

## HYDRODYNAMICS OF HIGH-SPEED MARINE VEHICLES

*Hydrodynamics of High-Speed Vehicles* discusses the three main categories of high-speed marine vehicles, vessels supported by submerged hulls, air cushions, or foils. The wave environment, resistance, propulsion, seakeeping, sea loads, and maneuvering are extensively covered based on rational and simplified methods. Links to automatic control and structural mechanics are emphasized. A detailed description of waterjet propulsion is given, and the effect of water depth on wash, resistance, sinkage, and trim is discussed. Chapter topics include resistance and wash; slamming; air cushion-supported vessels, including a detailed discussion of wave-excited resonant oscillations in air cushion; and hydrofoil vessels. The book contains numerous illustrations, examples, and exercises.

Odd M. Faltinsen received his Ph.D. in naval architecture and marine engineering from the University of Michigan in 1971 and has been a Professor of Marine Hydrodynamics at the Norwegian University of Science and Technology since 1974. Dr. Faltinsen has experience with a broad spectrum of hydrodynamically related problems for ships and sea structures, including hydroelastic problems and slamming. He has published more than 200 scientific papers, and his textbook *Sea Loads on Ships and Offshore Structures*, published by Cambridge University Press in 1990, is used at universities worldwide.

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# Hydrodynamics of High-Speed Marine Vehicles

**ODD M. FALTINSEN**

Norwegian University of Science and Technology



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Contents

<i>Preface</i>	<i>page</i> xiii
<i>List of symbols</i>	xv
1 INTRODUCTION	1
1.1 Operational limits	6
1.2 Hydrodynamic optimization	10
1.3 Summary of main chapters	10
2 RESISTANCE AND PROPULSION	12
2.1 Introduction	12
2.2 Viscous water resistance	13
2.2.1 Navier-Stokes equations	16
2.2.2 Reynolds-averaged Navier-Stokes (RANS) equations	18
2.2.3 Boundary-layer equations for 2D turbulent flow	19
2.2.4 Turbulent flow along a smooth flat plate. Frictional resistance component	20
2.2.5 Form resistance components	25
2.2.6 Effect of hull surface roughness on viscous resistance	28
2.2.7 Viscous foil resistance	31
2.3 Air resistance component	35
2.4 Spray and spray rail resistance components	36
2.5 Wave resistance component	38
2.6 Other resistance components	38
2.7 Model testing of ship resistance	39
2.7.1 Other scaling parameters	42
2.8 Resistance components for semi-displacement monohulls and catamarans	42
2.9 Wake flow	45
2.10 Propellers	47
2.10.1 Open-water propeller characteristics	53
2.10.2 Propellers for high-speed vessels	55
2.10.3 Hull-propeller interaction	60
2.11 Waterjet propulsion	61
2.11.1 Experimental determination of thrust and efficiency by model tests	63
2.11.2 Cavitation in the inlet area	70

vi • Contents

2.12 Exercises	73
2.12.1 Scaling	73
2.12.2 Resistance by conservation of fluid momentum	74
2.12.3 Viscous flow around a strut	75
2.12.4 Thrust and efficiency of a waterjet system	75
2.12.5 Steering by means of waterjet	77
3 WAVES	78
3.1 Introduction	78
3.2 Harmonic waves in finite and infinite depth	78
3.2.1 Free-surface conditions	78
3.2.2 Linear long-crested propagating waves	81
3.2.3 Wave energy propagation velocity	84
3.2.4 Wave propagation from deep to shallow water	86
3.2.5 Wave refraction	87
3.2.6 Surface tension	90
3.3 Statistical description of waves in a sea state	91
3.4 Long-term predictions of sea states	94
3.5 Exercises	95
3.5.1 Fluid particle motion in regular waves	95
3.5.2 Sloshing modes	97
3.5.3 Second-order wave theory	97
3.5.4 Boussinesq equations	98
3.5.5 Gravity waves in a viscous fluid	98
4 WAVE RESISTANCE AND WASH	99
4.1 Introduction	99
4.1.1 Wave resistance	99
4.1.2 Wash	101
4.2 Ship waves in deep water	103
4.2.1 Simplified evaluation of Kelvin's angle	105
4.2.2 Far-field wave patterns	105
4.2.3 Transverse waves along the ship's track	107
4.2.4 Example	110
4.3 Wave resistance in deep water	110
4.3.1 Example: Wigley's wedge-shaped body	112
4.3.2 Example: Wigley ship model	112
4.3.3 Example: Tuck's parabolic strut	114
4.3.4 2.5D (2D+t) theory	115
4.3.5 Multihull vessels	120
4.3.6 Wave resistance of SES and ACV	122
4.4 Ship in finite water depth	123
4.4.1 Wave patterns	126
4.5 Ship in shallow water	128
4.5.1 Near-field description	128
4.5.2 Far-field equations	129
4.5.3 Far-field description for supercritical speed	130

