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Numerical investigation of the components of calm-water resistance of a surface-effect ship

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ABSTRACT

The elements of the calm-water resistance of an surface-effect ship are studied with two different numerical methods. A potential-flow-based method that satisfies linearized free-surface boundary conditions is used to predict the wave resistance of the sidehulls and air cushion. A RANS-based program that employs a single-phase level set method is used to simulate the flow around an SES of a nonlinear viscous fluid. Detailed comparison of the dynamic wetted surface, the free-surface elevation, and the wave, cushion, and frictional drag is made for a geometry that has experimental resistance data. It is shown that the linear free-surface boundary conditions of an inviscid fluid are accurate for prediction of wave drag. Disagreement is present between the two methods for the free-surface elevation behind the vessel, which might possibly be due to the transom-stern model that is used in the potential-flow method. The small difference between the numerically predicted resistance and the experimental measurement is attributed to the error in the seal and air drag models that are used in this study.

1. Introduction

The Surface-Effect Ship (SES) is an attractive concept for applications that require a vessel to travel at high speeds. The vertical force that balances the weight of the craft is generated by a combination of buoyancy, hydrodynamic lift, and air-cushion support. For very high speeds, it is known that the wave resistance is small and the frictional drag dominates the total resistance of the vessel. The principal mechanism in which the SES shows an advantage over non-air-cushion-assisted vessels is the reduction in wetted surface that is achieved through reduced dependence of the vertical force on the action of buoyancy. Following this reasoning, the air-cushion vehicle (ACV) is a strong candidate for high-speed operation, although vessels that are fully supported by an air cushion have limited performance in medium to high sea states because it is difficult to maintain the air cushion. Thus, the SES shows a compromise between the displacement-type vessel and the ACV to deliver a ship that has reduced wetted surface and lower frictional drag but with desirable seakeeping properties.

The SES has been used for high-speed naval vessels for many decades with an early example found in Ford (1964). The prediction of the power required to operate in calm water is a primary characteristic that is used at the earliest stages of design to evaluate the SES concept and compare it to other candidates such as a planing boat, hydrofoil-assisted vessel, and/or multihull vessel. The total power required to propel an SES can be discussed as the sum of the power to generate the air cushion and that which is needed to overcome the aerodynamic and hydrodynamic forces on the hull. Indeed the two aspects are related, because the fan used to create the air cushion does alter the flow around the hull, but this interaction is assumed to be negligible with respect to the resistance of the vessel. The power required to generate the air cushion is generally significant with respect to the total power, although in this paper we focus solely on the fluid forces on the hull.

1.1. Previous work

The numerical predictions in this paper include those based on the traditional potential-flow analysis employing a linearized dynamic condition and a linearized kinematic condition on the free surface.

The method essentially allows one to represent the vessel by a distribution of singularities, which model the sidehulls (assumed to be thin) and the air cushion (assumed to be of low magnitude).

The method has been described in detail by Doctors et al. (2005) and Doctors (2006). In these papers, the linearized approach allows one to compute the resistance using computations based only on the

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Nomenclature

$\overline{\overline{\tau}}$	viscous stress tensor
Δ_F	displacement mass (full)
Δ_L	displacement mass (light)
η	free-surface elevation
$\boldsymbol{\sigma}$	stress vector
$\mathbf{i}$	unit normal that is aligned with the free-stream velocity
$\mathbf{n}$	surface normal vector
$\mathbf{U}$	Reynolds-averaged velocity vector
μ	fluid molecular viscosity
ρ_a	air mass density
A_{ref}	reference area for air-drag calculation
B	waterline beam
B_C	cushion beam
B_S	waterline beam (sidehull)
C_D	air-drag coefficient
F	Froude number $F = U/\sqrt{gL}$
$f_F R_F$	frictional resistance computed by linearized theory
f_W, f_F	form factors for wave and frictional resistance
$f_W R_W$	wave resistance computed by linearized theory
g	gravitational acceleration constant
L	waterline length
L_C	cushion length
p	fluid pressure
p_C	cushion pressure
R_F	flat-plate friction predicted by friction line
R_a	air drag
R_C	cushion drag
R_h	hydrodynamic drag
R_S	seal drag
R_T	total drag
S	total surface of SES
S_h	hull surface
S_s	seal surface
$S_{h,a}$	dry hull surface outside of the air cushion
$S_{h,c}$	dry hull surface inside the air cushion
$S_{h,w}$	wetted hull surface
$S_{s,a}$	dry seal surface outside of the air cushion
$S_{s,c}$	dry seal surface inside the air cushion
$S_{s,w}$	wetted seal surface
T	draft (20% hull-lift ratio)
U	speed of the craft
U_a	air speed
x_1	cushion start station
y^+	dimensionless distance to the surface using inner scaling

