Development of an Unstructured Grid Solver for Complex Wave Impact Problems

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（複雑な水面衝撃現象に関する非構造格子ソルバーの開発）

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論 文 内 容 の 要 旨

Thesis Summary

During the past two decades, much attention has been directed to the development of accurate simulation tools for wave impact problems. The significance of the research can be found in the maritime industry, ocean engineering, and coastal engineering. In the offshore industry, structures are installed in the sea for many years and sometimes decades. These structures must survive severe weather conditions including very large waves. In such conditions, offshore structures face the problem of wave impact. Furthermore, in extremely large wave conditions, water can flood the deck level of the structure causing damages to equipment on the deck. This is known as green water and it is an important problem not only for offshore structures but also for large ships. In addition to offshore and ocean engineering, wave impact problems are also important for the protection of coastal structures and stopping the recession of coastal lines. This requires accurate prediction of impact loading on coastal structures by very large waves such as tsunami waves. Thus, there is a great need for development of accurate simulation methods which are capable of predicting those impact loads by the green waters or violent waves and providing better understanding of wave impact phenomena. A promising method is the computational fluid dynamics (CFD) method based on the solution of Navier-Stokes equations of multi-phase turbulent flow.

The objective of this research is to develop an efficient CFD solver for accurate prediction of violent free surface motion and wave impact loading on structures with complicated geometry. To achieve that goal, a CFD solver that is based on the Navier-Stokes equations which describe the motion of the incompressible turbulent flow on unstructured meshes has been developed. The finite volume approach is employed to discretize the governing equations. The pressure-velocity coupling is handled by using the Pressure-Implicit with Splitting of Operators (PISO) method. The free surface is treated by the volume of fluid (VOF) method. The unstructured multi-dimensional tangent hyperbolic interface capturing method (UMTHINC) is used for interface capturing.

The work described in the present thesis aims to extensively investigate the accuracy of the UMTHINC VOF method as well as the numerical modeling aspects of wave impact phenomena. The dam break impact against a vertical cylinder is chosen as a model problem for this investigation.

The main results of this work are as follows:

(1) Error analysis is conducted to study the influence of the parameters on accuracy and stability of the UMTHINC method. The boundedness of the method is found to be compromised at high Courant numbers and sharp interfaces (i.e. the interface is diffused over few cells). The cause of this problem has been identified and a solution that ensures the boundedness of the VOF field without any mass loss has been proposed. The accuracy of the revised method is evaluated using several benchmark cases and it shows competitive accuracy with existing numerical results of other geometric based methods in literature.
(2) A new experiment of dam-break impact flow against a vertical wall and a vertical cylinder with square or circular cross-section has been conducted. The aim of the experiment is to provide more clear free surface images and more reliable pressure measurements than those in the literatures. A novel gate motion profile, obtained from the best fits of the gate motion measurements, has been proposed. A direct correlation is found between the parameters of the proposed gate motion profile and the wave impact event.
(3) Utilizing the newly obtained experimental data, the accuracy of the developed fluid solver has been confirmed both kinematically and dynamically. A novel simplified model for the gate motion in the dam-break experiment is developed and implemented on the unstructured grids. The effect of the gate motion on the wave-front speed is clearly demonstrated. The effect of the cylinder cross-section on the impact loading and on the free surface variation is studied. The square cross-section is found to produce a flow field with higher turbulence intensity which is clearly depicted in the free-surface profiles and pressure loading histories. The impact phenomenon on the circular cross-section is found to be rather mild in comparison with the square cylinder while the flow impact on the vertical wall shows more violent. This is owing to the different nature of flow separation for different cross-section of the cylinder.
(4) Finally, an investigation of the effect of the turbulence model on the flow characteristics, separation patterns, and impact loading on the obstacle and vertical wall has been conducted. All RANS models predict very similar results before the impact, while the differences among these models are observed after the impact. The LES model requires much finer meshes in order to provide reasonable predictions. Discussions have been made on how to choose a proper turbulence model for the problems with separated flows.

The thesis is organized as follows. In Chapter 2 a description of the governing equations is provided. In Chapter 3 finite volume discretization of the governing equations and their numerical solution procedure are introduced. In chapter 4, the UMTHINC VOF method is described in detail as well as the numerical aspects of the method on accuracy, efficiency, and boundedness. In chapter 5, a new dam break experiment is described. Free surface images and pressure measurements are presented and analyzed. In chapter 6, numerical simulation by the developed numerical solver is carried out on the dam break problem and the results are compared to the experimental data. Discussions of the effect of the gate obstruction, cylinder cross-section, and turbulence model are provided. In chapter 7, the thesis is summarized and suggestions for future work are given.