4.5.4 Far-field description for subcritical speed	131
4.5.5 Forces and moments	132
4.5.6 Trim and sinkage	134
4.6 Exercises	135
4.6.1 Thin ship theory	135
4.6.2 Two struts in tandem	136
4.6.3 Steady ship waves in a towing tank	136
4.6.4 Wash	137
4.6.5 Wave patterns for a ship on a circular course	138
4.6.6 Internal waves	138
<b>5 SURFACE EFFECT SHIPS</b>	<b>141</b>
5.1 Introduction	141
5.2 Water level inside the air cushion	141
5.3 Effect of air cushion on the metacentric height in roll	143
5.4 Characteristics of aft seal air bags	145
5.5 Characteristics of bow seal fingers	147
5.6 “Cobblestone” oscillations	149
5.6.1 Uniform pressure resonance in the air cushion	150
5.6.2 Acoustic wave resonance in the air cushion	154
5.6.3 Automatic control	158
5.7 Added resistance and speed loss in waves	159
5.8 Seakeeping characteristics	161
5.9 Exercises	163
5.9.1 Cushion support at zero speed	163
5.9.2 Steady airflow under an aft-seal air bag	163
5.9.3 Damping of cobblestone oscillations by T-foils	163
5.9.4 Wave equation	164
5.9.5 Speed of sound	164
5.9.6 Cobblestone oscillations with acoustic resonance	164
<b>6 HYDROFOIL VESSELS AND FOIL THEORY</b>	<b>165</b>
6.1 Introduction	165
6.2 Main particulars of hydrofoil vessels	166
6.3 Physical features	166
6.3.1 Static equilibrium in foilborne condition	166
6.3.2 Active control system	169
6.3.3 Cavitation	169
6.3.4 From hullborne to foilborne condition	173
6.3.5 Maneuvering	176
6.3.6 Seakeeping characteristics	178
6.4 Nonlinear hydrofoil theory	178
6.4.1 2D flow	178
6.4.2 3D flow	184
6.5 2D steady flow past a foil in infinite fluid. Forces	187
6.6 2D linear steady flow past a foil in infinite fluid	188
6.6.1 Flat plate	192

## viii • Contents

6.6.2	Foil with angle of attack and camber	193
6.6.3	Ideal angle of attack and angle of attack with zero lift	193
6.6.4	Weissinger's "quarter-three-quarter-chord" approximation	193
6.6.5	Foil with flap	194
6.7	3D linear steady flow past a foil in infinite fluid	195
6.7.1	Prandtl's lifting line theory	195
6.7.2	Drag force	197
6.8	Steady free-surface effects on a foil	199
6.8.1	2D flow	199
6.8.2	3D flow	202
6.9	Foil interaction	205
6.10	Ventilation and steady free-surface effects on a strut	208
6.11	Unsteady linear flow past a foil in infinite fluid	209
6.11.1	2D flow	209
6.11.2	2D flat foil oscillating harmonically in heave and pitch	210
6.11.3	3D flow	212
6.12	Wave-induced motions in foilborne conditions	212
6.12.1	Case study of vertical motions and accelerations in head and following waves	216
6.13	Exercises	219
6.13.1	Foil-strut intersection	219
6.13.2	Green's second identity	219
6.13.3	Linearized 2D flow	219
6.13.4	Far-field description of a high-aspect-ratio foil	219
6.13.5	Roll-up of vortices	219
6.13.6	Vertical wave-induced motions in regular waves	220
7	SEMI-DISPLACEMENT VESSELS	221
7.1	Introduction	221
7.1.1	Main characteristics of monohull vessels	221
7.1.2	Main characteristics of catamarans	221
7.1.3	Motion control	224
7.1.4	Single-degree mass-spring system with damping	226
7.2	Linear wave-induced motions in regular waves	229
7.2.1	The equations of motions	233
7.2.2	Simplified heave analysis in head sea for monohull at forward speed	236
7.2.3	Heave motion in beam seas of a monohull at zero speed	237
7.2.4	Ship-generated unsteady waves	238
7.2.5	Hydrodynamic hull interaction	240
7.2.6	Summary and concluding remarks on wave radiation damping	246
7.2.7	Hull-lift damping	246
7.2.8	Foil-lift damping	247
7.2.9	Example: Importance of hull- and foil-lift heave damping	249
7.2.10	Ride control of vertical motions by T-foils	249



