Data-driven tools for interpretation of roughness effects on turbulent flows

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ABSTRACT

Recent advancements in data-driven modeling provide cost-effective promising alternatives to fully-resolved DNS for predicting the impact of surface roughness on turbulent flows. Yang et al. (2023) introduced a model with 5–10% accuracy in estimating velocity profile shifts using geometric descriptors, such as the probability density function and power spectrum of roughness. However, this model operates as a "black-box", limiting insight into the underlying physical mechanisms. Here, we present two methods to connect predictive modeling to the physical understanding of roughness effects.

Firstly, we employ layer-wise relevance propagation (LRP) on the base prediction model to investigate the contribution of specific roughness scales to drag in turbulent flows. This approach identifies drag-relevant scales based on the spectral content of roughness. Consistent with existing literature, our analysis reveals that larger wavelengths contribute minimally to drag, as indicated by their negative relevance scores in the model. We validate these findings through DNS of high-pass filtered roughness samples, confirming that large-scale components have little impact on drag. These results demonstrate that only specific spectral ranges of roughness influence the skin-friction coefficient, providing a data-driven framework for optimizing roughness analysis and determining whether particular roughness samples significantly affect turbulent flow.

Secondly, we utilize symbolic regression to distill the base prediction model into interpretable mathematical expressions, similar to well-known roughness correlations. This approach translates the predictive capabilities of the neural network into symbolic forms, linking roughness characteristics to drag and thermohydraulic properties through well-known statistical parameters like skewness Sk or effective slope ES. The newly derived correlation demonstrates superior performance compared to existing empirical correlations in the literature, achieving a favorable coefficient of determination R^2 while maintaining robust predictive accuracy across diverse datasets (Dalpke et al. 2025). By preserving predictive accuracy while enhancing interpretability, these expressions bridge the gap between data-driven predictions and physical understanding, offering a valuable tool for engineering applications.

References

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