A linearized free-surface RANS method for unsteady ship maneuvering problems

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Highlights

- The unsteady linearized free-surface condition is implemented within a numerical framework based on the Reynolds-Averaged Navier-Stokes equations. The target application for the novel solver is the simulation of ship maneuvering, and in particular, cases in which the fluid viscosity and turbulence are important and the rudders and propellers are moving.
- The method is more computationally efficient than viscous-flow methods that satisfy the fully-nonlinear free-surface conditions and is computationally equivalent to a numerical method that solves for a velocity potential via discretization of the flow domain (not the domain boundary).
- The new solver is validated by comparing with results from other numerical methods and physical experiments of the waves generated by a heaving catamaran, and the force on the hull of the naval destroyer 5415 moving with prescribed horizontal-plane motion.

Introduction

This paper discusses the pursuit of simulating the unsteady Reynolds-Average Navier-Stokes (URANS) equations for problems in which ship-wave interaction and fluid turbulence are both important. The primary engineering problem of interest is the prediction of the trajectory of a maneuvering ship, although many other related problems are well suited for analysis with the proposed method, such as ship seakeeping and powering predictions. The key idea of the method is that state-of-the-art URANS technology can be employed together with the linearized free-surface conditions to produce a computational tool that is both accurate and efficient such that the results can be useful within the time constraints of the ship design process.

Prediction of ship maneuvering is challenging due to the complex relationship between the ship motion and the unsteady manner in which the flow separates (forms a recirculation region) from the body. The physical process of viscous separation is influenced by the wave system generated by the ship, and has a substantial role on the flow seen by the propeller and rudder. Thus it is necessary to consider the effects of viscosity and turbulence for accurate prediction of ship maneuvering. Indeed, methods that neglect viscosity are severely challenged to predict the force, moment, and trajectory of the ship in a general maneuver. While URANS methods are capable of simulating maneuvering flows, the computational expense of solving the URANS equations with the fully nonlinear free-surface boundary conditions is very large, and their use is limited to academic or research applications [5], and not widely used for industrial benefit. Indeed, the objective of this work is to substantially reduce the computational burden, by simplifying the algorithm with respect to the free-surface solution, so that RANS-based maneuvering simulations can be brought into engineering practice more immediately.

Two problems are studied in this abstract to motivate our approach. The first is the prediction of the unsteady wave generated by a heaving catamaran. This problem has been studied experimentally and numerically by several authors [1, 2, 3]. Although turbulence is not necessarily important for the model tests, the resonance behavior of the wave system can be grossly overpredicted by methods that do not rationally account for the dissipation and transport of energy away from the body. Furthermore, using this problem, the novel URANS approach is compared to a method in which the linearized problem is solved in terms of a velocity potential. This grants the opportunity to directly compare computational expense of each approach. It is shown that the costs are very similar between the two methods. Although the URANS approach has more than three unknowns (in two spatial dimensions), the bulk of the expense is due to the solution of the pressure variable that is governed by a partial differential equation that is elliptic in nature, just like the governing equation of the velocity potential. This implies that for problems in which viscosity and turbulence play an important role, a breakthrough in accuracy is available for the small incease in expense due to the addition of the primitive RANS variables.

The second problem studied in this abstract is the prediction of the force on the naval destroyer hull form DTMB 5415 that is undergoing prescribed horizontal-plane motion. In this problem, the turbulent-boundary layer on the body interacts with the unsteady-ship-generated wave system. Model-test results are available for a setup in which the hull is fitted with bilge keels, but otherwise unappended. Compared to fully nonlinear viscous flow methods, the linearized free-surface approach offers an extreme advantage in terms of the computational requirements. The novel method is more efficient for several reasons. First, the domain is inherently smaller since only the water portion is discretized. Second, the need for highly-resolved cells to capture or track an interface is eliminated. Instead, relatively large cells can be used, especially far from a body, while still accurately resolving the first-order wave field.