7.2.11 Roll motion in beam sea of a catamaran at zero speed	250
7.2.12 Numerical predictions of unsteady flow at high speed	253
7.3 Linear time-domain response	257
7.4 Linear response in irregular waves	259
7.4.1 Short-term sea state response	259
7.4.2 Long-term predictions	260
7.5 Added resistance in waves	261
7.5.1 Added resistance in regular waves	261
7.5.2 Added resistance in a sea state	263
7.6 Seakeeping characteristics	263
7.7 Dynamic stability	266
7.7.1 Mathieu instability	268
7.8 Wave loads	270
7.8.1 Local pressures of non-impact type	271
7.8.2 Global wave loads on catamarans	273
7.9 Exercises	282
7.9.1 Mass matrix	282
7.9.2 2D heave-added mass and damping	282
7.9.3 Linear wavemaker solution	283
7.9.4 Foil-lift damping of vertical motions	284
7.9.5 Roll damping fins	285
7.9.6 Added mass and damping in roll	285
7.9.7 Global wave loads in the deck of a catamaran	285
<b>8 SLAMMING, WHIPPING, AND SPRINGING</b>	<b>286</b>
8.1 Introduction	286
8.2 Local hydroelastic slamming effects	290
8.2.1 Example: Local hydroelastic slamming on horizontal wetdeck	298
8.2.2 Relative importance of local hydroelasticity	299
8.3 Slamming on rigid bodies	301
8.3.1 Wagner's slamming model	305
8.3.2 Design pressure on rigid bodies	309
8.3.3 Example: Local slamming-induced stresses in longitudinal stiffener by quasi-steady beam theory	310
8.3.4 Effect of air cushions on slamming	310
8.3.5 Impact of a fluid wedge and green water	313
8.4 Global wetdeck slamming effects	317
8.4.1 Water entry and exit loads	319
8.4.2 Three-body model	321
8.5 Global hydroelastic effects on monohulls	325
8.5.1 Special case: Rigid body	328
8.5.2 Uniform beam	329
8.6 Global bow flare effects	330
8.7 Springing	334
8.7.1 Linear springing	336
8.8 Scaling of global hydroelastic effects	338

x • Contents

8.9 Exercises	338
8.9.1 Probability of wetdeck slamming	338
8.9.2 Wave impact at the front of a wetdeck	339
8.9.3 Water entry of rigid wedge	339
8.9.4 Drop test of a wedge	340
8.8.5 Generalized Wagner method	340
8.9.6 3D flow effects during slamming	340
8.9.7 Whipping studies by a three-body model	341
8.9.8 Frequency-of-encounter wave spectrum in following sea	341
8.9.9 Springing	341
9 PLANING VESSELS	342
9.1 Introduction	342
9.2 Steady behavior of a planing vessel on a straight course	344
9.2.1 2.5D (2D+t) theory	345
9.2.2 Savitsky’s formula	349
9.2.3 Stepped planing hull	355
9.2.4 High-aspect-ratio planing surfaces	358
9.3 Prediction of running attitude and resistance in calm water	360
9.3.1 Example: Forces act through COG	360
9.3.2 General case	362
9.4 Steady and dynamic stability	363
9.4.1 Porpoising	365
9.5 Wave-induced motions and loads	373
9.5.1 Wave excitation loads in heave and pitch in head sea	374
9.5.2 Frequency-domain solution of heave and pitch in head sea	378
9.5.3 Time-domain solution of heave and pitch in head sea	378
9.5.4 Example: Heave and pitch in regular head sea	380
9.6 Maneuvering	383
9.7 Exercises	385
9.7.1 2.5D theory for planing hulls	385
9.7.2 Minimalization of resistance by trim tabs	386
9.7.3 Steady heel restoring moment	386
9.7.4 Porpoising	388
9.7.5 Equation system of porpoising	388
9.7.6 Wave-induced vertical accelerations in head sea	388
10 MANEUVERING	390
10.1 Introduction	390
10.2 Traditional coordinate systems and notations in ship maneuvering	393
10.3 Linear ship maneuvering in deep water at moderate Froude number	395
10.3.1 Low-aspect-ratio lifting surface theory	398
10.3.2 Equations of sway and yaw velocities and accelerations	399
10.3.3 Directional stability	400
10.3.4 Example: Directional stability of a monohull	401

