Mechanical Engineering Doctoral Defense

Wavelet Multi-resolution Analysis of Turbulence

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Abstract

In the first chapter of the study, wavelet multiresolution analysis (WMRA) is extended to describe inter-phase, cross-scale interactions involving turbulence kinetic energy (TKE) of particle-laden turbulence. Homogeneous isotropic turbulence suspended with inertial particles at the Stokes number of unity is analyzed. Effects of the two-way coupling on spectral TKE transfer are examined.
Particle concentration alone does not indicate a definite direction of inter-phase energy transfer. Rather, particle clusters behave as an energy source or sink with similar probabilities. In addition, the joint statistics show the qualitative consistency of the subgrid-scale (SGS) Stokes number in describing the two-way interactions, which should be considered in the SGS modeling of two-way coupled particle-laden turbulence.

In the second chapter, direct numerical simulation (DNS) of viscoelastic turbulent channel flow is conducted and the resulting velocity field is analyzed using the WMRA to identify the drag reduction mechanism by polymer additives. At the friction Reynolds number of 145 and the Weissenberg number $Wi = 40$, the DNS of a viscoelastic channel flow is performed using the finitely extensible nonlinear elastic model. In-plane WMRA is performed to investigate the modulation of TKE due to interactions between polymer solution and turbulence across different scales. A formulation is proposed to evaluate the effects of polymers on the spectral TKE transfer. Using joint probability analysis, it has been shown that polymers absorb TKE from the near-wall region and store it as elastic energy at $y+ < 20$, while they enhance TKE in the log layer.

Ultimately, this study introduces a framework for optimizing large-eddy simulation (LES) models via WMRA. By employing the spectrally and spatially localized decomposition of wavelets, an optimal balance between resolved inter-scale energy transfer and modeled SGS dissipation is enforced across a range of nominal LES grid widths. This formulation either determines a constant for the SGS model or offers an analytical expression for SGS closure that maximizes spectral energy transfer between resolved and unresolved scales at a specific cutoff scale. This proposed approach is assessed in the context of incompressible HIT. The constant of the one-parameter Smagorinsky closure model is optimized to align with the theoretical predictions.

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