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Shape optimization of axisymmetric cavitators in supercavitating flows, using the NSGA II algorithm

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ABSTRACT

The reduction of energy consumption for high speed submersible bodies is an important challenge in hydrodynamic researches. Supercavitation is a hydrodynamic process in which a submerged body gets enveloped in a layer of gas. As the density and viscosity of the gas is much lower than that of seawater, skin friction drag can be reduced considerably. If the nose of the body (cavitator) has a proper shape, the attendant pressure drag remains at a very low value, so the overall body drag reduces significantly. Total drag force acting on the supercavitating self-propelled projectiles dictates the amount of fuel consumption and thrust requirements for the propulsion system to maintain a required cavity at the operating speed. Therefore, any reduction in the drag coefficient, by modifying the shape of the cavitator to achieve optimal shape, will lead to a decrease of this force. The main objective of this study is to optimize the axisymmetric cavitator shape in order to decrease the drag coefficient of a specified after-body length and body velocity in the axisymmetric supercavitating potential flow. To achieve this goal, a multi-objective optimization problem is defined. NSGA II, which stands for Non-dominated Sorting Genetic Algorithm, is used as the optimization method in this study. Design parameters and constraints are obtained according to the supercavitating flow characteristics and cavitator modeling. Then objective functions will be generated using the Linear Regression Method. The results of the NSGA II algorithm are compared with those generated by the weighted sum method as a classic optimization method. The predictions of the NSGA II algorithm seem to be excellent. As a result, the optimal cavitator's shapes are similar to a cone.

1. Introduction

Supercavitation is the extreme form of cavitation, in which a single bubble of gas forms around a body moving rapidly through water, such as a projectile (Fig. 1). The bubble envelops the body in such a way that the water wets very little of the body's surface, thereby drastically reducing viscous drag. In order to generate a cavity enclosing the entire supercavitating self-propelled supercavitating body, the supercavitating body should have such a high thrust resulting in the required speed to counteract the effect of drag. Usually the drag divides into to two types of drag, pressure drag and viscous drag. In the case of supercavitation, the pressure drag is considerably higher than the viscous drag, since the fluid flow does not touch the body. As a result, the viscous drag is ignored in this work. The pressure drag can be calculated using the integral of the pressure distribution, caused by the fluid flow, over the nose of the supercavitating body. The shape of the nose section, which is called the cavitator, is significant in the case of a supercavitating self-propelled projectile, because it not only affects the generated cavity size, but also determines the magnitude of the drag force. Since the projectile is required to operate under high speeds, a reduction of the drag is the major design factor. Therefore, the objective of this study is finding the optimum shape of the cavitator that gives the required cavity size while producing minimum drag force.

In the process of cavitator shape optimization, supercavitating flow analysis needs to be carried out during each iteration of cavitator design calculations. This analysis, however, is a kind of free boundary value problem (BVP), which requires the use of an iterative scheme to reach the solution. In this problem, the shape of the cavity boundary is not known at first, while two conditions are imposed on the boundary: impermeability and constant pressure condition. The cavitator shape should be determined in such a way to meet these boundary conditions simultaneously. Due to this requirement, there have been many efforts to find an efficient solution process for the supercavitating flow problem.

Early research on supercavitating flows was performed by Reichardt [1], who experimentally studied the axisymmetric supercavitating flows. Efros [2] employed conformal mapping techniques to investigate the supercavitating flow problems. Tulin [3] introduced the use of perturbation methods for examination of two dimensional supercavitating flows. Cuthbert and Street [4] used

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Nomenclature

b	Cavitator geometric parameter
C_D	Drag Coefficient
C_p	Pressure coefficient
D	Drag
f_1	Objective function
f_2	Objective function
L	Cavity length
$\overrightarrow{n}$	Unit vector
P	Water pressure
P_c	Cavity pressure
R	Cavitator radius
S_c	Cavity surface
S_b	Body surface
U_∞	Free stream velocity
Φ	Total potential
φ	Disturbance potential
Γ	Body-cavity surface
σ	Cavitation number
ω	Cavitator geometric parameter.

sources and sinks along the axis of a slender axisymmetric body cavity system, along with a Riabouchinsky cavity closure model. They solved the problem for the unknown cavity shape, but they were successful only in a few cases. Brennen [5] employed a relaxation method in a transformed velocity potential-stream function plane for analyzing axisymmetric cavitating flows behind a disk and a sphere between solid walls. Chou [6] extended the work of Cuthbert and Street [4] to solve axisymmetric supercavitating flows using slender body theory. Until the 1970s, the analytical methods were the most important ones to solve the supercavitating flow problems. Beginning in 1980, some numerical methods were also developed. Aitchison [7] used a method of variable finite elements to consider the flow past a disk in a tube of finite diameter and infinite length. Uhlman [8] used the surface singularity method to solve the fully nonlinear potential flow past a supercavitating flat-plate hydrofoil numerically. Hase [9] employed interior source methods for modeling the planar and axisymmetric supercavitating flows. Verghese, Uhlman and Kirschner [10] used the boundary element method for numerical analysis of high speed bodies in partially cavitating axisymmetric flow. Shafaghat et al. [11] used the boundary element method for numerical analysis of axisymmetric unbounded supercavitating flows.

