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Leveraging Scale-interaction: Two-scale Approach to Turbulent Flow and Heat Transfer over Smooth and Micro-structured Wall

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Extended Abstract

A general issue of interest for wall bounded turbulent flow is how the inner near-wall and outer flow regions may influence/interact physically, and should be dealt with computationally. A focal area is the near wall-region, responsible for the drastic rise in computational cost at a high Reynolds number, manifested by the strong mesh count-Reynolds number scaling for DNS/Wall-resolved LES. A prevalent wisdom in the past has been that the near-wall be dominated by a self-sustained autonomous dynamic 'universal' behaviour. Thus, it should be amendable to a more generally applicable modelling treatment, which has served as a strong motivation for the Wall-modelled LES (notably DES) development. Remarkably however, recent findings on the Reynolds-number-dependent behaviour of near-wall turbulence in terms of the 'foot-printing' and 'modulation' originated from outer flow large-scale coherent structures have raised significant further challenges, hence call for new/alternative modelling and method development for general wall-bounded turbulence.

For a non-smooth wall, flow velocities in outer-flow regions can be reasonably well correlated to a general similarity profile for smooth and roughened surfaces (at least for cases of relatively low roughness). The near-wall flow and the main scaling parameters are however shown to depend on detailed roughness geometries. Comprehensive understanding of how roughness affects the boundary layer aerothermal performance is still lacking, particularly for relatively large scale roughness. Enhanced prediction of surface micro-structures is also motivated by the potential performance gains with manufacturable 'regular roughness' (e.g. by the rapidly developing Additive Manufacturing/3D Printing). For micro-structured surfaces, it has been shown that detailed shape and pattern of micro-structure elements can considerably affect the aerothermal performance. Given the background, there is a general need to develop methods to resolve detailed inner region flow dynamics over smooth or micro-structured wall surfaces under the influence of or interaction with the large-scale outer flow structures. The basic question then arises: how can we afford resolving both near-wall micro-scale dynamics and capturing large-scale outer-flow disturbances with strong history effect of the main domain scale at the same time?

We address the challenge by adopting a two-scale solution strategy. The starting point is to recognise the common conflict between Local resolution and Global conditioning. In general, we can easily solve a small local fine-mesh domain, but this local fine-mesh solution would be of little use due to its poor conditioning (unknown surrounding/BC). On the other hand, we can easily solve a global-domain of coarse mesh, but the global coarse-mesh solution would also be of little use due to its poor resolution. The primary intent of the strategy is to harness the scale interaction by facilitating the two domains/scales to correct each other interactively during a solution process. The final target of a converged solution to the coupled system should lead to both a better conditioned local-domain solution on the one hand, and a better resolved global domain solution on the other hand. The global-local scale-interaction is enacted by two key enablers: a) source terms generated simply and efficiently by a space-time averaged local fine-mesh solution, and b) the block-spectral mapping of those source terms to the global domain. The framework methodology is proposed by He (Intl J. Numer. Meth. Fluids, Vol. 86, 2018, https://doi.org/10.1002/fld.4472). It is examined for canonical channel flows to provide general and fundamental underpinning by Chen & He (J. Fluid Mech. 933, A47, 2022, https://doi.org/10.1017/jfm.2021.1075), and for tripped turbulent boundary layers by Chen & He (J. Fluid Mech. 955, A5, 2023, https://doi.org/10.1017/jfm.2022.1024). The two-scale methodology is also extended to fluid-solid coupled conjugate heat transfer for micro-structured surface by He (Intl J. Numer. Meth. Fluids, 2023, https://doi.org/10.1002/fld.5190). The rationale, validity and effectiveness of the approach will be further underlined in the talk.