Computation of Hydrodynamic Characteristics of Ships Using CFD

M. M. Karim and N. Naz

***Abstract*—This paper investigates various hydrodynamic characteristics of two conventional ships namely Wigley hull and Series 60 ship by commercial CFD software named Shipflow. Zonal approach is applied to incorporate 'potential flow solver' in the region outside the boundary layer and wake, 'boundary layer solver' in thin boundary layer region near the hull and 'Navier Stokes solver' in the wake region successively. Finally free-surface wave pattern, wave elevation, pressure coefficient on hull, boundary layer streamline and different resistance components at different speeds are computed and validated by comparing with experimental results.**

***Index Terms*—Potential flow, viscous flow, wave pattern, XPAN, XBOUND, XCHAP.**

I. Introduction

Computation of hydrodynamic characteristics of ship with free-surface effect is one of the most important topics in naval architecture for determining ship's performance at different speeds. Since the development of the landmark thin-ship theory of Michell [1], [2], considerable efforts have been devoted toward the development of Computational Fluid Dynamics (CFD) techniques in order to predict hydrodynamic characteristics of ship as a replacement for the towing-tank test. Although model testing is considered as the most reliable methods for performance prediction of ship hull form, robust and economical CFD tools can be used more efficiently for the same purpose. However, in order to use CFD, as a useful tool for determining hydrodynamics characteristics of the flow around ship hull, the numerical results must be credible and accurate enough. Furthermore, CFD should have the capability of predicting the changes in the flow pattern characteristics resulting from the variations of speeds and hull forms.

For the validation of CFD results, extensive research works have been carried out to examine the flow characteristic around different ship hull forms. Kajitani *et al.* [3] presented a report summarizing the cooperative experiment on Wigley parabolic model. Noblesse *et al.* [4] developed numerical results for five different hull forms to compute wave resistance. Sangseon [5] and Sakamoto *et al.* [6] made an extensive review on various types' resistance for the Wigley parabolic hull based on ITTC 1957 Model-Ship Correlation Line and using RANS (Reynolds Averaged Navier Stokes) simulation. Takeshi *et al.* [7] compute flow and resistance of Series 60 model by Experimental Fluid Dynamics (EFD).

The CFD software used in the study is SHIPFLOW 5.1 developed by FLOWTECH International AB from the research done at the Hydrodynamics group of Chalmers University of Technology. It is primarily being developed for applications within ship design and can handle several disciplines within this area covering both viscid and inviscid solutions. Three kinds of flow solvers [8] are used for determining hydrodynamic characteristics; XPAN a potential flow solver based on the surface singularity panel method, XCHAP is a RANS solver for steady incompressible flow, and XBOUND is an integral method for thin boundary layers. The solvers can be used separately or in combination as requirement.

In this paper, the main objective is to determine the free-surface wave pattern, wave elevation and various resistance components at different Froude numbers (Fr.) around Wigley and Series 60 hulls using Shipflow 5.1 which is finally validated by comparing with experimental results [3]-[7].

II. Computational Method

The coordinate system (x, y, z) for computation is defined as origin is located in the undisturbed free surface at fore perpendicular (F.P) of the hull so that the undisturbed incident flow with a constant speed U appears to be a streaming in the positive-x direction with y axis extends to the starboard side and z- axis upwards as shown in Fig. 1.

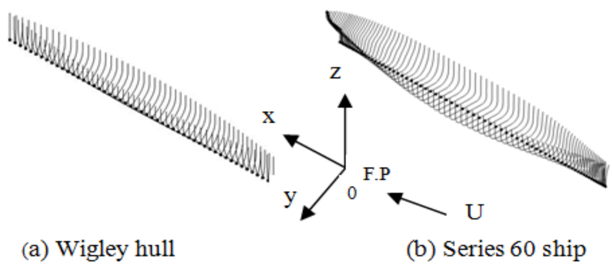

Fig. 1. Cartesian coordinate system.

To compute the flow around a ship in an efficient way, zonal approach [8] is used as shown in Fig. 2. Which divides the flow around a ship into three different zones with different solution methods. Region outside the boundary layer and wake is considered to be incompressible, inviscid and irrotational. Therefore, in the outer flow (zone 1), the potential flow theory is employed. The inner flow is divided into the thin boundary layer (zone 2) and stern/wake region (zone 3).

Manuscript received March 27, 2016; revised July 25, 2016. This work was supported by Bangladesh University of Engineering and Technology (BUET) and sub-project CP # 2084 of Department of Naval Architecture and Marine Engineering (NAME) under Higher Education Quality Enhancement Project (HEQEP), UGC, Ministry of Education, Govt. of Bangladesh.

