Adham BEKHIT

NUMERICAL SIMULATION OF THE SHIP HULL HYDRODYNAMIC PERFORMANCE

SIMULAREA NUMERICĂ A PERFORMANȚELOR HIDRODINAMICE ALE CORPULUI NAVEI

- Teză de doctorat -

EDITURA FUNDAŢIEI UNIVERSITARE„*Dunărea de Jos*” – GALAŢI – 2023
ISBN 978-973-627-689-7

UNIVERSITATEA „DUNĂREA DE JOS” GALAȚI
Facultatea de Arhitectură Navală

Editura Fundaţiei Universitare „Dunărea de Jos” din Galaţi
este acreditată de CNCSIS

Referent științific:
Prof. univ. dr. ing. Florin Popescu

©Editura Fundaţiei Universitare
“Dunărea de Jos”, Galaţi, 2023
ISBN 978-973-627-689-7
Directorul editurii.
Prof. univ. Emerit dr. Cosma TUDOSE

www.editura.ugal.ro
editura@ugal.ro

Acknowledgments

I would like to express my endless gratitude and thanks for those who helped me and offered their unconditional support.

Special thanks to Dr. Thomas B.

This work was entirely submitted for the accordance of the PhD title, public defense was held on September 22nd, 2021, while the confirmation of the PhD title was granted based on the Ministry of Education order nr. 5999/30.12.2021.

Nomenclatures

S_L	Minimum oscillation value in simulation
S_U	Maximum oscillation value in simulation
T_e	Wave encounter period
U_P	General parameter uncertainty
δ_P	General parameter error
Δ_y	Distance of the first point from the solid wall
$\mathrm{CD}_{\mathrm{k}\omega}$	Cross-diffusion in the $K-\omega$ model.
g_i	Gravity vector
Ω_{ij}	Vorticity magnitude
C_F	Frictional Resistance coefficient
C_R	Residual Resistance coefficient
CF_∞	Value of fitted function in verification process
C_T	Total resistance coefficient
C_i	Correction factor
E_{av}	Average absolute error
F_S	Factor of safety
I_j	Unity vector whose components vanish, except for the component j
Q^*	Second invariant Q criterion
R_F	Frictional Resistance
R_R	Residual Resistance
R_G	Grid convergence ratio
R_T	Time step convergence ratio
R_T	Total resistance
R_i	Convergence ratio
S_C	Simulation benchmark
S_{ij}	Total stress tensor
U_{S_CN}	Corrected uncertainty
U_{V_c}	Corrected validation uncertainty
$\vec{U}$	Velocity vector
U_∞	Far field velocity
U_D	Data uncertainty
U_G	Grid uncertainty
U_I	Iteration uncertainty
U_S	Simulation uncertainty
U_{SM}	Modeling uncertainty
U_{SN}	Numerical uncertainty
U_T	Time step uncertainty
U_V	Validation uncertainty
U_{reqd}	Required level of uncertainty
c_i	Volume fraction for fluid i
f_e	Wave encounter frequency
f_w	Wave frequency
$\vec{n}$	Unit normal vector directed outward
p_∞	Far field pressure
p_G	Grid order of accuracy
p_T	Time step order of accuracy
p_a	Atmospheric pressure

