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Near-field flow of submarines and ships advancing in a stable stratified fluid

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ABSTRACT

A methodology is presented to predict density stratified flows in the near-field of naval vessels. The approach uses a single-phase level set method for the free surface, a dynamic overset technique to handle motions and controllers for self-propulsion and maneuvering. The density is solved with a higher-order transport equation coupled with momentum and mass conservation. Turbulence is implemented with a $k-\varepsilon/k-\omega$ based Delayed Detached Eddy Simulation (DDES) approach modified to add density gradients. Evaluation tests were performed for a two-dimensional square cavity, including grid and time step studies, and the stratified flow past a sphere, showing good agreement with available data. The stratified flow was studied for a self-propelled ship and a submarine. Density, velocity, pressure and turbulent quantities at the exit plane of the near-field contain a description of the relevant scales of the flow and can be used to compute the far-field stratified flow. It is shown that, as is the case of surface waves, the generation of internal waves requires energy that results in an increase in resistance. Moreover, the presence of a density interface against the hull results in a thickening of the boundary layer, just as in a solid/free surface juncture flow.

1. Introduction

Stratification in the ocean occurs as a result of changes in salinity, temperature or sediment concentration, leading to horizontal or vertical fluid density variations. Just as surface waves can appear at the interface between two fluids, sustained periodic motions known as internal waves can appear under disturbances on stable stratified conditions. Stable stratification in the ocean can be disrupted by different natural processes including breaking waves, wind, Coriolis forces and tides, resulting in flows of interest in oceanography; the passage of a body, such as a surface ship or a submarine, can have a similar effect. The study of stratified flow problems is strongly scale-dependent: for the current application of flow in the near-field of a ship (defined as the region immediately close to the vessel, where all flow scales down to the boundary layer scales are relevant), perturbations to a horizontally uniform, stable vertical density profile will be considered.

The motion of ships and submarines in stratified media is a problem of importance and the focus of this paper. A surface ship or an underwater vehicle advancing in a stratified fluid generates complex flow structures, which in the far-field are characterized by internal waves in the bulk flow. These internal waves can be used to detect vessels: for instance, they can be observed using remote sensing devices (Watson et al., 1992; Jackson et al., 2013). Features of the oceanic stratification, such as the presence of a strong pycnocline (defined as a region where the density changes rapidly with depth separating the well mixed surface layer from the denser deeper layer), can also be used to avoid detection, and for this reason submarines often operate below the pycnocline surface, which can disrupt the acoustic signals of sonars. While the effects of stratification on resistance and propulsion can be strong for extreme conditions, as is the case of dead-water (Miloh et al., 1993), the main focus of the present study of stratification is the generation of wakes and signature effects. There is a considerable difference in scales between the near-field flow, which is restricted to the region around the vessel, and the far-field flow, where the internal waves are important at normal ship operational conditions. The near-field flow is produced by the direct interaction of the stable stratified flow in the ocean with the advancing vessel, while the far-field is the evolution of the downstream signature of that interaction. To a very good approximation the near-field and far-field computations can be decoupled, since the far-field flow has little effect on the near-field and can use information from the near-field calculation as input to predict the evolution of the internal waves away from the vessel. This paper focuses on a methodology to predict the near-field density stratified flows of ships and submarines, and the study of such flows for self-propelled vessels.

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Available numerical and experimental studies for interaction of bodies and stratified fluids have focused on simple geometries such as spheres and cylinders at low and moderate Reynolds numbers typical of a laboratory setup. Some of these results will be discussed in the following sections as evaluation tests for the present implementation of the computational fluid dynamics (CFD) solver. In the following paragraphs a brief description of the available data is presented.

