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A numerical and experimental study on the drag of a cavitating underwater vehicle in cavitation tunnel

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ABSTRACT: *For Super-Cavitating Underwater Vehicles (SCUV), the numerical analyses and experiments in a large cavitation tunnel are carried out at relatively large Reynolds numbers. The numerical results agree well with experiments and the drag coefficient of SCUV is rarely changed by the Reynolds number. As the cavitation number is decreased, the cavity occurs and grows, the cavitator drag decreases and the body drag is affected by the degree of covering the body with the cavity. The tunnel effects, i.e. the blockage and the friction pressure drop of the tunnel, on the drag and the cavitation of SCUV are examined from the numerical results in between the tunnel and unbounded flows. In the tunnel, a minimum cavitation number exists and the drag of SCUV appears larger than that in unbounded flow. When the super-cavity covers the entire body, the friction drag almost disappears and the total drag of SCUV can be regarded as the pressure drag of cavitator.*

KEY WORDS: Super-cavity; Cavitation tunnel; Cavitator; Underwater vehicle; Drag.

NOMENCLATURE

A_C	: Frontal area of cavitator
A_B	: Representative cross sectional area of objective
A_T	: Cross sectional area of test section of tunnel
C_D	: Drag coefficient
$C_D^{\ C}$	: Corrected drag coefficient considering blockage
C_{DC}	: Drag coefficient of cavitator in super-cavitating flow
C_{DF}	: Friction drag coefficient
C_{DP}	: Pressure drag coefficient
C_{DT}	: Drag coefficient in tunnel flow
C_{D0}	: Drag coefficient at cavitation number equal to 0
C_p	: Pressure coefficient
C_{pb}	: Base pressure coefficient
Re	: Reynolds number based on length ($= U_0 L / \nu$)
Re_d	: Reynolds number based on diameter ($= U_0 d / \nu$)
L	: Body length
L_T	: Tunnel length
P_{out}	: Pressure at outlet boundary
q_d	: Dynamic pressure ($0.5 \rho U_0^{\ 2}$)
U_0	: Inflow velocity
λ	: Local friction coefficient ($= 4C_f = \tau_w / (1/8 \rho U_0^{\ 2})$)
σ	: Cavitation number
$\sigma_{\min}$	: Minimum cavitation number in tunnel
σ_∞	: Infinite cavitation number which cavitation number in tunnel flow is converted to that in unbounded flow

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INTRODUCTION

There are many studies for technologies to speed up an underwater vehicle. Among them, a super-cavitation has been magnified as a technology that can overcome a very large friction and pressure drag acting on the underwater vehicle in high speed. In this technology a cavity generation device with a shape of disk or cone and etc., called cavitator, is mounted at the head of the underwater vehicle and the cavity is intentionally generated when the speed of underwater vehicle is increased sufficiently, e.g. above 50 *m/s* or higher. The entire body is covered with super-cavity, then the friction of body is almost vanished by contacting body surface with vapor and the pressure drag of body becomes very small by acting on the entire body with vapor pressure. Consequently, the drag of underwater vehicle is almost the cavitator drag.

The high speed torpedo of Russia, Shkval, is well known as a super-cavitating underwater vehicle whose speed is about 200 *knots* (100 *m/s*). Considering the speed of conventional torpedo is about 40~50 *knots*, the speed of Shkval can be regarded very high. Recently, the technical developments for super-cavitating underwater vehicle and the related researches are becoming increasingly active. The studies on the cavitator for the drag and the cavity generation have been performed experimentally and theoretically. However, in case of the super-cavitating underwater vehicle with relatively very long body, the study on its drag and cavitation with the interaction between the cavitator and the body is rarely found. Therefore, it is necessary, especially in a cavitator and body design point of view, to study on the drag characteristics of a super-cavitating underwater vehicle.

For this super-cavitating underwater vehicle, the experimental study is essential for two reasons. The first is to obtain reliable physical quantities that can be used in design process, and the second is to secure a data for verifying a numerical analysis. There have been some experimental studies on cavitators with super-cavitation at low cavitation numbers. To increase the inflow velocity for the captive object, Rouse and Mcnown (1948) performed an experiment in a free-jet vertical water tunnel using gravity and Knapp et al. (1970) used a high-speed water tunnel. Also Kirschner (2001) used submerged gun launcher to increase the speed of the objective and Ahn et al. (2012) did experiments in a cavitation tunnel to implement at once increasing inflow velocity and reducing pressure. In these experiments except in the cavitation tunnel, however, a drag was restrictively measured for simple shape cavitators, i.e. disk, cone, 2D-wedge and etc., due to the limitation such as the operation time was very short and the installation of measuring device inside small body, e.g. less than 100 *mm* diameter, was difficult.

In this point of view, the experiment in cavitation tunnel has a merit for the installation of measuring system. Moreover, in a large cavitation tunnel it is possible to experiment cavitating flow at relatively high Reynolds number (Suryanarayana, 2010). Nevertheless the drag measurement in cavitation tunnel has been rarely performed. Due to the tunnel effects, i.e., the blockage and the pressure drop in test section of a tunnel, drag and cavitation characteristics in tunnel are different from those in unbounded flow which are actually needed for the design. Therefore, it is necessary to investigate preferentially the tunnel effects on the drag and the cavitation.

Numerical studies for super-cavitating simple bodies have been mainly based on potential flow (Ahn et al., 2010) and along with some analytic solution they have a high utilization for simple cavitators because of the good agreement with experiments. However, when the cavitator and the body much longer than the cavitator diameter are together, e.g. a Super-Cavitating Underwater Vehicle (SCUV), the friction and pressure drag of the body are influenced differently depending on the degree of covering the body with the cavity. With the calculation based on potential flow, it is difficult to estimate the drag of SCUV realistically. Therefore, a numerical analysis for viscous turbulent flow is needed.

Recently, the works for the development and improvement of numerical cavitation model is presented (Park and Rhee, 2010) and through the numerical analyses, it is possible to investigate the super-cavitating flow with turbulence and to estimate the drag of cavitators (Park and Rhee, 2011a; 2011b; Lee et al., 2013). However, for SCUV at the high Reynolds numbers and low cavitation numbers, the numerical study is little and a data to verify a numerical result is rarely found. So, it is necessary to ensure the reliability of a numerical result and the experiment can provide that. From this, it could be confirmed the usefulness of numerical analysis, and further, be possible to obtain the physical information for SCUV under realistic operating conditions and environments.

In this paper, in order to investigate drag and cavity characteristics for a super-cavitating underwater vehicle of real size, the experiments are performed in a large cavitation tunnel. Also, the numerical analysis is performed in a modelled tunnel considering the tunnel effects, i.e., the blockage and the pressure drop by friction on the tunnel wall, and in unbounded domain