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Generalized Synthetic Inflow Turbulence Generation Method for LES and DNS of Divergence-Free Inhomogeneous Turbulence

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ABSTRACT

A generalized synthetic inflow (GSI) turbulence generation method is proposed in this study for divergence-free inlet boundary conditions where the flow properties can be inhomogeneous in space. The GSI [1] describes the turbulence with eigenmodes of spatiotemporal covariance of velocity fluctuations in the inhomogeneous directions to guarantee the orthogonality of the synthesizing bases, which is crucial to the preservation of the target spectral properties. To meet the solenoidal condition, the divergence is first minimized in the sense of integrated variance at the inlet boundary while keeping the spectral properties unchanged by optimizing the phases of the eigenmodes. Then, the divergence is eliminated by minimally adjusting the velocity by solving a quadratic programming problem. In cases where detailed spatiotemporal covariance is unavailable for the GSI framework, the targeted Reynolds-stress and length-scale (TRL) model is proposed, which reconstructs the covariance of the flow field with targeted Reynolds stress and length scales. The GSI framework is then validated in both idealized homogeneous turbulence with various settings of prescribed statistics and the turbulent boundary layer (TBL) with strong inhomogeneity and anisotropy. From Fig. 1, the GSI with matched boundaries significantly reduces the divergence, indicated by pressure fluctuations, at the inlet. Compared to existing synthetic methods [2,3], GSI demonstrates robust performance in reproducing the targeted turbulence properties at the inlet on the premise of the divergence-free condition and preserving downstream turbulence spectral properties in large-eddy simulation (LES).

Further, the GSI is validated in direct numerical simulation (DNS) of TBL. With either actual or TRL-modeled covariance, the GSI requires a recovery length of around 10 times the boundary-layer thickness at the inlet plane, which is less than half of that achieved with the tested recycling-rescaling-based method (denoted as LWS) [4], as in Fig. 2. Here, GSI-C and GSI-L denote GSI informed by the actual and TRL-modeled covariance, respectively. From the instantaneous streamwise velocity at $y^+ = 15$ (shown in Fig. 3), the flow fields generated by GSI quickly recover the reference values from DNS of the transition-to-turbulence case. This underscores the potential of the GSI framework for fundamental research and engineering applications in wall-bounded turbulent flows. The implementation of the GSI in generating the inflow turbulence of wall-bounded turbulence is available for download at https://github.com/LMNS3d/GSI.

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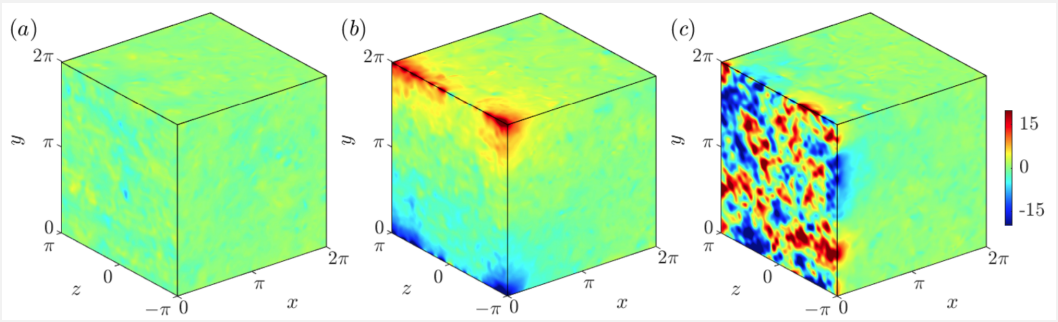


Fig. 1. Pressure fluctuation in the computational domain with inflow turbulence generated by GSI with matched boundaries (*a*), GSI with mismatched boundaries (*b*), and SFG without divergence-free treatments (*c*).

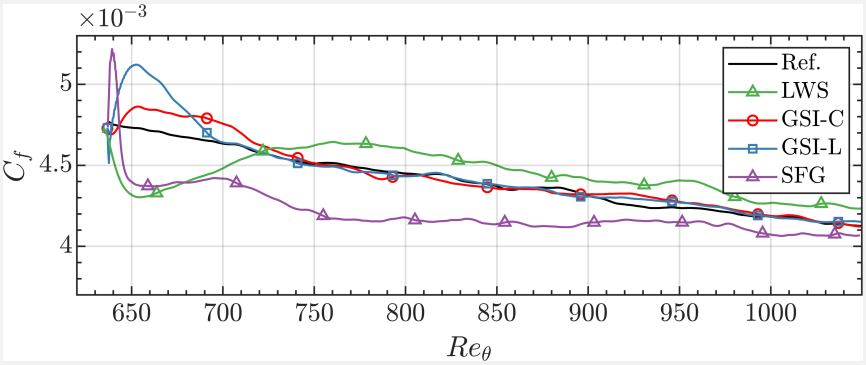


Fig. 2. Developments of the skin-friction coefficient C_f.

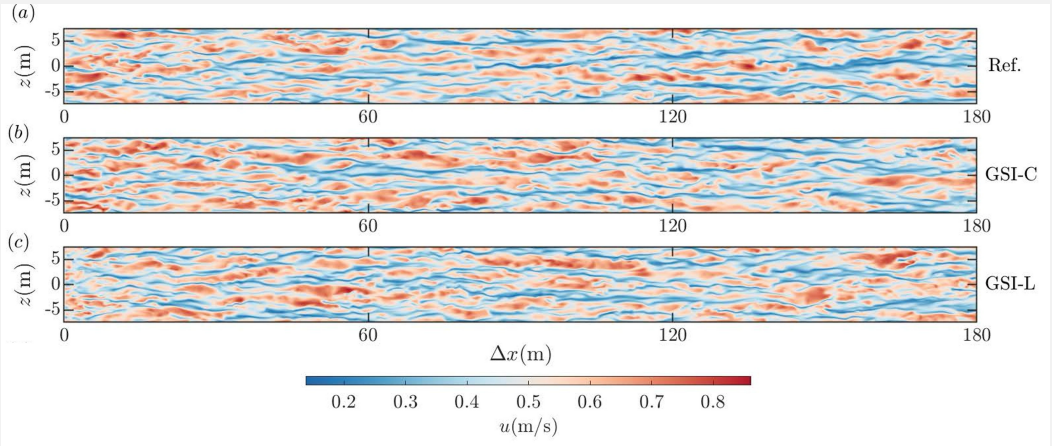


Fig. 3. Instantaneous streamwise velocity distributions at $y^+ = 15$.

KEYWORDS

Inflow turbulence generation; wall-bounded turbulence; large-eddy simulation; direct numerical simulation

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

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