116-126 (2010)