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Numerical study on cavitating flow due to a hydrofoil near a free surface

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Abstract

A numerical strategy is proposed for a viscous uniform flow past a 2-D partially cavitating hydrofoil placed at a finite depth from the free surface. The flow was modeled by the Reynolds-averaged Navier–Stokes (RANS) equations. A finite-volume method with the SIMPLE scheme and k-ε turbulence model were employed for computations. The "full cavitation model," which included the effects of vaporization, noncondensible gases and compressibility, was incorporated in the computation of cavitating flow. The cavity shape and free surface were updated iteratively till a reasonable convergence was reached. As for the determination of the free surface, the VOF approach was adopted. The test cases show the accuracy and stability of our procedure to capture the cavitating flow near the free surface.

Keywords: Cavitation; Viscous flow; Free surface; 2-D hydrofoil; Two-phase flow.

1. Introduction

Due to its complicated physics, cavitation has been an interesting and challenging flow problem for scientists and engineers. Phenomena involved in cavitation are usually highly nonlinear, unsteady, transient, multi-phase, mixing, and phase changing. Furthermore, in many practical applications, the device or vehicle which may induce cavitation operates within a finite water depth. The effects due to the free surface are usually not negligible. This fact makes the physics even more complicated and the analysis more time-consuming when the computational approach is taken in the study.

The pioneering study of cavitation near the free surface is primarily within the linear and inviscid scope. The conformal mapping technique is the main solution procedure. Due to its inherent mathematical properties, such an approach is restricted to two-dimensional problems. Applying the linearized cavitating flow theory developed for an infinite depth, Johnson [10] pioneered the design of supercavitating hydrofoils operating at a finite depth and zero cavitation number. Meanwhile, Auslaender [1] employed the linearized cavity flow theory and a mapping technique to study general characteristics of two-dimensional supercavitating or fully ventilated hydrofoils for operation near a free surface.

Later, the development of lifting-line and lifting-surface theories enables one to extend the study to three-dimensional linearized problems. Nishiyama and Miyamoto [16] used a lifting-surface theory to take into account the three-dimensional effects. Nishiyama [15] provided another solution procedure based on the lifting line method. Both of them are fully linearized theories and only applicable to the flow at small angles of attack and small cavitation numbers. In addition, they did not consider the effects due to the thicknesses of the body and the cavity.

With the progress of the theoretical development, the non-linear theories soon dominate the study of the cavitating flow near the free surface. Larock and Street [12] employed the conformal mapping approach to calculate the supercavitating flat-plate hydrofoil. Later, Furuya [6] developed an iterative procedure to investigate the two-dimensional gravity-free flow past supercavitating hydrofoils. The thickness effects of the body and/or the cavity were taken into account. The results were more accurate, compared to those

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obtained by the linearized theory. In addition, Furuya [7] investigated the three-dimensional flow past a supercavitating hydrofoil of large aspect ratio. He treated the flow near the foil as two-dimensional and introduced a three-dimensional correction based on Prandtl's lifting-line theory. It should be pointed out that the above-mentioned works were limited to the condition of infinite Froude number (zero gravity). A few years later, Doctors [4] linearized the free-surface condition for finite Froude numbers. He studied the flow past a two-dimensional supercavitating, arbitrarily-shaped hydrofoil by distributing Kelvin-type sources and vortices along the mean line of foil and cavity. His results show that the effect of the Froude number is more important when the cavity length is greater.

The advance of modern computers brings in rapid development of computational methods. The boundary element method (BEM) became an important tool in the study of the inviscid cavitating flow near the free surface which has been widely investigated theoretically. Through the computational approach, the shape of the cavity and body can be easily taken into consideration. Therefore, the cavitating flow can be more accurately predicted by using proper cavitation models. In addition, three dimensional effects can also be readily explored. Lee et al. [13] first pioneered such an approach to solve two-dimensional flows past partially and supercavitating hydrofoils under a free surface. Later, Young and Kinnas [21] developed a nonlinear BEM for surface-piercing propeller. The study which could trace cavity shape and free surface was carried out by Bal et al. [2].