For a self-propelled supercavitating body, the propulsion system provides the required thrust which is proportional to the drag acting on body. The propulsion system keeps the high speed motion of the body. Thus, any decreasing in the thrust by modifying the shape of the cavitator is desirable. Kinnas et al. [12] and Mishima &Kinnas [13] studied the flow around the supercavitating hydrofoils and supercavitating wings and obtained the optimized shape of hydrofoils, using the Lagrange multiplier method. Mishima [14] presented his studies on cavitator modeling and hydrofoil optimization using method of multipliers and penalty parameter update schemes in both constrained and unconstrained optimization problems. Alyanak et al. [15] have designed the variable shape of cavitators. They have adjusted the cavitator's parameters to obtain the optimized cavitator shape of a supercavitating torpedo. They introduced some non-dimensional parameters in their cavitator modeling [16]. Choi [17] has investigated the cavitator shape optimization procedure using design sensitively analysis. He used a different method for geometric definition of the cavitator in his work. It is noticeable that all researchers have used a

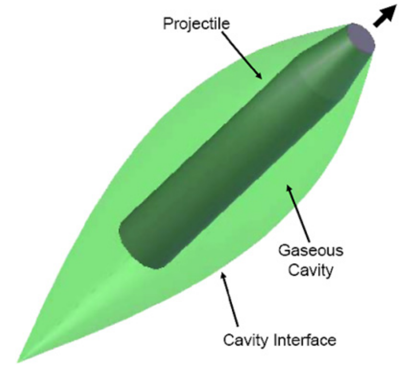

Fig. 1. Supercavitating projectile enclosed by a cavity.

type of gradient method to optimize the shape of cavitators or hydrofoils. These methods have been generally criticized for their problems obtaining optimum points in uneven and non-continuous objective functions. Shafaghat et al. used a non-gradient optimization method in order to obtain an optimized cavitator shape [18]. The final results of their work were very suitable. So, a non-gradient method is considered in this paper in order to optimize the shape of axisymmetric cavitators. The genetic-base optimization methods utilize a sorting algorithm to obtain optimum points in the domain of interest. In this study, a multi-objective genetic algorithm is selected to optimize cavitator shape.

It is confirmed by previous studies [11] that the potential flow assumption is accurate enough for supercavitating flow analysis. Usually, the main parameters in supercavitating flows are the geometry of the cavity and cavitator and also the cavitation number. Having specified objective functions and design parameters, a multi-objective optimization problem is used to minimize the drag coefficient and maximize the cavitation number. The required input data for this investigation is produced using a powerful software pack (developed by the authors) [11] and the so called NSGA II [19,20] optimization algorithm.

The mathematical formulation of axisymmetric supercavitating flow around the axisymmetric cavitator (such as a cone) comes first from a previous study [11] in the next part. Then, the general formulation for calculating the drag coefficient of axisymmetric cavitators in the axisymmetric supercavitating flows (with potential flow assumption) will be introduced. Finally, the optimum shape for the axisymmetric cavitators will be determined using the NSGA II algorithm.

2. Mathematical formulation of axisymmetric supercavitating flow

Consider the unbounded, steady and irrotational flow of an inviscid and incompressible liquid past a supercavitating axisymmetric cavitator (such as a cone) placed at a zero degree angle of attack in the flow direction (Fig. 2).

The flow is then a potential flow and hence possesses a potential function, Φ, which in the fluid satisfies Laplace's equation:

$$\nabla^2\Phi = \frac{\partial^2\Phi}{\partial r^2} + \frac{1}{r}\frac{\partial\Phi}{\partial r} + \frac{\partial^2\Phi}{\partial z^2} = 0 \tag{1}$$

where Φ is the total potential. A disturbance potential, φ, can be defined from the total potential by:

$$\Phi = U_\infty z + \varphi \tag{2}$$

where, U_∞ is the free stream velocity. So that the disturbance velocity is given by the gradient of the disturbance potential, the disturbance potential also obeys Laplace's equation:

$$\nabla^2\varphi = \frac{\partial^2\varphi}{\partial r^2} + \frac{1}{r}\frac{\partial\varphi}{\partial r} + \frac{\partial^2\varphi}{\partial z^2} = 0. \tag{3}$$