STEP FORWARD FOR CFD UNCERTAINTY ANALYSIS OF SHIP RESISTANCE BENCHMARK MODEL LHI-007

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ABSTRACT

Computational Fluid Dynamics (CFD) is a tool for solving the basic problems of equations for model flow motion. The CFD application can be used to predict the magnitude of the ship's resistance which is related to the engine power needed to move the ship. Benchmarking is the process of comparing different methods, procedures, and physical models to provide a common basis for the validation of numerical methods. This study simulates the resistance test on the LHI 007 benchmark ship model using FINE™/Marine with speed ranges 1.63 m/s – 2.47 m/s at a temperature of 27°C. The purpose of this research is to complete the simulation approach and numerical uncertainty for the previous study. By adding a time step component to the verification and validation of the uncertainty analysis, the error value gets smaller than the validation value for various speeds 1.63 m/s, 1.8 m/s, 1.91 m/s and 2.02 m/s. It shows that validation was achieved.

keyword: Resistance, CFD, benchmark, verification, validation

Introduction

The most important thing for designing a ship is to determine its resistance when focusing on the hydrodynamic performance [1]. Computational Fluid Dynamics (CFD) to predict ship resistance can be done as a virtual Towing Tank. Fluid dynamics calculations have advantages as a basis or even a reference before carrying out model testing.

In the last few decades, CFD has been a revolution in the world of engineering, and the rapid growth of computer capacities. CFD can be used to estimate resistance ship for solving Reynolds-average Navier-Stokes (RANS) equation using FINE™/Marine [2]. CFD methods provide relatively accurate results, fast and inexpensive in comparison with the experimental test [3].

Based on the results of the questionnaire recapitulation from the ITTC Committee regarding of using CFD in marine hydrodynamics, prediction of resistance to be the dominant application of CFD (64%). Other applications such as self-propulsion, propulsors, maneuvering, seakeeping, and ocean engineering are also of great interest with about 40% of respondents applying CFD to these problems [4] Based on the final report and recommendations to the 26th ITTC that have been held in Brazil, perform how often most respondents did quality checks for every computation, while a few do it rarely (6%) or sometimes (21%). Research that has been done by [5] related to the comparison between resistance simulation and experimental results from a fast ship, shows that the calculation of the medium Froude number Fr < 0.25 is an efficient and accurate tool to predict the curves of resistance for ship flow. Meanwhile, in the method that has been used to check the quality of computations only 16% follows the ITTC recommended verification and validation (V&V) procedure 7.5.03.01-01 [6]. However, most respondents are using other V&V procedures (26%) or best practices (23%) [4]. Verification and validation (V&V) of CFD codes and methods are essential for the improvement of the CFD methods and the quality assurance of the CFD applications. Since the derived uncertainty levels are only valid for a unique case and condition, each test case should be subjected to V&V studies. The research discussed by [7] is a study of ongoing efforts and updates toward increasing the uncertainty estimation of the Indonesian Hydrodynamics Laboratory with a special focus on the resistance test database for surface ships.

This study was designed to address a variety of important physics and expand the surface-ship database with quality datasets and uncertainty assessment. The previous study that has been carried out by Purnamasari, et al (in press) was to analyze the uncertainty of resistance prediction on the Ferry Ro-Ro LHI-007 benchmark model by discussing the analysis of uncertainty in variations in grid size (coarse, medium, and fine) in four-speed configurations. The paper concludes that the present solver can predict the resistance of the benchmark model with reasonable accuracy.

The purpose of this study is to complement the results of previous studies based on [8] which for the uncorrected simulation approach, the numerical error is decomposed into contributions from iteration number, grid size, time step, and other parameters. Here we discuss the measurement uncertainty analysis of the numerical resistance benchmark model which is validated based on the results of the resistance test at a temperature of 27° with 8-speed variations. This study focuses on the time step and grid size that have been studied in previous studies. This is needed to see the error value of the experimental data.

This study is a continuous effort and renewal towards the improvement of the Indonesian Hydrodynamics Laboratory in compliance as a testing laboratory accredited to ISO 17025:2017. It is hoped that in this study the results of numerical simulations in predicting total ship resistance (RT) complement the experimental data as well as the results of verification and validation which can later be used as a reference for the Indonesian Hydrodynamics Laboratory in benchmarking the LHI 007 ship model in the following year as a requirement for ISO 17025:2017 Accreditation [9].