Numerical Approach

All problems are solved in a *earth-fixed* Cartesian coordinate system, with z oriented upwards. The linearized flow domain is below $z = 0$. The governing equations are solved using the finite-volume method on a discretization of the flow domain comprised of non-overlapping polyhedra of arbitrary number of sides. The kinematic condition for the free-surface elevation is solved using a finite-area method on the linearized free-surface boundary $z = 0$. The solvers used in this work are developed using the OpenFOAM open-source CFD library.

URANS The URANS equations are solved in the arbitrary-Lagrangian-Eulerian (ALE) form to allow for a moving grid. The fluid velocity in the earth-fixed coordinate is denoted $\vec{U}$, and the velocity of the mesh is $\vec{U}_{\text{mesh}}$. The relative velocity is defined as $\vec{U}_{\text{rel}} = \vec{U} - \vec{U}_{\text{mesh}}$. The free-surface elevation is represented by η. The fluid pressure is p, and the effective viscosity is the sum of the molecular and turbulent viscosities $\mu_{\text{eff}} = \mu + \mu_t$.

The conservation of momentum and mass equations are written for each computational cell that has volume V and is bounded by the surface S with outward normal $\vec{n}$.

$$\frac{d}{dt}\int_V \rho\vec{U}\ dV + \int_S \rho\vec{U}\vec{U}_{\text{rel}}\cdot\hat{n}\ dS = \int_V \left(-\nabla\ p + \rho\vec{g}\right)\ dV + \int_S \mu_{\text{eff}}\left(\nabla\vec{U} + \nabla\vec{U}^T\right)\cdot\hat{n}\ dS \quad \text{and} \quad \int_S \vec{U}\cdot\hat{n}\ dS = 0 \tag{1}$$

Two fundamental steps are taken to numerically approximate the conservation equations on each cell. The flow unknowns are interpolated from the cell centers to the cell face centers, and then the surface integrals are approximated with a mid-point quadrature rule. Both the interpolation and quadrature are second-order accurate, with upwind-biased schemes used for the interpolation of the convection term and centered schemes otherwise.

Similarly, the ALE form of the kinematic free-surface boundary condition is used to evolve the free-surface elevation η via:

$$\frac{\partial}{\partial t}\int_{S_0} \eta\ dS - \int_l \eta\vec{U}_{\text{mesh}}\cdot\hat{n}\ dl = \int_{S_0} w\ dS \quad \text{on} \quad z = 0 \tag{2}$$

where S_0 is the portion of the boundary of a computational cell that is adjacent to the plane $z = 0$, and l is the contour of this area. The pressure boundary condition is applied according to the linear dynamic free-surface boundary condition:

$$p - \rho g \eta = 0 \quad \text{on} \quad z = 0 \tag{3}$$

Field potential The velocity-potential method used in the results section solves the discretized form of the Laplacian in the field. The Laplacian solver is second-order accurate in space. In the calm-water plane, the unsteady, zero-forward speed, combined free-surface boundary condition is satisfied. This equation is discretized with a second-order backward scheme for the time term, and a one-sided, second-order scheme for the vertical gradient of the potential.

$$\frac{\partial^2\phi}{\partial t^2} = -g\frac{\partial\phi}{\partial z} \quad \text{on } z = 0 \tag{4}$$

Results

Heaving catamaran with gap resonance The problem of a heaving catamaran is studied to demonstrate the ability to accurately predict the wave motion between the hulls and in the far field for a wide range of oscillation frequency. The experiments were performed at MARINTEK in 2010 [3]. The experiments were performed in a wave flume so that the radiated wave is practically two dimensional. The flow domain is two-dimensional and comprised of rectangular cells that are clustered around the body. The body boundary condition is satisfied on the mean position of the body for both the linearized RANS and potential-flow simulations.