10.3.5 Steady-state turning	401
10.3.6 Multihull vessels	402
10.3.7 Automatic control	403
10.4 Linear ship maneuvering at moderate Froude number in finite water depth	403
10.5 Linear ship maneuvering in deep water at high Froude number	403
10.6 Nonlinear viscous effects for maneuvering in deep water at moderate speed	406
10.6.1 Cross-flow principle	406
10.6.2 2D+t theory	410
10.6.3 Empirical nonlinear maneuvering models	415
10.7 Coupled surge, sway, and yaw motions of a monohull	416
10.7.1 Influence of course control on propulsion power	417
10.8 Control means	419
10.9 Maneuvering models in six degrees of freedom	421
10.9.1 Euler’s equation of motion	421
10.9.2 Linearized equation system in six degrees of freedom	425
10.9.3 Coupled sway-roll-yaw of a monohull	426
10.10 Exercises	431
10.10.1 Course stability of a ship in a canal	431
10.10.2 Nonlinear, nonlifting and nonviscous hydrodynamic forces and moments on a maneuvering body	432
10.10.3 Maneuvering in waves and broaching	432
10.10.4 Linear coupled sway-yaw-roll motions of a monohull at moderate speed	433
10.10.5 High-speed motion in water of an accidentally dropped pipe	433
APPENDIX: Units of Measurement and Physical Constants	435
<i>References</i>	437
<i>Index</i>	451

## Preface

Writing a book on the hydrodynamics of high-speed marine vehicles was challenging because I have had to cover all areas of traditional marine hydrodynamics, resistance, propulsion, seakeeping, and maneuvering. However, there is a need to combine all aspects of hydrodynamics in the design of which high-speed vessels are very different from conventional ships, depending on whether they are hull supported, air cushion supported, foil supported, or hybrids.

High-speed vessels are a fascinating topic, and I have been deeply involved in research on high-speed vessels since a national research program under the leadership of Kjell Holden started in Norway in 1989. We also started the International Conference on Fast Sea Transportation (FAST), which has a much broader scope than marine hydrodynamics. I have also benefited from being the chairman of the Committee of High-Speed Marine Vehicles of the International Towing Tank Conference (ITTC) from 1990 to 1993. Further, this book would not have been possible without the work done by the many doctoral students who I have supervised. Their theses are referenced in the book. Parts of the book have been taught to the fourth year, master of science students and doctoral students at the Department of Marine Technology, Norwegian University of Science and Technology (NTNU).

My philosophy in writing the book has been to start from basic fluid dynamics and to link this to practical issues for high-speed vessels. Mathematics is a necessity, but I have tried to avoid this when physical explanations can be given. Knowledge of calculus, including vector analysis and differential equations, is necessary to read the book in detail. The reader should also be familiar with dynamics and basic hydrodynamics of potential and viscous flow of an incompressible fluid.

Computational fluid dynamics (CFD) are commonly used nowadays, but my emphasis is on giving simplified and rational explanations of fluid behavior and its interaction with the vessel. This is beneficial in planning and interpreting experiments and computations. I also believe that examples and exercises are important parts of the learning process.

Automatic control and structural mechanics of high-speed marine vehicles are two disciplines that rely on hydrodynamics. These links are emphasized in the book and are also important aspects of the Centre for Ships and Ocean Structures, NTNU, where I participate.

