

PROCEEDINGS

Universality of the Inner-Outer Interaction Model and Its Connections to the Attached-Eddy Hypothesis

Justin E. Ka Ip Sun¹ and Lin Fu^{1,2,*}¹Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR, China²Department of Mathematics, The Hong Kong University of Science and Technology, Hong Kong SAR, China

*Corresponding Author: Lin Fu. Email: linfu@ust.hk

ABSTRACT

The inner-outer interaction model (IOIM), first proposed by Marusic et al. [1], based on the amplitude modulation mechanism, has proven to be a successful turbulence model for canonical and non-canonical flows, where a reference velocity signal from the logarithmic region acts as the input for predicting near-wall velocity fluctuations below the reference location. Its most recent iteration by Baars et al. [2] further proposes a user-independent scale separation point, refining model parameters. The IOIM model has been used extensively in various applications, where its framework and amplitude modulation mechanism have been validated in other types of turbulent flows other than canonical wall-bounded flows, such as free-stream turbulence, turbulent flows with different wall conditions, and different driving pressures. Yet, a holistic study on the universality of the framework across incompressible and compressible flow, which is vital for understanding the differences between the flow regimes and for future modelling, has not been conducted.

In this study, we compared the IOIM's parameters, including the linear transfer kernel, amplitude modulation coefficients, and the universal signal for a range of Reynolds and Mach numbers ($140 \leq Re_\tau \leq 2003$, $0.8 \leq Ma_b \leq 3$), where mathematical relationships between the parameters are quantified. We observed that while the universal signal is indeed universal, the amplitude modulation coefficients (Γ) and linear transfer kernels (\widetilde{H}_L) display Reynolds and Mach number effects, where varying the reference location also causes Γ and \widetilde{H}_L to exhibit significant changes. These quantitative variations of the parameters correspond well to the physical structures from the attached eddy hypothesis (AEH), consistent with previous studies for incompressible flow [3], where we find that the IOIM represents the balance between the effects of the attached and detached eddies at different locations. As the prediction signal nears the wall, the decreasing large-scale coherence between the reference and the prediction signal, due to the differing physical structures experienced at their respective locations, is compensated for by the amplitude modulation coefficients, representing the increased population of the smaller-scale attached eddies, while the near-wall viscous detached eddies are captured by the universal signal.

With this physical perspective in mind, we have found transformations to collapse Γ profiles for incompressible flows and differing reference locations, further asserting the profound robustness of the IOIM framework and its connections to the AEH, despite the differences in model parameters and flow settings.



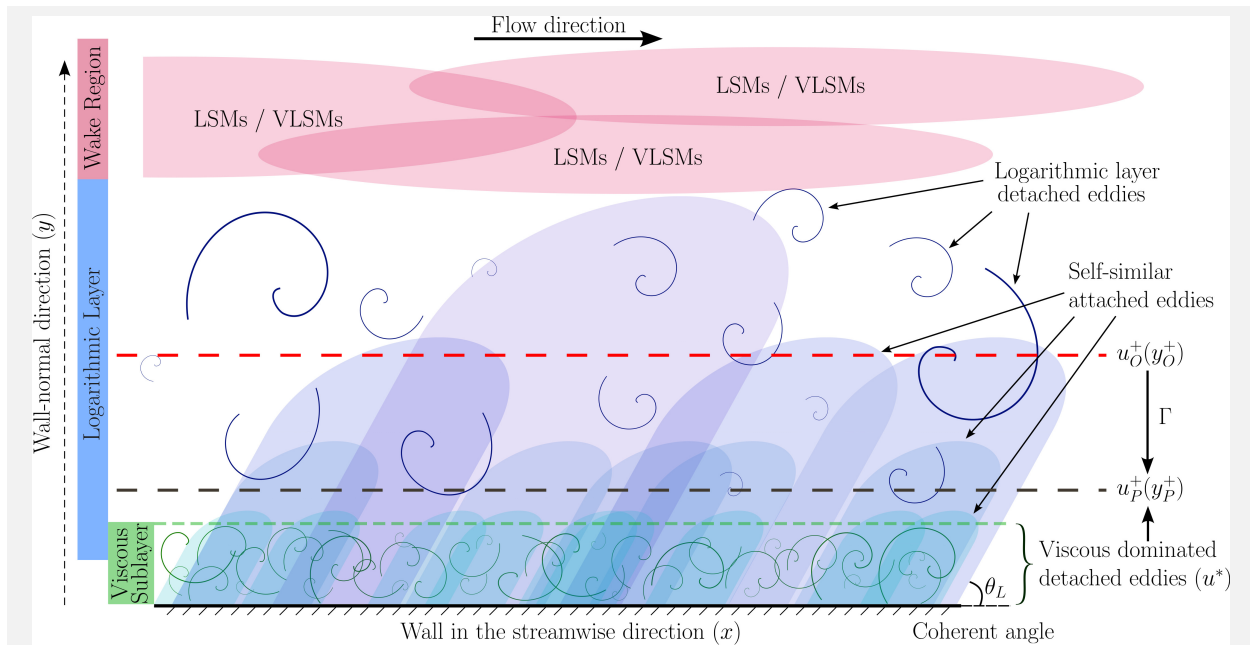


Figure 1: An illustration of the turbulent structures within wall-bounded turbulence based on the AEH, not to physical scale. The red dashed line indicates the reference layer within the IOIM framework, where the know velocity $u_0^+(y_0^+)$ lies. Large-Scale Motions / Very Large-Motions (LSMs / VLSMs) are shown to be detached from the wall for illustration purposes, but they may extend well into the logarithmic layer and influence the near-wall region. The known velocity signal is then used to predict $u_p^+(y_p^+)$ for $0 < y_p^+ < y_0^+$ based on Γ and the universal signal, u^* .

KEYWORDS

Turbulence modelling; turbulent boundary layers; boundary layer structure; compressible boundary layers

Acknowledgement: The authors are grateful for the data provided by Baars.

Funding Statement: This work was supported by the National Natural Science Foundation of China (No. 12422210). Justin E. Ka Ip Sun gratefully acknowledges the Hong Kong PhD Fellowship Scheme funded by the Research Grants Council (RGC) of the Hong Kong Special Administrative Region (HKSAR) Government (No. PF22-79233). Lin Fu also acknowledges the fund from the RGC of the HKSAR Government with RGC/ECS Project (No. 26200222), RGC/GRF Project (No. 16201023), RGC/STG Project (No. STG2/E-605/23-N) and RGC/TRS Project (No. T22-607/24N), and the fund from Guangdong Basic and Applied Basic Research Foundation (No. 2024A1515011798).

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

References

1. Marusic, I. Mathis, R., Hutchins, N. (2010). Predictive model for wall-bounded turbulent flow. *Science*, 329 (5988), 193–196.
2. Baars, W. J., Hutchins, N. Marusic, I. (2016). Spectral stochastic estimation of high-Reynolds-number wall-bounded turbulence for a refined inner-outer interaction model. *Physical Review Fluids*, 1 (5), 054406.
3. Cheng, C., & Fu, L. (2022). Consistency between the attached-eddy model and the inner–outer interaction model: a study of streamwise wall-shear stress fluctuations in a turbulent channel flow. *Journal of Fluid Mechanics*, 942, R9.