p_i	Simulation order of accuracy
r_G	Grid refinement ratio
r_i	General verification ratio
y^+	Non-dimensional distance from the wall
γ_I	Wave initial phase angle
δ_D	Data error
δ_G	Grid error
δ_I	Iteration error
δ_{RE}^*	Richardson Extrapolation error
δ_S	Simulation error
δ_{SM}	Modeling error
δ_{SN}	Numerical error
δ_{SN}^*	Estimated value with sign and magnitude of the numerical error
δ_T	Time step error
δ_{ij}	Kronecker (delta) operator
ε_{av}	Average relative error
ζ_i	Incident wave height
ν_t	Turbulent eddy viscosity
ρ_a	Mass density of air
ρ_w	Mass density of water
σ_a	Tangential force on the free-surface in water
σ_w	Tangential force on the free-surface in water
τ_{ij}	Viscous stress tensor
τ_{ij}	Mean viscous stress tensor
Δp_γ	Pressure jump at the free-surface interface
Δx	Cell size in x-direction
Δy	Cell size in y-direction
Δz	Cell size in z-direction
A	Wave amplitude
A_0	Propeller disk area
A_E	Expanded blade area
B	Beam of the ship
C_{AW}	Added resistance in waves coefficient
C_B	Block coefficient
C_H	Heave force coefficient
C_M	Mid-ship section coefficient
C_M	Pitch moment coefficient
C_{Tcw}	Calm water total resistance coefficient
C_{Tw}	Total resistance coefficient in waves
D	Measured value in tank test
D	Depth of the ship
D_h	Propeller hub diameter
D_p	Propeller diameter
Fr	Froude number
He	Helicity
H_w	Wave height
J	Propeller advance coefficient
k	Wave number
K_Q	Propeller torque coefficient
K_T	Propeller thrust coefficient
LCB	Longitudinal center of buoyancy
L_{PP}	Length between perpendicular

L_{ref}	Reference length
M_i	General representation for grid density, i=1:n, finest grids i=1, coarsest grid i=n
$Ø$	Roll angle
$Ø_0$	Initial roll angle
$Ø_m$	mean decay roll value
Q	Propeller torque
RAO	Response Amplitude Operator
Re	Reynolds number
S	Simulation value computed based on CFD
S_0	Wetted surface area of the ship without appendages
SFC	Shear Force Correction
S_R	Wetted surface area of the rudder
T	Draft of the ship
T	Simulation time
T	Propeller thrust
T	Wave period
t	Simulation time
TF	Response Transfer Function
U	Ship Speed, axial flow velocity in x-direction
V	Axial flow velocity in y-direction
W	Axial flow velocity in x-direction
x_{CG}	Longitudinal position of C.O.G
Z	Number of propeller blades
z_{CG}	Vertical position of C.O.G
Δ	Ship displacement
$\Delta Ø$	Roll angle decrement
Δt	Simulation time step
ζ	Absolute free-surface elevation
λ	Wave length
ω	Specific dissipation rate of turbulent frequency
ω	Wave circular frequency
E	Absolute error
K	Kinetic energy
$P(t)$	Fourier transform parameter
S	Control surface in fluid governing equation
V	Control volume in fluid governing equation
c	Volume fraction coefficient
n	Propeller rotation rate
p	Pressure field
u	Fluid velocity in x-direction
v	Fluid velocity in y-direction
w	Fluid velocity in z-direction
$\mathcal{D}(\,)$	Divergence operator
∇	Volume of displacement
β	Modeling coefficient for k-ω turbulence model
γ	Surface tension
ε	Turbulent energy dissipation
$\varepsilon\%$	Relative error
μ	Viscosity
ρ	Mass density of fluid
σ	Sinkage
τ	Trim

Abbreviations

A.P.	Aft Perpendicular
ABKV	Aft-Body Keel Vortices
AIAA	American Institute of Aeronautics and Astronautics
ALE	Lagrangian-Eulerian
ASM	Algebraic Stress Model
AW	Active Wall
BEM	Boundary Element Method
BKV	Bilge Keel Vortices
BSV	Bottom-Shaft Vortices
CAD	Computer Aided Design
CFD	Computational Fluid Dynamic
CFL	Courant–Friedrichs–Lewy number
CMT	Circular Motion Test
CPU	Central Processing Unit
DARPA	Defense Advanced Research Projects Agency
DDES	Delayed Detached Eddy Simulation
DES	Detached Eddy Simulation
DHRL	Dynamic Hybrid RANS/LES
DNS	Direct Numerical Simulation
DOF	Degrees of Freedom
DTMB	David Taylor Model Basin
DTRC	David Taylor Research Center
DW	Disabled Wall
EASM	Explicit Algebraic Stress Model
EEDI	Energy Efficiency Design Index
EEO	Energy Efficiency Operational Indicator
EFD	Experimental Fluid Dynamic
ESD	Energy Saving Devices
F.P.	Forward Perpendicular
FBKV	Fore-Body Keel Vortices
G2K	Gothenburg 2000 Workshop on Computational Ship Hydrodynamics
GD	General Domain
GHG	Green-House Gases
HMRI	Hyundai Maritime Research Institute
HPC	High Performance Computing
HSVA	Hamburgische Schiffbau-Versuchsanstalt (Hamburg Ship Model Basin)
IDB	International Data Base
IDDES	Improved Delayed Detached Eddy Simulation
IIHR	Iowa Institute of Hydraulic Research
IMO	International Maritime Organization
INSEAN	Istituto Nazionale per Studi Ed Esperienze di Architettura Navale
ITTC	International Towing Tank Conference
JBC	Japan Bulk Carrier
KCS	KRISO Container Ship
KRISO	Korea Research Institute of Ships and Ocean Engineering
KVLCC	KRISO Very Large Crude Carrier
LBM	Lattice Boltzmann Method
LDV	Laser Doppler Velocimetry
LES	Large Eddy Simulation
LIF	Laser Induced Fluorescence