Recently, the rapid development of computational fluid dynamics has made it possible to take into account the effects of viscosity and turbulence. Such progress makes the simulation more realistic. Furthermore, more complicated and practical cavitation models can be incorporated in the approach. Kubota et al. [11] first introduced a two-phase flow cavity model which could explain the interaction between viscous effects. More recently, Senocak and Shyy [18] conducted a systematic overview of numerical simulations of viscous cavitating flows based on the solution of Navier–Stokes equations. Singhal et al. [19] proposed a "full cavitation model," which took several factors related to the phase change into consideration. They include the formation and transport of vapor bubbles, the turbulent fluctuations of pressure and velocity, and the magnitude of noncondensible gases. In addition to the Reynolds-averaged Navier–Stokes equations (RANS), they also solved the Rayleigh–Plesset equations to simulate the detail of bubble dynamics. It is evident that the simulation of cavitating flow becomes more and more complicated.

However, it is quite unfortunate that all these studies have not yet included effects due to the free surface. In fact, the studies available in the literature seldom investigate viscous cavitation near a free surface. It is not until recently that study of this issue has been conducted. Jin et al. [9] carried out a numerical study on ventilated cavitating flow near a free surface with a cavitation model developed by Merkle et al. [14]. They focused on the ventilated cavitation process. Brizzolara and Young [3] investigated the physical and theoretical modeling of surface-piercing hydrofoils. They employed a volume-of-fluid technique with a mixture flow model in computations for both foil-born and take-off conditions.

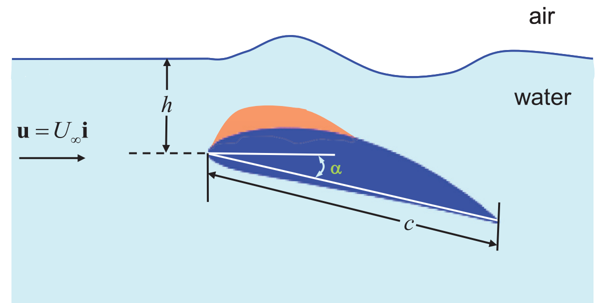

Fig. 1. The cavitating flow near the free surface.

The purpose of the present study is to develop a numerical procedure to compute such a flow with complicated physical phenomena. Our approach employs the full cavitation model to simulate the cavitating flow and a volume of fluid (VOF) method [8] to capture the free surface. Although both of them are based on the concept of volume of fraction, they have to be treated separately. This is due to the fact that the former must satisfy the Rayleigh–Plesset equations but the latter need not. An iteration procedure was developed to update iteratively the free surface and the cavity surface. We focus on the 2-D partial cavitating hydrofoil at a finite depth from the free surface. The flow field was governed by RANS (Reynolds-averaged Navier–Stokes equations) and solved by finite-volume method with SIMPLE algorithm. The turbulence model is k-ε turbulence model.

2. Theoretical formulation and numerical procedure formatting

Shown in Fig. 1, a uniform viscous flow with free surface passes around a two-dimensional hydrofoil with a chord length c. The far-upstream incoming velocity is U_∞ in the x-direction. The angle of attack is α. The depth from the free surface of calm water to the leading edge of the hydrofoil is h. Partial cavitation takes place on the upper surface of the hydrofoil and waves are generated on the free surface when the fluid passes around it.

The equations governing the cavitation phenomena can be expressed by

$$\frac{\partial \rho_m}{\partial t} + \nabla\cdot(\rho_m \mathbf{u}_m) = \dot{m}, \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_m \mathbf{u}_m) + \nabla\cdot(\rho_m \mathbf{u}_m \mathbf{u}_m) = \rho_m \mathrm{g} - \nabla p + \nabla\cdot\left[\mu_m(\nabla \mathbf{u}_m + \nabla \mathbf{u}_m^T)\right] + \nabla\cdot\left[\sum_{k=1}^{2} \alpha_k \rho_k \mathbf{u}_{dr,k}\mathbf{u}_{dr,k}\right]. \tag{2}$$

The symbols are defined as follows. First of all, the index m represents "mixture;" ρ_m is the density of liquid-gas mixture fluid defined as

$$\rho_m = \sum_{k=1}^{2} \alpha_k \rho_k, \tag{3}$$