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doi: 10.18178/ijmmm.2017.5.4.322

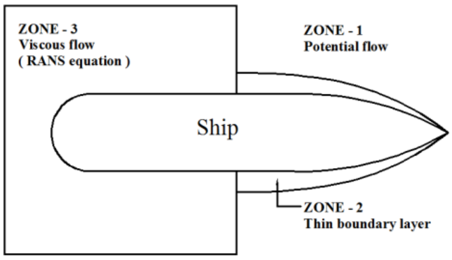


Fig. 2. Shipflow zonal approach [8].

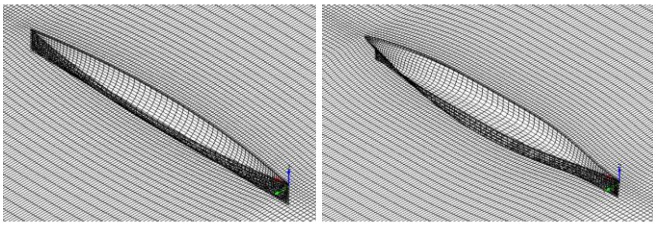
A. Governing Equation

To compute the flow around ship hull three types of governing equations are used depending on the hypothesis and considerations assumed in different regions. For potential flow region XPAN solver [8] is used where continuity equation becomes:

$$\vec{\nabla}.\vec{U} = \vec{\nabla}.(\vec{\nabla}\Phi) = \nabla^2\Phi = 0 \tag{1}$$

where $\vec{\nabla}$ is the Laplace operator, $\vec{U}$ is the uniform velocity in the positive x-direction in m/s and Φ is velocity potential.

XPAN solver uses potential-flow panel method based on Rankine sources [9] with hull and nonlinear free-surface boundary conditions [10] by discretizing the hull and the free-surface by flat quadrilateral panels as shown in Fig. 3.



(a) Wigley hull. (b) Series 60 ship

Fig. 3. Discrtetization of hull and free-surface for potential flow solver.

Thin boundary layer near the hull is computed with XBOUND solver [8] using the momentum integral equation:

$$\frac{d\theta}{dx} + \frac{\theta}{u}.(H+2)\frac{dU}{dx} = \frac{C_f}{2} \tag{2}$$

where θ, H, C_f denote momentum thickness, shape factor and C_f friction coefficient respectively.

The viscous flow at stern region is solved with XCHAP solver [8], [11] using steady RANS equations coupled with the time-averaged continuity equation:

$$\frac{\partial}{\partial x_j}(\bar{u}_i\bar{u}_j) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + F_i + \frac{1}{\rho}\frac{\partial}{\partial x_j}(\bar{\sigma}_{ji} + R_{ji}) \tag{3}$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{4}$$

where $\bar{u}_{i(j)}, \bar{p}, \bar{\sigma}_{ji}, \rho, F_i$ denote the average velocity, pressure , stress, water density and body force respectively; $R_{ji} = R_{ij} = -\rho\overline{u_i^{'}u_j^{'}}$ denotes the Reynolds stresses which is computed using turbulence model EASM (Explicit Algebraic Stress Model) [12].

B. Boundary Conditions for Viscous Flow Computation

Due to symmetry on the x-z plane, quarter of a cylinder is used as computational domain with radius 3.0 L, downstream length 0.8L and for zonal approach viscous computation starts from 0.5L behind the F.P of the ship as shown in Fig.4.

In XCHAP solver the boundary conditions are implied on the computational domain to solve partial differential equations of RANS equation. Boundary types employed are no slip, slip, inflow, and outflow [11]. Both Dirichlet and Neumann boundary conditions are formulated in terms of pressure p, velocity u_i, turbulent kinetic energy k, and turbulent frequency ω. Descriptions of boundary types are given in Table I and in Fig. 4.

TABLE I: BOUNDARY CONDITIONS FOR COMPUTATIONAL DOMAIN

Description	u	p	k	ω
No slip	$u_i = 0$	$\frac{\partial p}{\partial \xi_b} = 0$	$k = 0$	$\omega = f(u_\tau)$
Slip	$u_i n_i = 0$ $\frac{\partial u_i}{\partial \xi_b} = 0$	$\frac{\partial p}{\partial \xi_b} = 0$	$\frac{\partial k}{\partial \xi_b} = 0$	$\frac{\partial \omega}{\partial \xi_b} = 0$
Inflow	$u_i =$ constant	$\frac{\partial p}{\partial \xi_b} = 0$	$k =$ constant	$\omega =$ constant
Outflow	$\frac{\partial u_i}{\partial \xi_b} = 0$	$p = 0$	$\frac{\partial k}{\partial \xi_b} = 0$	$\frac{\partial \omega}{\partial \xi_b} = 0$

where n_i, u_τ, ξ_B denote normal to the surface, velocity at characteristics time and parameter direction crossing the boundary respectively.