MAC	Marker-And-Cell
MARIN	Maritime Research Institute of Netherlands
MEPC	Marine Environment Protection Committee
MOERI	Maritime and Ocean Engineering Research Institute
NMRI	National Maritime Research Institute
NSE	Navier-Stokes Equations
NSWC	Naval Surface Warfare Center (Carderock Division)
NTNU	Norwegian University of Science and Technology
ONRT	Office of Naval Research Tumblehome
OU	Osaka University
PISO	Pressure-Implicit with Splitting of Operators
PIV	Particle Image Velocimetry
PMM	Planar Motion Mechanism
POW	Propeller Open Water
PTV	Particle Tracking Velocimetry
RANS	Reynolds-Averaged Navier-Stokes
RANSE	Reynolds-Averaged Navier-Stokes Equations
RAO	Response Amplitude Operator
RE	Richardson Extrapolation
RSM	Reynolds Stress Model
RTV	Rudder Tip Vortices
SDV	Sonar Dome vortices
SIMMAN	Workshop on Verification and Validation of Ship Manoeuvring Simulation Methods
SIMPLE	Semi-Implicit method for Pressure-Linked Equations
SPIV	Stereo Particle Image Velocimetry
SST k-ω	k-ω Shear Stress Transport turbulence model
SV	Shaft Vortices
TKE	Turbulent Kinetic Energy
URANSE	Unsteady Reynolds-Averaged Navier-Stokes Equations
VLM	Vortex Lattice Method
VOF	Volume Of Fluid

List of Figures

		Pg.
Figure 1.1	Classification of methods used in viscous computational hydrodynamics	8
Figure 1.2	The development of CFD in ship hydrodynamics	12
Figure 2.1	General CFD process	36
Figure 3.1	Sources of errors in CFD results	37
Figure 3.2	Geometrically similar grid for a simple cube configuration	47
Figure 3.3	Geometrically similar grids for the JBC ship model	48
Figure 4.1	JBC model geometry highlighting stern, fore, duct, propeller and rudder	50
Figure 4.2	Computational domain, dimensions and boundary conditions	51
Figure 4.3	Computational grid, showing: (a) JBC with ESD, (b) duct and strut, (c) free-surface refinement, (d) fore and (e) stern comparison between fine and coarse grids	53
Figure 4.4	Computed total resistance coefficient C_T with: (a) JBC w/o. ESD, (b) JBC w. ESD and (c) Richardson Extrapolation error	56
Figure 4.5	Computed free-surface at T=30 s, showing: (a) free-surface configuration, (b) mass fraction, (c) CFD vs. EFD for the free-surface topology, (d, e and f) CFD vs. EFD for wave profile at the hull, at distances y/L_{PP}=0.1043 and y/L_{PP} =0.19, respectively	57
Figure 4.6	PIV measuring sections	58
Figure 4.7	EFD and CFD results for the axial velocity contours computed at T=30s for ship without ESD at section S2 using different turbulence models	59
Figure 4.8	Section S4 EFD and CFD results for the axial velocity contours computed at T=30s for ship without ESD using different turbulence models	59
Figure 4.9	Section S7 EFD and CFD results for the axial velocity contours computed at T=30s for ship without ESD using different turbulence models	60
Figure 4.10	Comparison between the streamwise velocity contours measured and computed at T=30 s using EASM turbulence model for ship with ESD for sections S2, S4 and S7	60
Figure 4.11	Workshop data for the second invariant iso-surface Q^*=25 colored by helicity and the corresponding CFD results computed at T=30 s using EASM model	61
Figure 4.12	KVLCC2 model geometry highlighting propeller and rudder	62
Figure 4.13	Discretization grid for ship with; simplified rudder (left) and actual rudder (right)	64
Figure 4.14	Obtained results for ship without rudder: (a) Computed total resistance coefficient C_T compared to the EFD, (b) estimated error as a function of grid density	64