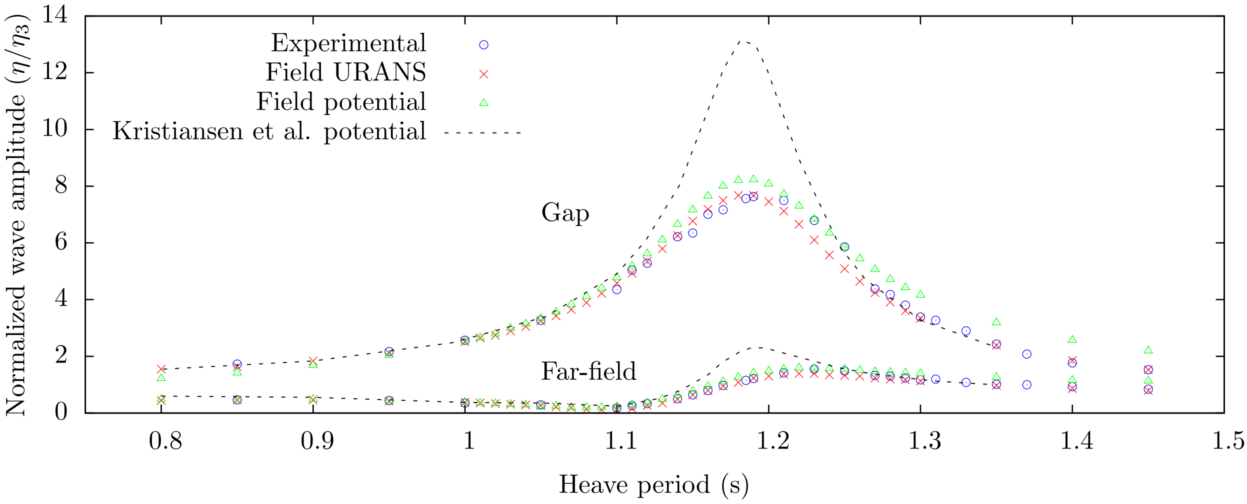

Figure 1: Wave amplitudes from heaving catamaran

A summary of the results appears in Figure 1. In this figure, two groups of data are shown, one for the wave amplitude in the gap, and another for the wave amplitude in the far-field. For each group of data, four sources of prediction are represented: the experimental measurements, the present linearized URANS, the present field potential, and potential results from [3], labeled Kristiansen et al. potential. The Kristiansen et al. potential results are said to be consistent with the linear analytical potential solution from [1].

As shown in Figure 1, the Kristiansen et al. potential results significantly overpredict the wave amplitude both in the gap and the far-field near the resonant frequency. On the other hand, the field potential only slightly over predicts the wave amplitude near resonance, with an increasing over-prediction as the oscillation period increases. The substantial improvement in the potential-flow prediction for the wave amplitude in the gap can be attributed by the fact that the second-order-accurate field discretization has a dissipative quality that is sufficient to prevent the artificial accumulation of energy in the gap between the hulls. The dissipation in the scheme depends on the grid resolution, but for the set of grids tested in our work, the results are very weakly dependent on the grid. Between the medium and fine grids, the relative error of the wave amplitude in the gap is only 0.3% for the period of 1.2 s.

The field URANS approach shows very strong agreement with the experimental measurements throughout the frequency range, and a small improvement over the field potential results. In addition, the computational time required for the field potential and linearized URANS formulations is nearly identical.

DTMB 5415 in pure yaw motion A pure yaw planar motion mechanism (PMM) test is simulated for the DTMB 5415 hull form. Experiments are included for testing done on a model of length $L = 3.048$ m [4]. The Froude number is 0.28, and length-based Reynolds number is 4.46 million. The hull is unappended with the exception of bilge keels. The hull is fixed at the dynamic sinkage and trim for both the simulation and the experiment. The sway motion has amplitude $\eta_0/L = 0.1073$ and period 7.48 s. The body-boundary condition is satisfied exactly as $\vec{U} = \vec{U}_{\text{body}}$.