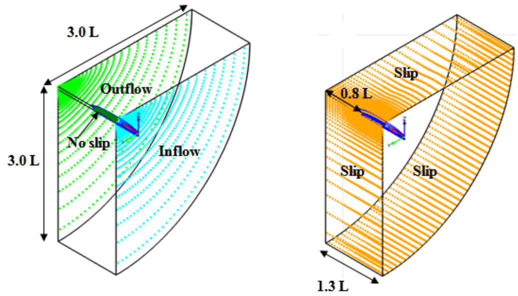


Fig. 4. Boundary conditions.

C. Grid Generation for XCHAP Solver

Finite volume method requires grid cells in order to discretize the partial differential equations and approximate algebraic equations. In XCHAP module only structured grids are used. Computational domain along with hull geometry is represented by a single block structured grid of H-O type with 0.45 M cells as shown in Fig. 5.

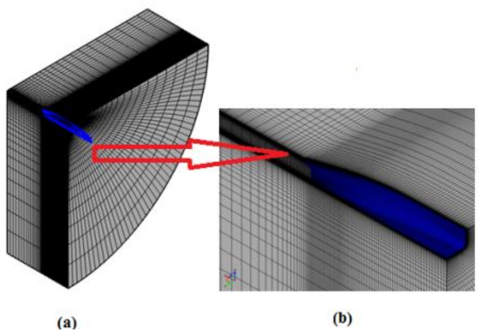


Fig. 5. H-O type structured grid for XCHAP solver.
(a) computational domain (b) close-up view

III. Results and Discussion

The free-surface wave pattern, wave elevation along the hull, pressure coefficient on hull with potential flow streamlines and variation of different resistance components with Fr. are determined in the present work, which are discussed in this section.

A. Wave Pattern at Different Speed

Wave patterns for Wigley hull at Fr. 0.177 and 0.408 and Series 60 hull at Fr. 0.20 and 0.35 are shown in Figs. 6 and 7 respectively, it is apparent that divergent waves which are the primary wave system at lower Fr., start at the bow and stern region at an angle of 19.47° and transverse waves which are more important at higher Fr. are perpendicular to the ship's line of motion. Both wave patterns are contained within two straight lines making an angle of 19.47° on each side of line of motion show the characteristics of Kelvin wave pattern [13].

B. Free Surface Wave Elevation

The computed free-surface wave elevations around Wigley and Series 60 hulls with different mesh configuration at Fr. 0.267 and at Fr. 0.316 respectively are compared with the experimental results [3], [7] as shown in Fig. 7.

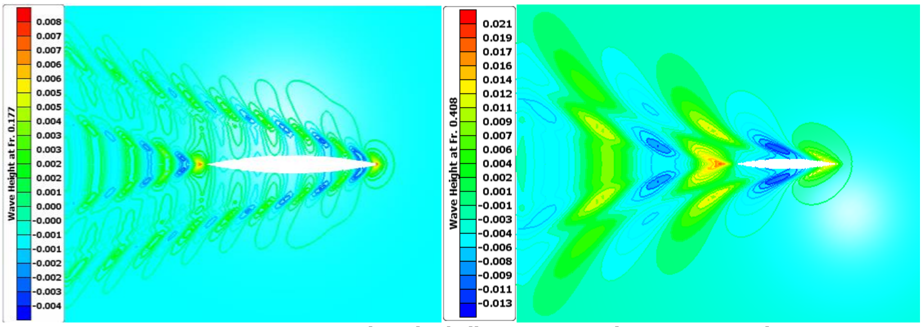


Fig. 6. Wave pattern around Wigley hull at Fr. 0.177 and 0.408 respectively.