Methodology

The stages in this study can be described in the flowchart below, see Figure 1. The research starts by collecting literature studies and the required data. Performing numerical analysis with variations in grid size and time step along with preparing resistance test data and uncertainty analysis. Then the error calculation is performed and numerical uncertainty analysis is obtained and compared with the test uncertainty analysis.The particulars of the experimental model in this study are given in full in Table 1 and Figure 1.

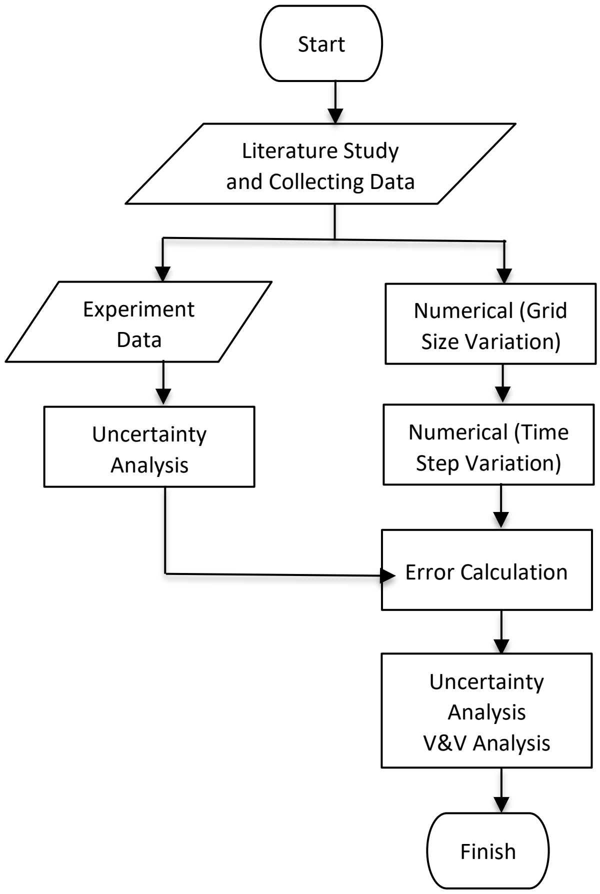

Figure 1. Step forward analysis flowchart

Mathematical Modelling

A mathematical model of the FINE™/Marine CFD based on Reynolds Averaged Navier Stokes (RANS) equations. The solver applied a finite volume method for the spatial discretization and the discretization of the transport equations. Considering an incompressible multi-phase flow of viscous fluid equations are represented in Equations (1-3) as follows:

A detailed description of the mathematical model and numerical methods for solving is presented below. Equations (1) and (2) are the incompressible RANS equations in tensor form and Equation (3) is the volume fraction transport equation [10].

$$\frac{\partial}{\partial t}\int_{v} \rho dV + \int_{s} \rho(U - U_d).n\, dS = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\int_{v} \rho U_i dV + \int_{s} \rho U_i (U - U_d)\, n\, dS = \int_{s} (\tau_{ij} I_j - p I_i) . n\, dS + \int_{s} \rho g_i\, dV \quad (2)$$

$$\frac{\partial}{\partial t}\int_{v} c_i dV + \int_{s} c_i (U - U_d) . n\, dS = 0 \quad (3)$$

In Equations (1-3), V is the domain of interest, or a control volume, bounded by a closed surface S moving at the velocity Ud with a unit normal vector n directed outward. U and p represent, respectively, the velocity and pressure fields. Further, τij and gi are the components of the viscous stress tensor and the gravity vector, whereas Ij is a vector whose components vanish, except for the component, which is equal to unity. ci is the i-th volume fraction for fluid i and is used to distinguish the presence (ci=1) or the absence (ci=0) of fluid i.

The two-equation k-ω SST turbulence model (SST stands for shear stress transport) was applied in the present study. This turbulence model combines the k-ω model for the flow in the inner boundary layer and the k-ε model for the flow in the outer region of and outside of the boundary layer. The transport equations for the k-ω SST model are as follows: [10].

$$\frac{\partial}{\partial_t}(\rho k) + \frac{\partial}{\partial_{x_i}}(\rho k u_i) = \frac{\partial}{\partial_{x_j}}\left(\Gamma_k \frac{\partial_k}{\partial_{x_j}}\right) + G_k - Y_k \quad (4)$$

$$\frac{\partial}{\partial_t}(\rho \omega) + \frac{\partial}{\partial_{x_i}}(\rho \omega u_i) = \frac{\partial}{\partial_{x_j}}\left(\Gamma_\omega \frac{\partial_\omega}{\partial_{x_j}}\right) + G_\omega - Y_\omega + D_\omega \quad (5)$$

Geometry

This paper as a benchmark model used the LHI-007 Ferry Ro-Ro Ship model. The geometry of the benchmark model and principles dimension of the LHI-007 Ferry Ro-Ro Ship is shown in Figure 1 and Table 1.