Figure 4.15	CFD results compared to EFD showing: (a) total resistance coefficient C_T (b) sinkage σ and (c) trim τ	65
Figure 4.16	Free-surface topology (left), and wave cuts at y/L_{pp}=-0.0964 and -0.1581(right)	66
Figure 4.17	CFD vs. EFD streamwise velocity contours at sections: x/L_{pp}=0.85 and 0.9825	66
Figure 4.18	Velocity and TKE contours in the wake	67
Figure 4.19	Second invariant iso-surface Q^*=25 colored by non-dimensional helicity	67
Figure 4.20	DTMB model geometry viewing: front, profile, bottom and rear	68
Figure 4.21	Computational grids showing: (a) Fine and coarse grids, (b) free-surface refinement and (c) a forward section	70
Figure 4.22	Total resistance results based on the grid density	71
Figure 4.23	Total resistance error computed for Fr=0.28 based on the wall treatment approach	72
Figure 4.24	Free-surface profile (left), and wave cuts at y/L_{pp}=0.082 and y/L_{pp}=0.172 (right)	73
Figure 4.25	CFD vs. EFD streamwise velocity contours at different sections	74
Figure 4.26	Discretization grid highlighting the appendages refinement	75
Figure 4.27	Resistance results for the fully appended ship and hull components individually	76
Figure 4.28	Free-surface profiles for bare and appended hull	77
Figure 4.29	Comparison between bare and appended hull for axial velocity contours (U) and Turbulent Kinetic Energy (TKE)	79
Figure 4.30	Second invariant iso-surface Q^*=10 colored by non-dimensional helicity bottom view: (a) Bare hull, (b) appended hull, and (c) appended hull profile	80
Figure 4.31	Ship model and the towing carriage arrangement	82
Figure 4.32	Free-surface topology at ship extremities during the test: bow (left), stern (right)	84
Figure 4.33	Extrapolated data of the UGAL – Model compared to INSEAN – Model	85
Figure 4.34	Wave pattern for active tank walls domain showing wave reflection at the wall	87
Figure 4.35	Wave elevation diagram: (a) general domain, (b) active walls domain	88
Figure 4.36	The numerically predicted against the measured free-surface profile at model extremities	88
Figure 5.1	Simulation domain dimensions and boundary conditions in x-z and y-z view	91
Figure 5.2	Discretization grids for the finest grid illustrating blades grid and refinement zone	92
Figure 5.3	Thrust coefficient K_T, torque coefficient K_Q and propeller open water efficiency η curves compared to EFD data	93
Figure 5.4	Pressure distribution on the suction and pressure sides of the propeller at different advance ratios J: a) J=0.7, a) J=0.5, a) J=0.3 and a) J=0.1	93

