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RESEARCH ARTICLE

Supplementary Material

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1. Governing Equations and Numerical Method

The governing equations are the incompressible Navier–Stokes equations with an Arbitrary Lagrangian-Eulerian (ALE) formulation. The grid velocity is included in the convection term, which avoids the tracking of multiple reference frames for moving meshes. LES directly accounts for the large scales resolved by the spatially filtered Navier–Stokes equations, and models the small scales. The filtered Navier–Stokes equations with the ALE formulation are as follows:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u}_i \overline{u}_j - \overline{u}_i V_j) = -\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j},$$
$$\frac{\partial \overline{u}_i}{\partial x_i} = 0, \tag{1}$$

where u_i is the velocity in the inertial frame, p is the pressure, ν is the kinematic viscosity, V_j is the grid velocity, the overbar $\overline{(.)}$ denotes the spatial filter and $\tau_{ij} = \overline{u_i u_j} - \overline{u}_i \overline{u}_j$ is the sub-grid stress tensor. To model the sub-grid stress terms, the dynamic Smagorinsky model proposed by Germano et al. (1991) and modified by Lilly, D. K. (1992) is used. In addition, the Lagrangian time scale is dynamically computed based on surrogatecorrelation of the Germanoidentity error (Park & Mahesh , 2009). This approach has shown good performance for a variety of flows including a marine propeller in crashback (Verma & Mahesh , 2012).

Mahesh et al. (2004) developed an unstructured numerical algorithm for LES of complex flows that emphasizes discrete kinetic energy conservation, ensuring robustness at high Reynolds number without numerical dissipation. This method has been successful in simulating a variety of complex marine flows (Chang et al., 2008; Verma et al., 2012; Jang & Mahesh , 2013; Kumar & Mahesh , 2017, 2018). In order to address rotational motion, these previous simulations were performed with the incompressible Navier–Stokes equations being solved in a reference frame that rotates with the propulsor. To handle general, relative movement between bodies, the method used in the present computations is an unstructured overset grid method based on the above algorithm of Mahesh et al. (2004) on arbitrary overlapping and moving meshes (see Horne & Mahesh , 2019a,b). It uses an ALE method coupled to a 6 degrees of freedom rigid body equation system (6-DOF) for body motion. At boundary edges of meshes, boundary conditions are obtained by performing flow field reconstructions using overlapping meshes and geometry. This enables the use of body-fitted meshes, ensuring high resolution on the relevant geometries while saving on overall mesh size and providing increased grid generation flexibility. In addition, this method addresses the conservation challenges of overset methods through use of a volume-conservative supercell interpolation. The algorithm has been validated for a variety of problems over a range of Reynolds numbers (Horne & Mahesh , 2019a,b).

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