Figure 2. The geometry of the benchmark model (LHI-007 Ro-Ro Ferry)

Table 1. Principle dimension of Ferry Ro-Ro Ship and CFD Model

Principle Dimension	Ship	CFD Model
Scale	1	20.97
Length overall (m)	154.94	7.25
Length on Waterline (m)	146.94	7.00
Breadth (m)	24.00	1.15
Draft (m)	6.50	0.31
Wetted Surface Area (m^2)	4042.00	9.19
Displacement Volume (m^3)	14.21	1.58
Block Coefficient (C_b)	0.80	0.80

The ship resistance simulation was used in calm water conditions and the LHI-007 Ro-Ro Ferry Ship model is used free to sink and trim as described in Purnamasari, et al (in press). The prediction of ship resistance simulation was used real value in the experimental set up in Towing Tank Indonesian Hydrodynamics Laboratory as follows in table 2. The numerical simulation uses steady-state flow, calm water, ship models free from trim and sinks, and models turbulence using k-ε shear-Stress.

Table 2. Data simulation ship resistance

Description	Unit	Data
Temperature	°C	27
Density	kg/m^3	996.515
Kinematic Viscosity	m^2/s	$8.54x10^{-7}$
Speed	m/s	1.63 to 2.47

In this study, a numerical simulation of the benchmark model is symmetrical in geometry hence only half of the ship hull. The global coordinate system (x, y, z), domain and boundary conditions indicate fluid flow around the hull model. The x-axis is positive from the midship to the bow and the z-axis is positive when opposite to gravity. Boundary conditions used include: "slip" on the deck model, "prescribe pressure" on the top and bottom, inlet and outlet using "far field", top-bottom. The meshing used in the numerical simulation uses C-Wizard with variations including coarse, medium, and fine. The course, medium and fine grid had 448.158; 669.058; and 967.939 cells. The total resistance of the ship calculated by varying grid (coarse, medium and fine), 8 (eight) speed variations (1.63 m/s; 1.81 m/s; 1.91 m/s; 2.02 m/s; 2.14 m/s; 2.25 m/s; 2.36 m/s and 2.47 m/s) and time step (Δt) sizes are an important factor effect on numerical accuracy. Δt must be smaller than 0.01 L/U if one or two equation turbulence models are used, while it should be smaller than 0.001 L/U if Reynolds stress turbulence model is used [11].

Uncertainty Analysis Based on ITTC

Uncertainty analysis is a systematic study conducted to assess the consistency and accuracy of the solver in this case the CFD simulation in solving the problem in question. Uncertainty analysis is divided into two processes, verification and validation. Verification assesses the consistency of the solver, while validation evaluates its accuracy [12]. Verification and validation (V&V) of the CFD code method is very important for improving the CFD method and guaranteeing the quality of CFD applications. Since the derived level of uncertainty applies only to unique cases and conditions, each test case must be subjected to a V&V study. The basic strategy of validation is to assess how accurate the computational results are compared to experimental data, with measured errors and estimated uncertainties for both. ITTC Standards and Procedures are used as a method for the verification and validation of numerical resistance tests. In procedures include verification procedures for estimation of numerical uncertainty and validation procedures for the estimation of modelling errors [8].

Verification Procedure

The verification procedure includes convergence studies, followed by Richardson Extrapolation and Estimating Uncertainties in accordance with [8]. Convergence studies require a minimum of m=3 solutions to evaluate convergence concerning the input parameters. Note that m=2 is inadequate, as it only indicates sensitivity and not convergence, and that m>3 may be required, Changes between medium-fine $\varepsilon_{i,21}=S_{i,2}-S_{i,1}$ and coarse medium $\varepsilon_{i,32}=S_{i,3}-S_{i,2}$ solutions are used to define the convergence ratio:

$$R_i = \frac{\varepsilon_{i,21}}{\varepsilon_{i,32}} \tag{6}$$

Based on the value of Ri, obtained three convergence conditions as follows:

(i). Monotonic convergence: 0< Ri <1
(ii) Oscillatory convergence: Ri <0 (7)
(iii) Divergence: Ri >1