Figure 5.5	Axial flow velocity, pressure distribution, turbulent viscosity and TKE in the propeller wake for J=0.3 and J=0.6	94
Figure 5.6	Vortical structure of the wake flow computed at T=5 sec. for: (a) J=0.3, (b) J=0.6	95
Figure 5.7	Longitudinal cut in the vortical structure of the wake flow at J=0.6	95
Figure 5.8	Computational domain and boundary conditions for self-propulsion simulation	96
Figure 5.9	Sliding grid arrangement for JBC without ESD (left) and with ESD (right)	97
Figure 5.10	Grid arrangement for: actuator disk(left) and sliding grid (right) approches	98
Figure 5.11	CFD results for nominal (a and b) and effective (c and d) velocity contours computed for ship without and with ESD, respectively, using actuator disk method	100
Figure 5.12	Results interpolation to predict the propeller revolution rate	101
Figure 5.13	Comparison between the streamwise velocity contours measured and ship without ESD for sections S4 and S7	102
Figure 5.14	Comparison between the streamwise velocity contours for ship without ESD and the second invariant Q^*=50 for ship with and without rudder, computed using DES turbulence model	103
Figure 5.15	Mesh arrangement of the fine grid	105
Figure 5.16	Open water propeller performance curves CFD results against EFD data	106
Figure 5.17	Vorticity at J=0.2: (a) vector form, (b) magnitude, (c) trajectory and (d) vortex cores	106
Figure 5.18	Second invariant computed for J=0.2 based on different turbulence models for iso-surface=500	107
Figure 5.19	Flow characteristics computed for J=0.2 based on DDES turbulence model	107
Figure 5.20	Second invariant computed for J=0.4 based on different turbulence models for iso-surface=250	108
Figure 5.21	Flow characteristics computed for J=0.4 based on DDES turbulence model	108
Figure 5.22	Second invariant computed for J=0.6 based on different turbulence models for iso-surface=125	109
Figure 5.23	Flow characteristics computed for J=0.6 based on DDES turbulence model	109
Figure 5.24	Grid geometry for actuator disk approach (top) and fully discretized propeller (bottom) highlighting the propeller and rudder	111
Figure 5.25	Prediction of the self-propulsion point using interpolation method	112
Figure 5.26	Streamwise velocity contours comparison between CFD and EFD	113
Figure 5.27	Vortices formation in the wake showing the profile and bottom view	113
Figure 6.1	Domain geometry, dimensions and boundary conditions	117
Figure 6.2	Grid configuration showing: stern, bow, longitudinal section free-surface top view	118

Figure 6.3	Resistance C_T, Heave C_H and Pitch C_M coefficients compared to EFD	119
Figure 6.4	Grid resolution effect on the total resistance coefficient	120
Figure 6.5	Comparison between the time history of the total resistance based on wave steepness for *Ak* = 0.025, 0.050 and 0.075	120
Figure 6.6	Schematic diagram for the quartering wave instants corresponding to the encountering moment with the F.P. of the ship	121
Figure 6.7	Computed free-surface at four wave quarters compared EFD	121
Figure 6.8	Wave visualisation at the bow and stern of the ship for *Ak=0.075* at different encountering instants	122
Figure 6.9	Wave profile and mass fraction for *Ak=0.075* when the peak and trough encounter F.P., from left to right, respectively	122
Figure 6.10	Relative velocity contours at x/L_{PP}=0.935 and t t/T=0 compared to EFD	123
Figure 6.11	Streamwise velocity contours for different wave steepness	123
Figure 6.12	Total resistance coefficient C_{TW} computed based on grid convergence study for C1	126
Figure 6.13	Heave response computed based on the grid convergence study for C1	127
Figure 6.14	Pitch response computed based on the grid convergence study for C1	128
Figure 6.15	Added resistance in wave schematic representation	129
Figure 6.16	Unsteady signal of the total resistance time history at λ=1.0 L_{pp} and λ=1.25 L_{pp}	130
Figure 6.17	RAO for: (a) heave and (b) pitch compared to EFD data [87] at cases2~8	130
Figure 6.18	Relative wave elevation computed for free and fixed ship conditions	132
Figure 6.19	Free surface profile and mass fraction computed for case C11 at Fr=0.41	132
Figure 6.20	Hull wave interaction at t/T=0 and t/T=0.5	133
Figure 6.21	Relative velocity contours at x/L_{PP}=0.935 and t/T=0 compared to EFD	133
Figure 6.22	Axial velocity contours computed at equal distances Δx=0.1L_{pp}, and second invariant iso-surface=50 at a random momewnt during simulation	134
Figure 6.23	Vortices formation in wave at t/T=0 and 0.5 compared to calm water	133
Figure 6.24	Simulation domain and boundary conditions	136
Figure 6.25	Finest grid discretization, spotting: (a) 3D hull; (b): longitudinal section; (c,d): lateral section depicting the refinement boxes around the hull and bilge keels; (e): the free-surface refinement section top view	137
Figure 6.26	Time history for roll simulation at altered initial roll angles	139
Figure 6.27	Fitted decay curves for computed results compared to EFD data	140
Figure 6.28	Time history for roll decay based on: (a) grid & (b) time step convergence tests	141
Figure 6.29	Free-surface topology recorded in the second roll period at the four quarters in case of initial roll angle $Ø_0$=10 and Fr=0.28	142
Figure 6.30	Time history for roll decay curves corresponding to various ship speeds	143
Figure 6.31	Computed free-surface at the 6th roll for various ship speeds	143
Figure 6.32	Computed and measured velocity contours at x/L_{pp}=0.675 for the second roll period instances: (a) t/T=0.5; (b): t/T=0.75	144
Figure 6.33	Vortices formations during the roll period quarters showing: (a) ship bottom, (b, c) starboard port sides, respectively for t/T=0	145

