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Large eddy simulation of free-surface flows*

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Abstract: This paper introduces and discusses numerical methods for free-surface flow simulations and applies a large eddy simulation (LES) based free-surface-resolved CFD method to a couple of flows of hydraulic engineering interest. The advantages, disadvantages and limitations of the various methods are discussed. The review prioritises interface capturing methods over interface tracking methods, as these have shown themselves to be more generally applicable to viscous flows of practical engineering interest, particularly when complex and rapidly changing surface topologies are encountered. Then, a LES solver that employs the level set method to capture free-surface deformation in 3-D flows is presented, as are results from two example calculations that concern complex low submergence turbulent flows over idealised roughness elements and bluff bodies. The results show that the method is capable of predicting very complex flows that are characterised by strong interactions between the bulk flow and the free-surface, and permits the identification of turbulent events and structures that would be very difficult to measure experimentally.

Key words: Large eddy simulation, free-surface, level set method, volume of fluid

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Prof. Thorsten Stoesser is the Director of the Hydro-environmental Research Centre at Cardiff University. His main research interest is in developing advanced CFD tools and their application to hydraulic engineering and environmental fluid mechanics problems. Thorsten has published 100+ peer reviewed journal and conference papers on developing, testing and applying advanced CFD methods to predict hydrodynamics in rivers, estuaries and coastal waters, fluid-structure interaction of hydro turbines, and the near-field dynamics of plumes and jets. He has co-authored the IAHR monograph "Large-eddy simulation in Hydraulics" and in 2012 and 2016 Dr. Stoesser received the American Society of Civil Engineers (ASCE) Karl Emil Hilgard Hydraulic Prize. In 2013, Prof. Stoesser won the International Association for Hydro-Environment Engineering and Research (IAHR) Harold Jan Shoemaker Award. His CFD group at Cardiff University currently consists of 8 Ph. D. students and 2 post-doctoral research associates, two of which have co-authored this feature article.

Introduction

The water surface is present in a wide range of flows that are of interest within engineering hydrodynamics, from the ubiquitous open channel flow to low submergence coastal flows past marine structures such as tidal stream turbines. Such surfaces, often termed "free-surfaces", represent the boundary between the water body and the air above it, and may deform in response to the local flow physics including turbulence and bathymetric features. Deformation due to turbulence is generally small when compared to spatial and temporal variations of the mean surface position due to bed non-uniformity, ocean waves and the presence of hydraulic structures.

The equations governing free-surface flow are

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significantly more complex than those governing internal flow as they are subject to additional kinematic and dynamic boundary conditions at the (free) surface[1,2]. The kinematic condition is hyperbolic in nature and states that, since there can be no convective mass transfer across the air-water interface, the component of fluid velocity in the direction normal to the surface must be equal to the velocity of the surface itself. The dynamic boundary condition stipulates a force equilibrium at the interface, implying that the pressure and viscous forces exerted by the air and water respectively must balance. The boundary conditions introduce new nonlinear terms into the Navier Stokes equations, complicating their numerical solution significantly, although in hydraulics the dynamic condition is generally ignored since it is assumed that the surface tension can be neglected and the pressure on the air side can be assumed to be constant.

A number of novel approaches have been developed over the last thirty or so years to deal with the increased complexity introduced by the kinematic boundary condition; the interested reader is referred to Tsai and Yue[3] and Scardovelli and Zaleski[4] for in-depth reviews of these developments. This paper focus on the application of free-surface modelling techniques within the framework of large eddy simulation (LES), a powerful eddy-resolving technique that is increasingly used to study complex turbulent flows in engineering scenarios[5]. The paper begins by presenting a concise overview of the numerical techniques that have been developed to deal with the free-surface problem by researchers working in diverse areas of engineering fluid dynamics. A numerical method that has been employed by the authors to compute free-surface flows in the field of environmental hydraulics is then presented. Finally results from two case studies involving low submergence open channel flow over (1) a rough bed and (2) a bed-mounted bluff body are presented and discussed.

1. Numerical methods for the computation of free-surface problems

There are various ways to handle the free-surface boundary in CFD. The easiest approach is to "ignore" free surface deformations and do the rigid lid approximation as will be described in Section 1.1. More complicated are numerical approaches that compute free-surface deformations as the numerical solution progresses (for instance at every time step) and these are largely grouped into two distinct categories: interface tracking methods and interface capturing methods (described in Sections 1.2 and 1.3, respectively).

1.1 *The rigid lid approximation*

Within the field of hydraulics, the vast majority of simulations of flows involving water surfaces to date have employed the so-called rigid lid approximation, in which a fixed (generally flat) fixed surface or lid is used to represent the water surface. A free-slip boundary condition is stipulated at the lid, and the simulation is in fact that of a closed conduit with an artificial, frictionless condition at the lid. By definition the shear stress at the lid is zero, as is the component of the fluid velocity in the direction normal to it, but the pressure is free to vary as it would along a wall, which in turn produces zero shear stress there. This in effect constitutes a symmetry boundary condition. Rather than calculating the surface height with knowledge of the local fluid pressure, the problem is now reformulated and it is necessary to calculate the pressure based on the known height of the surface. The surface-elevation-gradient terms in the momentum equations for free-surface flows are thereby replaced by pressure gradients so that the dynamic effects of surface-elevation variations are properly accounted for by the rigid lid approximation method. The suppression of the actual surface deformation introduces an error in the continuity equation, but this is small when the surface deviation is small compared with the local water depth, say below 10% of the depth. Since local surface perturbations due to turbulence satisfy this condition in a large range of engineering flows the rigid lid approach has been applied with considerable success in a number of studies. This is particularly true of open-channel flows, where rigid lid LES and direct numerical simulations (DNS) have led to important insights on the structure of bed-generated turbulence[6-10].

To assess the validity of the rigid lid assumption Komori et al.[11] included the surface variations in their computation by including the kinematic boundary condition and compared the results with those from the rigid lid simulations of Lam and Banerjee[9]. They found that the free-surface deformations and near-surface normal velocities remained extremely small, leading them to conclude that the calculated flow behaviour near the free-surface did not differ from the rigid lid simulations. However it is expected that the errors will be more significant when the surface fluctuations are not small compared with the local water depth. In fact it is generally accepted that the rigid lid approximation is only strictly applicable to low Froude number (i.e., $Fr \le 0.5$) flows[12,13]. Kara et al.[14] performed two LES for flow through the same bridge contraction geometry, one with a rigid lid boundary and one with a free-surface capturing algorithm. The bulk Reynolds number was 27 200 and although the bulk Froude number was relatively low at $Fr =$ 0.37, locally values of $Fr = 0.78$ were reached as a result of the significant constriction imposed on the flow by the abutment (the ratio of channel width to abutment width was 3). Kara et al.'s results showed