If the convergence obtained is monotonic, Richardson extrapolation is used to estimate the error δ*i and the order of accuracy Pi which can be expressed in the equation:

$$p_i = \frac{\ln(\varepsilon_{i,32}/\varepsilon_{i,21})}{\ln(r_i)} \tag{8}$$

$$\delta^{*(1)}_{RE_{i,1}} = \frac{\varepsilon_{i,21}}{r_i^{p_i} - 1} \tag{9}$$

If the obtained convergence is oscillatory, then,

$$U_i = \frac{1}{2}(S_U - S_L) \tag{10}$$

where S_U is the average of oscillating maximums and S_L is the average of oscillating minimum. Meanwhile, if the convergence obtained is divergence, error, and uncertainty cannot be estimated. Alternatively, a factor of safety approach can be used to define the uncertainty Ui, where an error estimate from RE is multiplied by a factor of safety Fs to bound simulation error, the equation as below:

$$U_i = F_s\left|\delta^*_{RE_{i,1}}\right| \tag{11}$$

Fs = 1.25 is used when Ci is close to 1 (0.875<Ci<1.125).

For the uncorrected simulation approach, the numerical error is decomposed into contributions from iteration number δ_I, grid size δ_G, time step δ_T, and other parameter δ_P. Simulation numerical uncertainty can be described below:

$$U_{SN}^2 = U_I^2 + U_G^2 + U_T^2 + U_P^2 \tag{12}$$

Validation Procedure

The comparison error E is given by the difference in the data D and simulation S values [8].

$$E = D - S \tag{13}$$

After predicting the simulation numerical uncertainty, validation uncertainty is calculated by adding the involved data uncertainty. So, with validation uncertainty, Uv, error E, and the required level of validation uncertainty Ureqd, six possible scenarios can be observed.

1. $U_{reqd} < U_v < |E|$
2. $|E| < U_{reqd} < U_v$
3. $U_{reqd} < |E| < U_v$
4. $U_v < |E| < U_{reqd}$ (14)
5. $U_v < U_{reqd} < |E|$
6. $U_{reqd} < U_v < |E|$

Where to get U is by adding the value of UD (experimental) with the value of USN (numerical). Validation is defined as a process for assessing simulation modelling uncertainty by using benchmark data and when conditions permit.

Result and Discussion

The total resistance of LHI 007 using experimental data and simulation grid variation was shown in Figure. 3., resistance total used fine grid was more approach experiment data. There was a significant difference in total resistance for speed numbers 2.36 m/s and 2.47 m/s.

The deviation between simulation value (S) and experimental value D was shown in Table 3 and Table 4. The biggest deviation was 6.810% for speed number 2.47 m/s in the coarse grid and the smallest deviation was 0.027% for speed number 2.14 m/s in the medium grid. Overall fine grid number the deviation was smallest than other grids in the highest speed (2.25 m/s, 2.36 m/s, and 2.47 m/s).

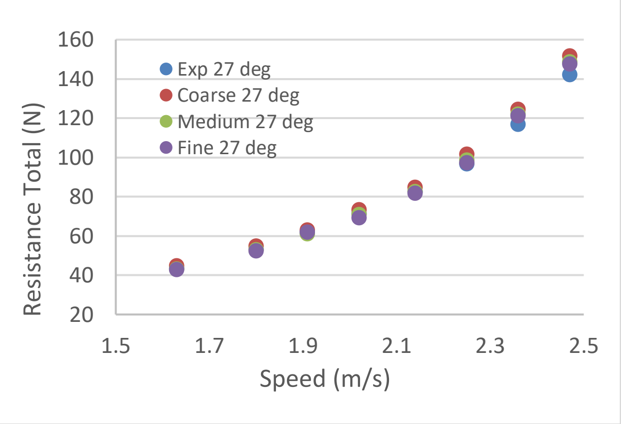

Figure 3. The total ship resistance in various grids was compared through the simulation and the experimental

And then, to make sure the result of simulation must be calculated uncertainty. In this study, uncertainty the results of the calculation of the uncertainty of the grid variation in the speed range of 1.24 m/s d 2.47 m/s at a temperature of 27°C were shown in Table 5 and the uncertainty of the various time steps was shown in Table 6. From the Table 5 and Table 6, it can be seen that convergence conditions consist of monotonic convergence (0<R<1), oscillatory convergence (R<1) and divergence (R>1). As for oscillatory convergence to Equation (8) and (9) is not estimated and uncertainty is estimated by equation 10. and for case of divergence convergence, uncertainty cannot be estimated (NE).