Boyer et al. (1989) investigated the flow of a linearly stratified fluid past a long circular cylinder in a channel through a series of experiments. Results were presented for various Reynolds (*Re*) and internal Froude (*Fi*) numbers and fluid depth ratios covering a wide range of flow regimes. Note that the internal Froude number, which is relevant for internal waves, relates to the standard free surface wave Froude number by $Fi = Fr\sqrt{\frac{\rho_0}{\Delta\rho}}$, with $Fr = U_0/\sqrt{gL_0}$. A similar experimental study was conducted by Lin et al. (1992a, 1992b) for the stratified flow past a sphere and different flow patterns were mapped on a detailed *Re* versus *Fi* flow regime diagram. Bonneton et al. (1993) presented an experimental investigation related to the internal gravity wave field generated by a sphere towed in a stratified fluid. A fluorescent dye technique was used to show the difference between lee waves generated by internal waves and random waves generated by turbulence from the wake. Spedding et al. (1996) showed the complex effects of stratification on the far-field wake of a sphere, observing that even though the vertical velocity is much smaller than the horizontal one, the wake scaling corresponds better to an axisymmetric, unstratified wake than to a planar wake. Meunier and Spedding (2004) examined the effect of body geometry on the intermediate and late wake structure in a stratified fluid at moderately high *Fi* by comparing the wakes of various bluff bodies. It was observed that the size and amplitude of the long-lasting wakes strongly depend on the body geometry. Meunier and Spedding (2006) investigated the wake of a bluff body in three configurations: momentum-excess, zero-momentum, and zero-momentum with a slight angle of attack, finding that the coherent structures in the wake were different for all three cases. Brucker and Sarkar (2010) used direct numerical simulation (DNS) to study towed sphere and self-propelled spheroid wakes at $Re = 50{,}000$. The authors compared the mean velocity and observed that in the self-propelled case, due to the higher shear, the mean velocity decayed more rapidly than for the towed case, resulting in a faster rate of energy transfer to turbulence. Using the same simulation, de Stadler et al. (2010) studied the turbulent wake behind an accelerating self-propelled axisymmetric body in a stratified environment. To create the acceleration for studying the effects of excess momentum on the initially momentumless self-propelled wake, a velocity profile corresponding to net thrust was added to the self-propelled velocity which resulted in small and moderate excess momentums. The study shows that parameters such as wake width, mean kinetic energy and defect velocity depend on amount and shape of this excess momentum. Also, the turbulent kinetic energy (TKE) and the dissipation rate increase as the shear in the mean profile increases.

Some efforts studying the effects of density stratification on surface ship waves are available in the literature; in general these efforts are geared towards a description of the far-field rather than the accurate prediction of the interaction between the ship and the stratification field. Earlier works by Hudimac (1961) and Crapper (1967) presented analytical approaches to study the internal wave modes caused by a moving body in a two-layered ocean. It follows from their work that, just as for surface waves, at ship speeds sufficiently larger than the internal wave speed only divergent waves travel downstream of the ship, while both divergent and transverse waves are present for slower vessels. Tulin et al. (2000) suggested a nonlinear theory to capture internal wave behavior at high *Fi* in weakly stratified flow that compared satisfactorily with available experimental results for a semi-submerged spheroid. Chang et al. (2006) presented one of the few available examples of CFD computation for a vessel in a stratified medium. They computed the generated internal and surface waves of the notional DARPA Suboff submarine advancing in a two-layer fluid, for different Froude numbers, and found the evolution of the wave pattern consistent with previous predictions.

In this work the evolution of the stratified flow in the near-field of a surface ship and a submarine is studied. The description of the vessels' geometry includes their moving control surfaces and propellers, resulting in localized intense mixing absent in previous calculations of this type of problem. Specific implementations to the CFD code to address variable density effects in momentum transport and turbulence modeling are discussed. Evaluation of the implementation is discussed for a two-dimensional square cavity and the three-dimensional stratified flow past a sphere. Finally, demonstration cases for the surface ship Athena R/V and the notional submarine Joubert operating near the surface in a stably stratified fluid are presented.

2. Modeling

Variable density capabilities were incorporated to REX, a URANS code with DES/DDES capabilities, specifically designed for naval applications. As opposed to the more limited Boussinesq approximation, where body forces caused by density variations are accounted for but all other effects of density are neglected, variable density effects are fully incorporated into the conservation equations. The incompressibility assumption for the fluid is preserved since density changes are only due to external parameters (temperature, salinity, sediments) and not to pressure. The implementation also includes modifications to the turbulence model to take into account the effects of stratification on TKE production. The model consists of a scalar transport equation for the density, changes in the definition of the piezometric pressure to maintain a zero piezometric pressure in the far field and free surface, and modifications to the turbulence model to account for turbulence generation or suppression by density gradients. For density changes caused by variations in salinity or temperature, in which the water remains incompressible (meaning that pressure changes do not affect density), most terms needed are accounted for, including density changes in the momentum and continuity equations, but at this time the viscosity is still considered constant. Future work will include viscosity change effects too, though viscosity changes with the salinity and temperature variations in the ocean are small, and for most applications can be neglected. The scalar transport is standard and follows the same numerical methodologies as the momentum transport, and the turbulence treatment is taken from Yeoh and Tu (2010) and Venayagamoorthy et al. (2003).

A brief summary of the governing equations and their implementation is presented next.

2.1. Governing equations

The dimensionless Navier–Stokes conservation equations governing the stratified flow are expressed as:

$$\frac{\partial}{\partial t}\left(\tilde{\rho}RiFr^2\right)+\nabla.\left(\left(1+\tilde{\rho}RiFr^2\right)\mathbf{u}\right)=0 \tag{1}$$