Computational Analysis of Sphere Wakes in a Linearly Stratified Fluid

Liushuai Cao1, Fenglai Huang1, Decheng Wan1*, Qing Xiao2

1 Computational Marine Hydrodynamics Lab (CMHL), State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai, China
2 Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, UK
*Corresponding author

ABSTRACT

The motion and turbulent wake characteristics of underwater vehicles in stratified fluid is of great importance and not yet fully understood. In this work, a methodology is proposed to predict density stratified flows and wakes past a sphere. The density difference is set based on the thermal stratification background, turbulence is implemented with a Shear Stress Transport (SST) based Delayed Detached Eddy Simulation (DDES) approach. Two kind of simulations are performed in both non-stratified and stratified conditions. Drag force, wakes as well as coherent vortex structures are studied to assess the influences of the stratification. Results show that internal waves are generated by the presence of the sphere in stratified fluid, which results in an increase in resistance. The vertical motions and vortices are suppressed due to the stratification in vertical direction compared to that of horizontal plane.

KEY WORDS: Stratified fluid; density stratification; thermal stratification; sphere; DDES; wakes

INTRODUCTION

The research of wakes induced by the motion of three-dimensional blunt bodies through homogenous fluid has been of long-standing interest to the marine industry. As a canonical case, the sphere geometry draws obvious attention for validation of numerical methods due to its wide applicability and simplicity. Plenty of researchers have predicted its hydrodynamic performance in homogenous flow, special focus has been devoted to flow separation and evolution (Son, Choi, Jeon and Choi, 2010), the Reynolds number effect on wakes (Ploumhans, Winckelmans, Salmon, Leonard and Warren, 2002), and validation for innovative numerical methods (Bassi, Botti, Colombo, Crivellini, Ghidoni and Massa, 2015).

It is well known that stratification exists extensively in underwater environment of oceans, where naval vessels are commonly operated. On the other hand, most of the fundamental researches on flow field characteristics of moving bodies have neglected the stratification effects. According to the early experiments by Lin and Pao (1979) of a grid, a two-dimensional body and an axisymmetric body in stratified fluids, density stratification would induce changes in the flow such as the generation of internal gravity waves, the alteration in the level and distribution of turbulent wakes and fluctuations, and the appearance of coherent vortex structures. Spedding (2014) showed that bluff-body wakes in stably environments have an unusual degree of coherence and organization, such as arrays of alternating-signed vortices have very long lifetimes, as measured in units of buoyancy timescales, or in the distance scaled by a body length.

Initially, most of the works that intent to study the development of bluff-body generated turbulent wakes in stably stratified fluids were conducted experimentally by towing spheres horizontally through a linear density gradient background, created by continuously varying the concentration of dissolved salt in a stationary tow tank. Examples of these experimental studies are provided by Afanasyev (2004), Bonneton, Chomaz and Hopfinger (1993), Chomaz, Bonneton and Hopfinger (1993), Lin, Lindberg, Boyer and Fernando (1992), Meunier and Spedding (2006), and Spedding (1996, 1997). These experiments systematically investigated the effects of the tow speed, the body diameter, and strength of the density gradient on the wake onset and evolution. It was concluded that the wake of a body with characteristic diameter D that moving with speed U in a stable background with buoyancy frequency N is governed by the internal Froude number, Fr, and the Reynolds number, Re

\[ Fr = \frac{U}{ND} \quad \text{Re} = \frac{UD}{\nu} \]  

(1)

where \( \nu \) is the kinematic viscosity of the ambient fluid, \( N \) is the Brunt-Vaisala frequency or buoyancy frequency, defined as follows:

\[ N = \left( -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z} \right)^{1/2} \]  

(2)

where \( g \) is the gravitational acceleration, \( \rho \) is the undisturbed density profile, \( z \) is the vertical coordinate, being positive upwards. The Brunt-Vaisala frequency can be interpreted as the oscillating frequency of a