Table 3. Deviation of the total resistance experimental to the simulation (grid variations)

V (m/s)	Deviation (%) Coarse	Deviation (%) Medium	Deviation (%) Fine
1.63	-3.211	0.723	0.963
1.81	-3.387	0.109	1.343
1.91	-1.939	1.405	-0.073
2.02	-2.694	0.589	2.773
2.14	-2.767	-0.027	0.895
2.25	-5.145	-2.139	-0.738
2.36	-6.610	-4.607	-3.836
2.47	-6.810	-4.634	-3.895

Table 4. Deviation of the total resistance experimental to the simulation (time step variations)

V (m/s)	Deviation (%) Time Step#1	Deviation (%) Time Step#2	Deviation (%) Time Step#3
1.63	1.766	1.498	1.157
1.81	-0.498	-0.505	-0.698
1.91	0.765	0.451	-0.157
2.02	1.033	0.435	0.236
2.14	0.587	-0.441	0.005
2.25	-1.049	-1.874	-1.893
2.36	-3.531	-3.719	-3.815
2.47	-4.439	-4.959	-4.605

Table 5. Result of total resistance for grid verification

V (m/s)	ε_{21}	ε_{32}	R_G	P_G	δ^*_{RE}	U_G
1.63	0.104	1.704	0.061	8.069	0.007	0.008
1.81	0.654	1.854	0.353	3.007	0.356	0.446
1.91	-0.914	2.068	-0.442	NE	NE	1.034
2.02	1.556	2.340	0.662	1.177	3.088	3.860
2.14	0.760	2.260	0.336	3.145	0.385	0.481
2.25	1.354	2.904	0.466	2.202	1.183	1.478
2.36	0.900	2.336	0.385	2.752	0.564	0.705
2.47	1.048	3.090	0.339	3.120	0.538	0.672

Table 6. Result of total resistance for time step verification

V (m/s)	ε_{21}	ε_{32}	R_T	P_T	δ^*_{RE}	U_T
1.63	0.116	0.148	1.276	NE	NE	NE
1.81	0.040	0.102	2.550	NE	NE	NE
1.91	0.194	0.376	1.938	NE	NE	NE
2.02	0.426	0.142	0.333	-3.170	-0.639	-0.799
2.14	0.848	-0.368	-0.434	NE	NE	0.424
2.25	0.798	0.018	0.023	-10.941	-0.816	-1.021
2.36	0.220	0.112	0.509	-1.948	-0.448	-0.560
2.47	0.738	-0.502	-0.680	NE	NE	0.369

Then from the results of the analysis, the uncertainty of the numerical simulation measurement is verified and validation with experimental data analysis of resistance test uncertainty ship model in the Indonesian Hydrodynamics Laboratory Towing Tank. The value Uncertainty of single Resistance experimental at temperature 27°C was calculated.

From the results of the calculations in Table 5 and Table 6, the uncertainty value of simulation numerical was estimated by Equation 11. the U_{SN} results is obtained from the combination of the numerical value of the grid size and the time step. The U_{SN} value obtained is then compared with the experimental uncertainty analysis obtained. Validation of Total resistance is shown in Table 7. Validation can be accepted by comparing Error values which can be estimated by Equation (12) where if $E<U_{val}$ then validation is achieved. From Table 7 we can see that the value of E is smaller than U_{val} except at high speeds 2.25 m/s, 2.36 m/s, and 2.47 m/s.

Table 7. Validation of the total resistance (27^{0}C)

V (m/s)	*U_{SN}*	*U_D*	*U_V*	*E*
1.63	0.008	0.784	0.784	0.765
1.81	0.446	0.828	0.940	-0.264
1.91	1.034	0.755	1.280	0.473
2.02	3.061	0.778	3.159	0.736
2.14	0.905	0.758	1.181	0.484
2.25	0.458	0.737	0.868	-1.013
2.36	0.145	0.666	0.682	-4.118
2.47	1.041	0.916	1.387	-6.302

Conclusion

From the results of the LHI-007 benchmark simulation study using the steady RANSE method, the deviation of total resistance from experiment result area ranges from 0.027%-6.810%.

Uncertainty analysis in CFD has become an important part of CFD to ensure its consistency and reliability. Numerical uncertainty of the total resistance is predicted by a combination of grids (UG) and time-step (UTS) uncertainty, this demonstrates uncertainty in a simulation which is quantified by the conditions of consistency and convergence.

Systematic and reliable verification and validation study for benchmark model LHI-007 for calm water simulation. According to the result and discussion, the simulation uncertainty analysis has shown grid and timestep respectively, have an impact on resistance.

The result of uncertainty analysis with various grids and the time steps concludes that the error value is smaller than the uncertainty validation value for speed 1.63 m/s, 1.8 m/s, 1.91 m/s and 2.02 m/s it means validation achieved.

Furthermore, needs to have simulation of different ship model was studied to obtain a proper verification and validation.

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