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Experimental and numerical hydrodynamic analysis of a stepped planing hull

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ABSTRACT

This work addresses the experimental and numerical study of a stepped planing hull and the related fluid dynamics phenomena typically occurring in the stepped hull in the unwetted aft body area behind the step. In the last few years, the interest in high-speed planing crafts, with low weight-to-power ratios, has been increasing significantly, and, in such context, naval architects have been orienting toward the stepped hull solution. Stepped planing hulls ensure good dynamic stability and seakeeping qualities at high speeds. This is mainly due to the reduction of the wetted area, which is caused by the flow separation occurring at the step. This paper presents the experimental results of towing tank tests in calm water on a single-step hull model, which is the first model of a new systematic series. The same flow conditions are analyzed via Reynolds Averaged Navier-Stokes (RANS) and Large Eddy Simulations (LES), with different moving mesh techniques (overset/chimera and morphing grid), performed at different model speeds. The numerical results are in accordance with experimental data, and overset/chimera grid is found to be the best approach between the analyzed ones. The flow patterns obtained numerically through LES on a refined grid appear similar to the ones observed in towing tank investigations through photographic acquisitions. These flow patterns are dominated by a rather complex 3D arrangement of vortices originating from air spillage at both sides of the step. The understanding of these phenomena is important for the effectiveness of stepped hull designs.

1. Introduction

In the last few years, the development of lightweight engines and propulsion systems, along with the development of lighter boats built by shipyards with new technology and materials, has forced designers to pay increasing attention to hull design. Outboard engines in particular are characterized nowadays by a very low weight to power ratio and high reliability. These features make them suitable for several installation types, including military, commercial, pleasure, and racing. The new composite materials allow a boat weight reduction of 30% with respect to a traditional hand-made layup. In this scenario in recent years, the high-speed planing craft for military, commercial, and pleasure use, with a very low weight to power ratio has spread even further.

The reduction of weight to power ratio involves an increase of maximum speed; as a consequence, naval architects are oriented even more in stepped hull design to reduce the resistance at high speed and ensuring good dynamic stability and seakeeping. The step is a sharp discontinuity located in the bottom surface of the hull; it is transversal and usually V-shaped, with the vertex facing aftward, on the outboard sides of the hull the step terminates with large apertures (also named 'inlets') for incoming air.

As pointed out by [1], the stepped hull is characterized by a low hydrodynamic drag-to-lift ratio at high speeds and by a wetted area reduction due to a flow separation, which occurs at step location and then reattaches at the aft body [2]. Moreover, stepped planing hulls have a small variability of trim angle and improve control of the longitudinal attitude because they are sailed always on a $n+1$ wetted triangle, where n represents the number of steps. In fact, for a single stepped hull, an additional aft-lift is created, due to the presence of the reattachment line (stagnation line) in the aft-body. This force keeps the running trim of the vessel almost constant with Froude number (at high speed). This feature is beneficial because avoids the porpoising instability, which occurs instead to stepless planing hulls.

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Nomenclature

B	Breadth (m)
B_r	Bias systematic uncertainty
c_j	Basis constant
C_k	Correction factor
D	Vertex displacement
E	Comparison error
D	Experimental data
Fr_{∇}	Volumetric froude number
F_s	Factor of safety
Fr	Froude number
K	Constant value
L	Water line length (m)
L_{OA}	Length overall (m)
N	Number of control vertices
S_n	Numerical simulation result
p_k	Observed order of accuracy
P_r	Precision uncertainty
r_{ij}	Magnitude of distance between two vertices
r_k	Refinement ratio
R_k	Convergence ratio
R_{TM}	Total model resistance (N)
S	Wetted surface (m^2)
$SDev_j$	Standard deviation of jth run
U	Uncertainty
U_r	Total uncertainty
U_k	k-input parameter uncertainty
U_I	Iterative uncertainty
U_G	Grid uncertainty
U_{TS}	Time step uncertainty
U_{SN}	Numerical simulation uncertainty
U_V	Validation uncertainty
U_D	Experimental data uncertainty
V	Hull speed (m/s)
Z	Sinkage (m)
∇	Displacement volume (m^3)