downstream far-field wave system. Thus, the approach is very efficient in terms of computer resources.

Comparison of these predictions with experimental data in the literature suggests very strongly that linear theory provides an excellent starting point for estimating the required propulsion power.

More recent work is that of Doctors (2012), in which the identical basic theory is used. However, the advancement was to also compute the near-field wave system. This permits one to (a): study the details of the dynamic shape of the wetted surface, (b) predict the sinkage and trim, and (c) estimate more accurately the interaction between the cushion seals with the water.

Fully nonlinear viscous methods have been used to study the calm-water resistance of air-cushion assisted vessels. The single-phase level-set method that is used in this paper was previously used to examine the components of the flow generated by a two-dimensional pressure patch in Maki et al. (2012). Note that this reference also shows results from the same linearized theory that is employed in this paper.

Additional examples of the numerical prediction with a RANS tool of the flow generated by an ACV are found in Bhushan et al. (2011). An interesting aspect of this paper is the numerical validation and verification study that is summarized, and the investigation of the side force that is generated during operation with a nonzero-yaw angle. The nonlinear method that is used in Bhushan et al. (2011) could be applied to a surface-effect ship, in principle. In our work, we extend what is presented in Bhushan et al. (2011) for the case of an SES and provide the details to properly account for the interaction between the hull and the air cushion.

In the paper Donnelly and Neu (2011), a commercial CFD software that uses the volume-of-fluid method is evaluated to predict the drag on an SES. The commercial solver is a two-fluid implementation, and comparisons are made with physical model tests. In their simulations the seal geometry is modeled explicitly, but the seals are not allowed to deform. Also, the air-cushion is modeled using a momentum source technique that requires explicit discretization of the air plenum. In the current work, the fully nonlinear method does not require discretization of the air plenum, and the seals are modeled in a flexible manner according to the approach described in Doctors and McKesson (2006).

A unique numerical tool that simulates the operation of an SES in waves with detailed description of the lift-fan control characteristics is found in Connell et al. (2011). The simulation tool is called ACVSIM, and the hydrodynamic solution is found using the potential-flow based AEGIR program. Also, the paper Kring et al. (2011) demonstrates how AEGIR can predict wave forces on an SES while maneuvering. An interesting element of this paper is how the viscous code CFX is used to determine corrections that are used by AEGIR in the simulation of a maneuver in waves.

1.2. Current Work

In this paper two numerical methods are used to predict the fluid force acting on an SES that is advancing at steady-forward speed in calm water. The first method exploits the irrotational nature of the flow around high-Reynolds number bodies such as ships, and computes the wave drag due to the sidehulls and air cushion through numerical evaluation of the integral equations governing a velocity potential. The second method uses a field discretization to find a numerical solution of the unsteady RANS equations. In the potential-flow based method the solution satisfies linearized free-surface boundary conditions on the calm-water plane. The RANS solution satisfies the fully nonlinear free-surface boundary conditions on the predicted free-surface elevation.

This paper is organized into the following sections. First, a mathematical description of the fluid forces that act on an SES that is operating in calm-water is presented. This provides for the precise definition of each component of resistance, and allows for a clear connection to be made between the predictions gathered from each of the numerical tools and experiments. Then, an overview of each of the numerical methods is briefly presented. Next, the numerical predictions of each of the components of resistance are shown in the results section. This allows for evaluation of the different numerical methods, and elucidates the relative importance of each component of resistance. Finally,