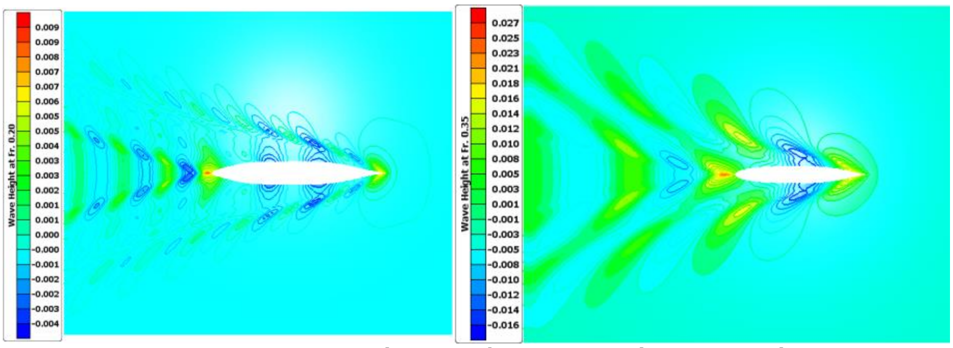
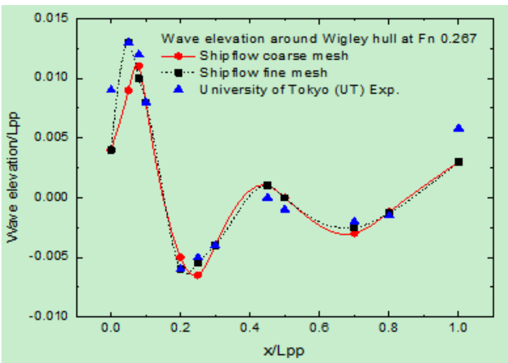
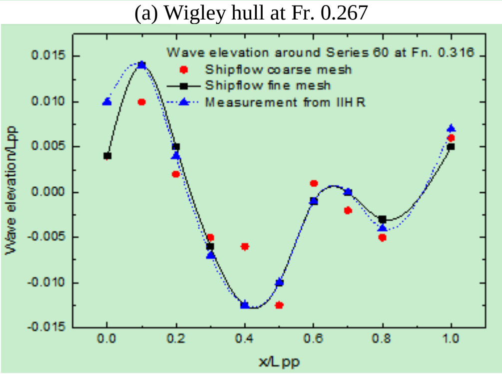


Fig. 7. Wave pattern around Series 60 ship at Fr. 0.20 and 0.35 respectively.



(a) Wigley hull at Fr. 0.267

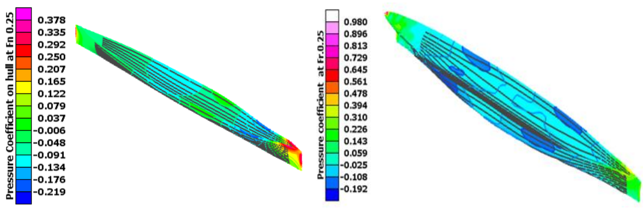


(b) Series 60 ship at Fr. 0.316

Fig. 8. Free surface wave elevation along ship hulls.

From Fig. 7, it appears that with fine mesh wave elevation along hull shows good agreement with the experimental results except the stern region for Wigley hull and bow region for Series 60. This discrepancy is likely to have been caused by the following reasons: (i) the wave profiles are taken from the free- surface elevations at the panels next to the body, not at the actual hull surface, which resulted in error especially near the bow and stern region. (ii) Potential flow methods assumes free surface as flat and rigid to avoid air/water interface of viscous flow which also results in variation between computed and experimental results.

C. Pressure Coefficient and Potential Flow Streamline



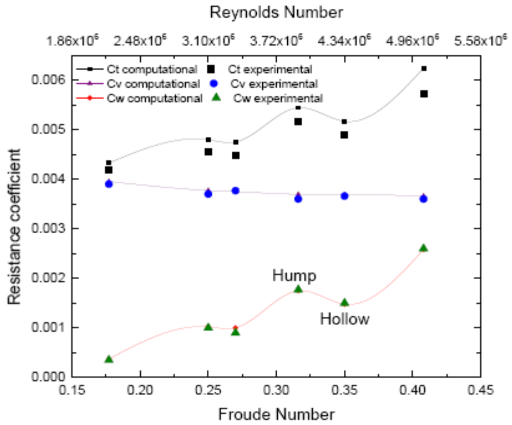
(a) Wigley hull (b) Series 60 ship

Fig. 9. Pressure coefficient and potential flow streamlines.