Greek symbols

A	Constant value
Δ	Displacement weight (N)
E	Solution change
P	Density (kg/m^3)
Λ	Expansion coefficient
Δt	Time step (s)
T	Dynamic trim angle (deg)

Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AMG	Algebraic multi grid
ASME	American Society of Mechanical Engineer
CF	Correction Factor
CFD	Computational fluid dynamics
CFL	Courant Friedrichs Lewy number
CNC	Computer numerical control
DAQ	Data acquisition device
DFBI	Dynamic fluid body interaction
DOF	Degree of freedom
DT	Down thrust
EFD	Experimental fluid dynamics
FRP	Fiber reinforced plastic
GCI	Grid convergence index
HRIC	High resolution interface capturing scheme
ITTC	International Towing Tank Conference
LCB	Longitudinal centre of buoyancy
LCG	Longitudinal centre of gravity
LES	Large eddy simulation
NV	Numerical ventilation
PVC	Polyvinyl chloride
RANS	Reynolds average navier-Stokes
RBF	Radial basic function
RBM	Rigid body motion
RE	Richardson extrapolation
RIB	Rigid inflatable boat
RSS	Root sum square
SIMPLE	Semi implicit method pressure linked equations
UA	Uncertainty analysis
VOF	Volume of fluid
V&V	Verification and validation

Another way to obtain a hydrodynamic resistance reduction is the application of the artificial bottom cavities with side skegs. The state of the art of the air lubrication technologies together with research activities in Russia until 2010 can be found in Sverchkov [3].

Nowadays there are three options for the hydrodynamic analysis of stepped hulls: experimental testing, empirical estimation methods, and numerical simulations.

Experimental Fluid Dynamics (EFD) tests, that is towing tank tests, are very expensive and time consuming. Moreover, the only stepped hull systematic series experimental results available are those performed at the University of Southampton [4].

Two empirical hydrodynamic prediction methods are those published in [1] and [5]. The first method experimentally studied the longitudinal surface wake profiles aft of prismatic hulls; the second method combines the equations of [1] with the equations of Savitsky's method for conventional planing hulls for power prediction of a stepped hull.

Numerical methods, such as those based on Computational Fluid Dynamics (CFD) simulations, can be used nowadays to calculate the hydrodynamic performance of a stepped hull with good accuracy. In the last few years, several studies investigated this research field. Garland and Maki [6] conducted a numerical study on a 2D stepped planing surface. Their results showed that the lift-to-frictional-drag ratio varies very little with respect to the step location. Makasyeyev [7] developed a solution method for the 2D mathematical problem of planing of the stepped air cavity hulls. Matveev [8] applied hydrodynamic discrete sources for 2D modeling of stepped planing surfaces, calculating the water surface deformations, wetted hull lengths, and pressure distribution at given hull attitude and Froude number (*Fr*). Matveev, in another study [9], presented the steady hydrodynamic modeling of semi-planing hulls with pressurized and open air cavities. This method is based on a linearized potential-flow theory for surface flows. Brizzolara and Federici [10] developed an integrated semi-theoretical/numerical (CFD) method for the design of V-shaped stepped planing hulls that presented a considerable resistance reductions with respect to conventional hull forms. Lotfi [11] used an unsteady RANS solver (ANSYS-CFX) based on a Volume of Fluid (VoF) approach for examining the characteristics and performance of a planing hull having one transverse step. Similar research was conducted by Bakhtiari [12]. Moreover, an extended overview of the state of art of the simulations in the air layer drag reduction is reported in Stern et al. [13].

It is clear, nowadays, that CFD is becoming a fundamental support for hydrodynamic investigations in order to perform detailed analysis and to reduce the number of more expensive towing tank