Figure 6.34	(a): U contours, (b): TKE contours and (c): Q*=25 second invariant visualized at section x/L_{pp}=0.675 at 8 segments of the roll period	147
Figure A.1	Main components of the ship hydrodynamics computational methods	169
Figure A.2	Hierarchy of turbulence models based on physical modeling and computational cost	171
Figure A.3	Most popular turbulence models used in CFD applications	176
Figure A.4	Height function for a 2D open interface	179
Figure A.5	Interface representation using MAC method	180

List of Tables

		Pg.
Table 3.1	Geometrically similar grids parameters for a cube	47
Table 4.1	Principal particulars of ship and duct	50
Table 4.2	Boundary conditions for open boundaries and solid walls	52
Table 4.3	Computational grids	53
Table 4.4	C_T results computed at T=30s Compared to EFD data	54
Table 4.5	Sinkage and trim results computed at T=30s Compared to EFD data	54
Table 4.6	Grid convergence parameters for total ship resistance Coefficient C_T	55
Table 4.7	Validation data for total ship resistance Coefficient C_T	55
Table 4.8	Principal particulars of ship and rudder	62
Table 4.9	Computational cases and corresponding ship speed parameters	63
Table 4.10	Computational grids for ship with and without rudder	64
Table 4.11	Grid convergence parameters for total ship resistance Coefficient C_T	65
Table 4.12	DTMB ship models and full scale characteristics	69
Table 4.13	Computational cases and corresponding ship speed parameters	69
Table 4.14	Computational grids for ship based on the wall treatment modeling	70
Table 4.15	Verification and validation parameters for total ship resistance in the wall modeled case	71
Table 4.16	Sinkage and trim results	72
Table 4.17	Computational grids for ship based on the wall treatment modeling	75
Table 4.18	Total resistance computed for the appended hull and appendages drag force	75
Table 4.19	Total resistance coefficient C_T computed for the bare hull component compared to EFD data	76
Table 4.20	Sinkage and trim values computed for the fully appended hull compared to the measured value	77
Table 4.21	Test cases and corresponding ship speed parameters	81
Table 4.22	Measured total resistance and corresponding resistance coefficients	82
Table 4.23	Extrapolated data from the UGAL model to the INSEAN model scale	84
Table 4.24	Total resistance comparison between CFD and EFD results	86
Table 5.1	Principal characteristics and parameters of the JBC propeller	90
Table 5.2	POW simulation cases and flow parameters	91
Table 5.3	Computational grids	92
Table 5.4	Number of grid cells based on simulation conditions and grid density	97
Table 5.5	Self-propulsion results for ship with and without ESD based on actuator disk method	99
Table 5.6	Self-propulsion coefficient for ship with and without ESD using sliding grid method	101
Table 5.7	Self-propulsion results for ship with and without rudder	102
Table 5.8	Principal particulars of KVLCC2 E698 propeller model	104
Table 5.9	Computational grids for the self-propulsion simulation	110
Table 5.10	Thrust and torque coefficients computed using the actuator disk method compared to the EFD data extracted	111
Table 5.11	Interpolation of the propeller rotation based on resistance and thrust results	112
Table 6.1	Simulation conditions and corresponding wave parameters	117
Table 6.2	Computed versus measured C_T, C_H, C_M coefficients	119
Table 6.3	Simulation cases parameters and corresponding grid density	124

