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DNS of Turbulence-Wave Interaction and Physical Insights to SGS Modeling for LES

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ABSTRACT

We perform direction numerical simulation (DNS) of wave-turbulence interaction to investigate the underlying physics for subgrid-scale (SGS) modeling for large-eddy simulation (LES) of free-surface turbulence. Two canonical problems are set up. The first is turbulence generated in the water interacting with the free surface and surface waves. With a random force linearly proportional to local velocity fluctuations in physical space (Lundgren 2003; Rosales & Meneveau 2005), nearly isotropic turbulence is generated in the bulk flow to mimic grid turbulence below a free surface. The turbulence then diffuses to the near-surface region to interact with the free surface. We further add dominant waves generated by a surface pressure, of which the distribution is given by solutions to the Cauchy-Poisson problem of surface waves (Mei, Stiassnie and Yue 2005). The second problem is turbulent Couette flow over wavy surfaces to mimic wind-wave interactions. For both problems, a projection method with a moving boundary-fitted grid is employed to solve the Navier-Stokes equations with high accuracy.

Utilizing the extensive DNS data, we investigate the underlying mechanism of wave-turbulence interaction to obtain the physical basis necessary for turbulence modeling. It is found that on the water side, the turbulence is largely affected by the strain and destrain cycle of the water wave, and the surface boundary layer imposes unique kinematic and dynamic constrains on the turbulence velocity and vorticity fields. To the turbulence on the air side, the wave surface acts like a moving wall. Our numerical results verify that a dominant parameter governing the interaction of air turbulence with water waves is the wave age, which is defined as c/u^* with c being the wave phase velocity and u^* the air friction velocity. In addition, wind-induced surface drift is found to have a strong effect on air turbulence for young waves (low c/u^* values).

We perform *a priori* test to evaluate SGS models (Rogallo and Moin 1984; Lesieur and O. Métais 1996; Meneveau and Katz 2000; Sagaut 2006) in free-surface turbulence. In the test, a low-pass filter is applied to DNS data on fine grid to obtain SGS quantities on course grid. Comparison between the true SGS quantities and eddy-viscosity, similarity, and mixed SGS models at the tensor, vector, and scalar

levels are performed. It is found that the presence of a free surface poses more stringent requirement on SGS modeling. In general, correlation between the true SGS quantities and the model predictions decreases towards the air-water interface. As a result, sophisticated dynamic procedures for determining model coefficients are called for.

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