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Numerical Simulation of Wave Generation due to Body Motion near Free Surface

*Jifei Wang and Decheng Wan**
State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University
Shanghai, China
*Corresponding author

ABSTRACT

In this paper, a transient incompressible viscous fluid flow is considered, and the ALE (Arbitrary Lagrangian-Eulerian) moving mesh method is applied to simulate the wave generation due to body motion near the free surface. The algorithm consists of three stages in each time step: a) the incompressible Navier-Stokes equations in the ALE frame are solved by finite element method (FEM) over the whole domain, while wave absorption being considered as well; b) the fluid velocities are used for updating the positions of the free surface nodes; c) the interior nodes are moved by solving a pseudo elastic problem so as to minimize mesh distortion. With the numerical method described above, free surface flows around 2D NACA0012 hydrofoil under different Froude numbers, submerged depths and attack angles are systematically investigated, respectively.

KEY WORDS: Submerged body motion, viscous flow, free surface, ALE moving mesh technique, FEM.

INTRODUCTION

Wave generation due to body motion near the free surface has an extensive application background in ship and ocean engineering. When a submarine sails in the shallow water, it generates the surface wave. The generated wave pattern can be detected by the aircraft or satellite submarine-hunter, and reveal the trace of the submarine. Another research object is hydrofoil. The hydrofoil is commonly used for the wing-like structure mounted on struts below the hull of a variety of boats, which lifts the boat out of the water during forward motion, in order to reduce hull drag. The designers interest in drag, lift and wave pattern of the hydrofoil. This configuration has been tested experimentally by Duncan (1981) for high Reynolds numbers and modeled numerically by several authors (see Hino *et al.*, 1993, Idelsohn *et al.*, 1999, Lohner *et al.*, 1999, Onate *et al.*, 2001, and Burg *et al.*, 2002). Compared to the motion under deep-water, the flow of body's motion near free surface is more complicated, which need to consider the nonlinear interaction between wake and free surface.

One of the difficulties in accurately solving these flows is that the free surface is not known a priori, since its shape must be computed as part of the solution. There are two main approaches for the computation of free surface flows: interface capturing and interface tracking. In the interface capturing methods, an Eulerian computation mesh is employed and the moving boundaries are captured by solving a transport equation of an additional component, like a new variable or a fluid fraction. The techniques popularly adopted in the fixed grid method are volume of fluid (VOF) method and level set (LS) method. The interface capturing methods allow topological changes as breaking up or merging of the interface. However, the additional variable make the numerical method become complicated. There are also some other drawbacks for the interface capturing methods. For the VOF method, the reconstruction of the interface from the volume fractions is complicated, and computation of geometric quantities such as curvature is not straightforward. For the LS method, unresolved flows can exhibit a merger or breakup that may not be physical, which means, there is no build in volume conservation. Interface tracking methods can be purely Lagrangian, as particle methods, or they are developed as Arbitrary Lagrangian-Eulerian (ALE) approaches. The most widely used particle methods are Smoothed Particle Hydrodynamics (SPH) and Moving Particle Semi-Implicit (MPS). These methods can deal with the free surface flows straightforward. However, the particle methods are expensive in three dimensional simulations. In the ALE method, the interface is defined over grid entities such as facets or edges. Then the mesh must be deformed or regenerated in order to take into account the interface movement. The advantages of the ALE method include: a) no need to introduce additional variable, and the increased computation cost is not too much; b) the free surface is explicit, and no need to reconstruction; c) the accuracy of the free surface tracking can be guaranteed. The drawback of the ALE method is that, when the interface undergoes large deformations, involving the phenomena of breaking or overturning waves, the deformation or the regeneration of meshes becomes difficult. However, if the problem only involves small deformation wave, the ALE method is the best choice.

In this work, the transient incompressible viscous fluid flow is considered, and the ALE moving mesh method is applied to track the free surface evolution. The algorithm consists of three stages in each time step: the first one solves the incompressible viscous flow over the whole domain. In this stage, the incompressible Navier-Stokes equations in the ALE frame are discretized by finite element method (FEM) in space, the Streamline Upwind Petrov-Galerkin (SUPG) (Brooks & Hughes, 1982) and Pressure Stabilizing Petrov-Galerkin (PSPG) (Tezduyar *et al.*, 1992) strategies are used to stabilize the discretized system. Wave absorption (Gao *et al.*, 2002) is considered as well. At the second stage, the fluid velocities are used for updating the positions of the free surface nodes, based on the kinematics boundary conditions of the free surface. Free surface smoothing technique (Longuet-Higgins *et al.*, 1976) is adopted to remove the instability. At last, the interior nodes are moved by solving a pseudo elastic problem so as to minimize mesh distortion. The numerical solver is developed based on the open source library PETScFEM (Storti *et al.*, 2009), which relies on the Portable