Table 6.4	Grid convergence parameter for the total resistance coefficient in wave $C_{Tw\text{-}G}$	126
Table 6.5	Time step convergence parameter for the total resistance coefficient in wave $C_{Tw\text{-}T}$	126
Table 6.6	Grid convergence parameter for the heave response	127
Table 6.7	Time step convergence parameter for the heave response	127
Table 6.8	Grid convergence parameter for the pitch response	128
Table 6.9	Time step convergence parameter for the pitch response	128
Table 6.10	Validation parameter for resistance in wave, heave and pitch in C1	129
Table 6.11	Added resistance in waves for cases C2~C8	130
Table 6.12	Heave and pitch responses in at different *Ak* from C9	131
Table 6.13	Grid arrangement for the grid convergence study	138
Table 6.14	Computed results for roll amplitudes compared to EFD data and corresponding average and mean values for decay fitting curves	140
Table 6.15	Grid convergence study parameters	141
Table 6.16	Time step convergence study parameters	141
Table 6.17	Results for validation test	141
Table 7.1	Ship performance contribution in the present study	154

Table of Contents

Acknowledgments i
Nomenclatures i
Abbreviations v
List of Figures vii
List of Tables xii
Table of Contents xiv
Chapter I 1
Introduction 1
1.1 Motivation 1
1.2 Background 2
1.3 Literature Review 4
1.3.1 Resistance 5
1.3.2 Propulsion 12
1.3.3 Seakeeping 16
1.3.4 Maneuvering 19
1.4 Scope and Objectives 20
1.5 Structure of the Book 22
Chapter II 25
Mathematical Model 25
2.1 Governing Equations 26
2.2 Turbulent Closure Equations 27
2.2.1 Menter Two-Equation Model $\boldsymbol{k-\omega}$ SST [110] 28
2.2.2 Explicit Algebraic Stress Model (EASM) [110] 29
2.3 Boundary Conditions 31
Solid Body (Ship Hull) 32
Free-Surface 32
Infinity 33
The Turbulence Model 33
2.4 CFD Process 34
Chapter III 37
Verification and Validation 37

3.1 Verification and Validation Concept 38
3.2 Verification Methodology 40
Iterative uncertainty and errors 41
Convergence uncertainty and errors 42
3.2.1 Generalized Richardson Extrapolation (RE) 43
3.2.2 Estimating Errors and Uncertainties with Correction Factor 44
3.2.3 Estimating Uncertainties with Factor of Safety 45
3.3 Validation Methodology 45
3.4 Unstructured Grid Generation for Verification and Validation Studies 46
Chapter IV 49
Ship Resistance Performance 49
4.1 Japan Bulk Carrier (JBC) 50
4.1.1 Analysis Conditions 51
4.1.2 Domain & Boundary Conditions 51
4.1.3 Computational Grids 52
4.1.4 Simulation Strategy 53
4.1.5 Resistance and Motion Results 54
4.1.6 Free-Surface Results 56
4.1.7 Local Flow Results 57
4.2 KRISO Very Large Crude Carrier (KVLCC2) 62
4.2.1 Analysis Conditions 63
4.2.2 Domain & Boundary Conditions 63
4.2.3 Computational Grids 63
4.2.4 Resistance and Motion Results 64
4.2.5 Free-Surface Results 66
4.2.6 Local Flow Results 66
4.3 David Taylor Model Basin (DTMB) Surface Combatant 68
4.3.1 Bare Hull Ship Model 69
4.3.1.1 Analysis Conditions 69
4.3.1.2 Domain & Boundary Conditions 69
4.3.1.3 Computational Grids 70
4.3.1.4 Resistance and Motion Results 70
4.3.1.5 Free-Surface Results 73

