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Chimera RANS Simulation of a Berthing DDG-51 Ship in Translational and Rotational Motions

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ABSTRACT

A Reynolds-Averaged Navier-Stokes (RANS) method has been employed in conjunction with a chimera domain decomposition technique for time-domain simulation of transient flow induced by a berthing DDG-51 ship undergoing translational and/or rotational motions. The method solves the mean flow and turbulence quantities using an arbitrary combination of embedded, overlapped or matched grids. The unsteady RANS equations were formulated in an earth-fixed reference frame and transformed into general curvilinear, moving coordinate systems. A chimera domain decomposition technique was employed to accommodate the relative motions between different grid blocks. Calculations have been performed for a DDG-51 guided missile destroyer in translational and rotational motions to demonstrate the capability of the chimera RANS approach for time-domain simulation of the ship and berthing structure interactions. The numerical solutions successfully captured many important features of the transient flow around berthing ships including the underkeel flow acceleration, separation around the bow and stern area, flow recirculation behind the ship, water cushion between the ship and harbor quaywall, and the complex interaction among bow, shoulder and stern wave systems.

INTRODUCTION

Berthing damage can result in substantial economic and operational penalties. Even in a well-executed berthing, a large ship possesses enormous kinetic energy that can seriously damage the berthing structure as well as the ship itself. Fender systems are provided at a berth to absorb the kinetic energy of the berthing ship and to mitigate impact forces. The amount of the energy to be absorbed and the maximum impact force are the prevailing criteria for fender system design. Currently, the most commonly used fender-system design methodology accounts for the influence of the ambient water with a simple constant coefficient (Lee et al., 1975; Plotkin, 1977; Keuning and Beukelman, 1979; Fontijn, 1980, 1988). In order to improve the fender-system design, it is desirable to develop a reliable and robust method for the simulation of the structural and fluid interactions among the ship, fender system and the surrounding water. The model must be able to include the effects of the fluid viscosity, underkeel clearance and free surface variations for the accurate prediction of the ship motion during typical berthing operations.

Recently, the authors (Chen and Chen, 1996a, b; Chen, Chen and Davis, 1997; Chen, Chen and Huang, 1996) developed a chimera RANS method for time-domain simulation of complex free surface flow induced by 2-dimensional and 3-dimensional berthing ships undergoing simple lateral motions. The results obtained thus far clearly demonstrated the feasibility of the chimera RANS method for detailed resolution of the transient flow field induced by the ship and harbor interactions. In the present study, the method has been further generalized for time-domain simulation of a DDG-51 guided missile destroyer approaching a harbor quaywall in various combinations of translational and rotational motions.

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KEY WORDS: Chimera domain decomposition, translational motions, rotational motions, turbulent flows, free surface waves, berthing ships, underkeel clearance, water cushion.

CHIMERA RANS METHOD

In the present study, the chimera RANS method of Chen, Chen and Davis (1997) and Chen, Chen and Huang (1996) has been extended for time-domain simulation of transient flow induced by a berthing ship. In the following, we shall briefly summarize the governing equations and numerical methods for the berthing simulations.

Governing Equations

Consider the nondimensional Reynolds-Averaged Navier-Stokes equations for incompressible flow in orthogonal curvilinear coordinates $(x^i,t) = (x^1, x^2, x^3, t)$:

$$U^i_{,i} = 0 \tag{1}$$

$$\frac{\partial U^i}{\partial t} + U^j U^i_{,j} + \left(\overline{u^i u^j}\right)_{,j} + g^{ij} p_{,j} - \frac{1}{\mathrm{Re}} g^{jk} U^i_{,jk} = 0 \tag{2}$$

where U^i and u^i represent the mean and fluctuating velocity components, and g^{ij} is the conjugate metric tensor. t is time, p is pressure, and $Re = U_o L/\nu$ is the Reynolds number based on a characteristic length L, a reference velocity U_o, and the kinematic viscosity ν. Eq. 1 represents the continuity equation, and Eq. 2 represents the mean momentum equation. The equations are written in tensor notation with the usual summation convention assumed. The subscripts, $_{,j}$ and $_{,jk}$, represent the covariant derivatives.

In the present study, the two-layer turbulence model of Chen and Patel (1988) is employed to provide closure for the Reynolds stress tensor $\overline{u^i u^j}$. In this approach, the Reynolds stresses are related to the corresponding mean rate of strain through an isotropic eddy viscosity ν_t:

$$-\overline{u^i u^j} = 2\nu_t S^{ij} - \frac{2}{3} g^{ij} k \tag{3}$$