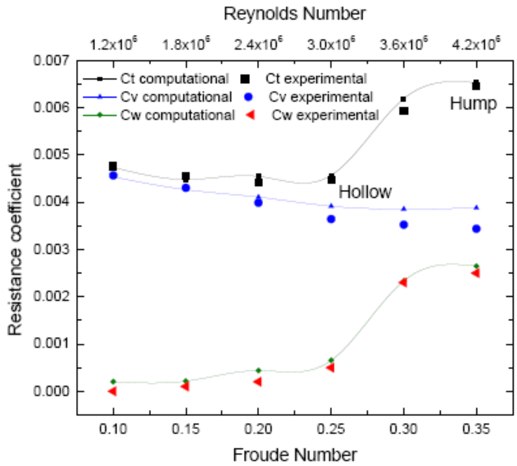
Pressure coefficient and potential flow streamlines are automatically traced from the potential flow solution. Boundary layer tracing is started from 0.05L behind the fore perpendicular to the beginning of the after hull part, and the number of points per streamline is 25 as shown in Fig. 9 at Fr. 25 for both hulls.

D. Resistance Components

Total (Ct), wave making (Cw) and viscous (Cv) resistance coefficients have been computed for both Wigley and Series 60 hulls at different Froude numbers (Fr) and Reynolds numbers (Re) as shown in Fig. 10.



(a) Wigley hull.



(b) Series 60 ship.

Fig. 10. Resistance coefficient as a function of Fr.

Fig. 10 shows that Cv decreases with increasing Re for both hulls as it largely depends on Re. Curves of Cw and Ct consist of number of humps and hollows which occur when bow and stern waves are in and out of phase respectively which is validated with experimental results [4], [7].

A relative error analysis of total resistance coefficient (Ct) has been done for both hull as shown in Table II and Table III.

TABLE II: WIGLEY HULL: RELATIVE ERRORS OF TOTAL RESISTANCE COEFFICIENTS BETWEEN CFD AND EFD

Fr.	Re.	Ct CFD	Ct EFD	Error (%)
0.177	$2.2*10^6$	0.00433	0.00419	-3.34129
0.25	$3.1*10^6$	0.00479	0.00455	-5.27473
0.27	$3.3*10^6$	0.00475	0.00447	-6.26398
0.316	$3.9*10^6$	0.00544	0.00516	-5.42636
0.35	$4.3*10^6$	0.00517	0.00489	-5.72597
0.408	$5.0*10^6$	0.00624	0.00573	-8.90052

From Table II it is seen that for Wigley hull CFD results of Ct is greater than the EFD results for all Fr. and maximum relative error is 8.9% at the highest Fr. of the range.

TABLE III: SERIES 60 SHIP: RELATIVE ERRORS OF TOTAL RESISTANCE COEFFICIENTS BETWEEN CFD AND EFD

Fr.	Re.	Ct CFD	Ct EFD	Error (%)
0.1	$1.2*10^6$	0.00474	0.00476	0.42017
0.15	$1.7*10^6$	0.00448	0.00456	1.75439
0.2	$2.2*10^6$	0.00455	0.00442	-2.94118
0.25	$3.1*10^6$	0.00457	0.00448	-2.00893
0.3	$3.8*10^6$	0.00619	0.00594	-4.20875
0.35	$4.3*10^6$	0.00653	0.00645	-1.24031

Table III shows that for Series 60 ship at low Fr. CFD results of Ct is smaller than the EFD results but as Fr. increases, CFD starts to overestimate the Ct than EFD with maximum relative error of 4.21% at Fr. 0.3.

IV. CONCLUSION

In this paper, potential flow, boundary layer flow and viscous flow theories are used to determine flow characteristics at different regions. From the above mentioned results and discussions, following conclusions can be drawn: (i) Zonal approach for computing flow characteristics takes less computational time than global approach as three solvers act successively to give results significant to that region. (ii) Wave pattern around ship hulls with different Fr. show characteristics of Kelvin wave pattern and computed wave elevations agree satisfactorily with experimental results. (iii) With increasing Fr. wave making and total resistance is accompanied by a number of humps and hollows due to interaction of divergent waves and frictional resistance decreases as Re. increases for both hulls. (iv) The computed results depend to a certain extent on the discretization of the body and the free-surface. The agreement between the computed and experimental results is quite satisfactory with increasing number of panels. However, it takes longer computation time.

ACKNOWLEDGMENT

Authors are grateful to Bangladesh University of Engineering and Technology (BUET) and sub-project CP # 2084 of Department of Naval Architecture and Marine Engineering under Higher Education Quality Enhancement Project (HEQEP), UGC, Ministry of Education, Govt. of Bangladesh for providing necessary research facilities during the current research work.

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