4.3.1.6 Local Flow Results 73
4.3.2 Appended Hull Ship Model 74
4.3.2.1 Analysis Conditions 74
4.3.2.2 Domain & Boundary Conditions 74
4.3.2.3 Computational Grids 74
4.3.2.4 Resistance and Motion Results 75
4.3.2.5 Free-Surface Results 77
4.3.2.6 Local Flow Results 77
4.3.3 Experimental Test 81
4.3.3.1 Experiment Setup 81
4.3.3.2 Resistance Measurements 82
4.3.3.3 Free-Surface Measurements 83
4.3.3.4 Measurements Validation 84
4.3.3.5 CFD Approach 85
Chapter V 89
Ship Propulsion Performance 89
5.1 Propulsion Performance of the JBC 90
5.1.1 Propulsion Performance in Open Water 90
5.1.1.1 Analysis Conditions 90
5.1.1.2 Domain & Boundary Conditions 91
5.1.1.3 Computational Grids 91
5.1.1.4 Simulation Strategy 92
5.1.1.5 Thrust and Torque Results 92
5.1.1.6 Wake Flow Analysis 94
5.1.2 Self-Propulsion Simulation 96
5.1.2.1 Analysis Conditions 96
5.1.2.2 Domain & Boundary Conditions 96
5.1.2.3 Computational Grids 97
5.1.2.4 Simulation Strategy 97
5.1.2.5 Self-Propulsion Results 98
5.2 Propulsion Performance of the KVLCC2 104
5.2.1 Propulsion Performance in Open Water 104
5.2.1.1 Analysis Conditions 104

5.2.1.2 Domain & Boundary Conditions 104
5.2.1.3 Computational Grids 105
5.2.1.4 Simulation Strategy 105
5.2.1.5 Thrust and Torque Results 105
5.2.1.6 Local Flow Results 106
5.2.2 Self-Propulsion Performance 110
5.2.2.1 Analysis Conditions 110
5.2.2.2 Domain & Boundary Conditions 110
5.2.2.3 Computational Grids 110
5.2.2.4 Simulation Strategy 110
5.2.2.5 Thrust and Torque Results 111
5.2.2.6 Local Flow Results 112
Chapter VI 115
Ship Seakeeping Performance 115
6.1 Seakeeping Performance in Regular Head Waves 116
6.1.1 Seakeeping in Wave Diffraction Condition 116
6.1.1.1 Analysis Conditions 116
6.1.1.2 Domain & Boundary Conditions 117
6.1.1.3 Computational Grids 118
6.1.1.4 Simulation Strategy 119
6.1.1.5 Resistance, Forces and Moments Results 119
6.1.1.6 Free-Surface Results 120
6.1.1.7 Local Flow prediction 123
6.1.2 Seakeeping in Wave Radiation Condition 124
6.1.2.1 Analysis Conditions 124
6.1.2.2 Domain & Boundary Conditions 125
6.1.2.3 Computational Grids 125
6.1.2.4 Simulation Strategy 125
6.1.2.5 Results 125
6.2 Roll Decay Performance in Calm water 136
6.2.1 Simulation Conditions 136
6.2.2 Domain & Boundary Conditions 136
6.2.3 Computational Grids 137

6.2.4 Simulation Strategy 138
6.2.5 Roll Motion Results 138
6.2.6 Free-Surface Analysis 141
6.2.7 Local Flow Analysis during Roll Damping 144
Chapter VII 149
Conclusions, Contributions and Recommendations 149
7.1 Concluding Remarks 150
For resistance performance 150
For propulsion performance 151
For Seakeeping performance 152
7.2 Personal Contributions 153
7.3 Recommendations and Future Perspectives 157
References 159
Appendix A 169
Numerical Methods used in Ship Hydrodynamics Applications 169
A.1. Physical Modeling 170
A.1.1 Flow Modeling 170
A.1.2 Turbulence Modeling 170
A.1.2.1 Direct Numerical Simulation (DNS) 171
A.1.2.2 Large Eddy Simulation (LES) 171
A.1.2.3 Hybrid RANS/LES (HRL) 172
A.1.2.4 Reynolds-Averaged Navier Stokes (RANS) 173
A.2 Numerical Modeling 176
A.2.1 Reference Frames 176
A.2.2 Spatial Discretization 176
A.2.3 Temporal Discretization 177
A.2.4 Grid Generation 178
A.2.5 Interface Modeling 178
A.2.6 Velocity-Pressure Coupling 181