Three numerical grids are used, denoted coarse, medium, and fine. The coarse grid contains about 200,000 cells, and the fine grid about 920,000 cells. Figure 2 (left) shows the discretization of the free-surface plane for the coarse grid. The posteriori calculation of the dimensionless near-wall spacing indicates the average y^+ value is 60 for the coarse grid and 40 for the fine grid. The Spalart-Allmaras turbulence model is used with a universal wall-function. The numerical simulations are performed on the parallel computer flux hosted by the University of Michigan.

Figure 2 (right) presents the time series of the yaw moment through one PMM period. The numerical results from each grid are compared to the experimental measurements. It is striking to note the manner in which the numerical results converge with refinement of the grid. This behavior is not frequently seen for fully nonlinear URANS results because it is rarely possible to use a sufficiently fine discretization such that the solution has converged. In the present case, the first-order wave system requires fewer computational cells. The first-order system has the same range of length-scales as the higher-order system, but does not permit breaking, and the simplified condition is satisfied on a known boundary, $z = 0$.

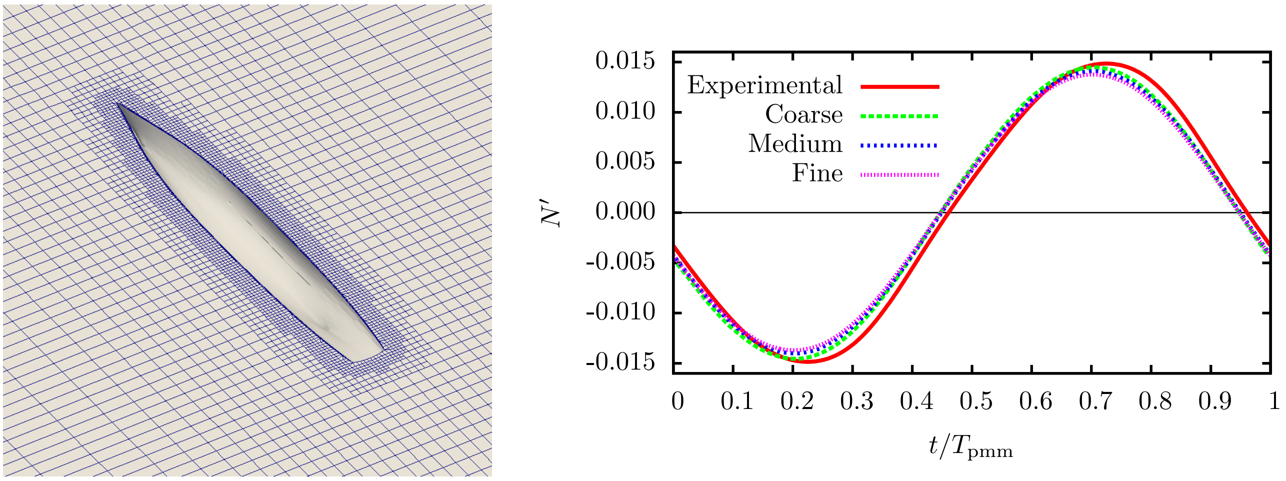

Figure 2: Coarse grid discretization (left), Yaw moment during pure yaw (right)

Also, any of the numerical results agree well with the experiment. Although not shown here, the present results are comparable to fully nonlinear URANS results [5]. Furthermore, the computational time required to perform a single PMM period ranges from 10 to 200 cpu-hours. This means that the coarse grid set-up is well-suited for desktop computing on a multi-core workstation.

Conclusions and future work

Linearized free-surface approximations provide an efficient alternative to fully nonlinear, multiphase CFD methods. While employing a simplified theory, they can produce suitably accurate results for a variety of engineering problems. Within the approach of a linearized free-surface, a URANS method is shown to be as computationally efficient as a field potential method. However, in addition to efficiency, the linearized URANS formulation benefits from the inclusion of viscous effects. Force and moment predictions are shown to compare well with experimental data. This technology has been expanded to include rotating propellers for prescribed motion simulations. Future work includes developing the technology for self-propelled, free-running model tests by solving for the motion of the ship in the horizontal directions.

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