My presentation of the material is inspired by the book *Marine Hydrodynamics* by Professor J. N. Newman.

xiv • Preface

I am thankful to Professor Newman for reading through the manuscript and offering suggestions for improvement. Dr. Svein Skjördal spent a lot of time giving detailed comments on different versions of the manuscript. He was also helpful in seeing the topics from a practical point of view. Sun Hui also did a great job in confirming all my calculations and providing solutions to all exercises. I have benefited from Professor K. J. Minsaas' expertise in propulsion and hydrodynamic design of hydrofoil vessels. Many other people should be thanked for their critical reviews and contributions, including Dr. Tony Armstrong, Professor Tor Einar Berg, J. Bloch Helmers, Professor Lawrence Doctors, Dr. Svein Ersdal, Lars Flåten, Professor Thor I. Fossen, Dr. Chunhua Ge, Dr. Marilena Greco, Dr. Martin Greenhow, Dr. Ole Hermundstad, Egil Jullumstrø, Dr. Toru Katayama, Professor Katsuro Kijima, Professor Spyros A. Kinnas, Dr. Kourosh Koushan, David Kristiansen, Professor Claus Kruppa, Dr. Jan Kvaalsvold, Dr. Burkhard Müller-Graf, Professor Dag Myrhaug, Professor Makoto Ohkusu, Professor Bjørnar Pettersen, Dr. Olav Rognebakke, Renato Skejic, Dr. Nere Skomedal, Professor Sverre Steen, Gaute Storhaug, Professor Asgeir Sørensen, Professor Ernest O. Tuck, and Dr. Frans van Walree.

The artwork was done by Bjarne Stenberg. Anne-Irene Johannessen and Keivan Koushan were helpful in drawing figures. Jorunn Fransvåg organized and typed the many versions of the manuscript in an accurate and efficient way, which required a tremendous amount of work.

The support from the Centre of Ships and Ocean Structures and the Department of Marine Technology at NTNU is appreciated.

List of symbols

$A$	area; planform area of foil
$A_D$	developed area, propeller blades
$A_E$	expanded area, propeller blades
$A_{jk}$	3D added mass coefficient in the $j$ th mode due to $k$ th motion
$a_{jk}$	2D added mass coefficient
$A_O$	area of propeller disc
$AP$	after perpendicular
$A_R$	rudder area
$A_W$	waterplane area
$AHR$	average hull roughness
$B$	beam
$b$	beam of section
$BAR$	blade area ratio
$B_{cr}, b_{cr}$	critical damping
$B_{jk}$	3D damping coefficient in $j$ th mode due to $k$ th motion
$b_{jk}$	2D damping coefficient
$c$	chord length; half wetted length in 2D impact; speed of sound
$C_B$	block coefficient, ship
$C_D$	drag coefficient
$C_f$	friction coefficient
$C_F$	frictional force coefficient
$CFD$	computational fluid dynamics
$C_H$	head coefficient
$C_{jk}$	restoring force coefficient in $j$ th mode due to $k$ th motion
$C_L$	lift coefficient
$C_{L\beta}$	lift coefficient for planing vessel
$C_{L0}$	$C_{L\beta}$ at zero deadrise angle
$C(k_f)$	Theodorsen function
$C_M$	midship section coefficient; mass coefficient in Morison's equation
$COG$	center of gravity
$C_p$	pressure coefficient
$C_{pmin}$	minimum pressure coefficient
$C_P$	longitudinal prismatic coefficient
$C_R$	residual resistance coefficient
$C_T$	propeller thrust-loading coefficient; total resistance coefficient
$C_W$	wave-making resistance coefficient
$C_{WP}$	wave pattern resistance coefficient

xvi • List of symbols

$C_Q$	capacity coefficient
$D$	draft; drag force; propeller diameter
DNV	Det Norske Veritas
$D_T$	transom draft
$E$	Young’s modulus of elasticity
$EI$	flexural rigidity of a beam
$E_k$	kinetic fluid energy
$E(t)$	energy
$f$	frequency (Hz); maximum camber
$F$	densimetric Froude number; fetch length
$F_n$	Froude number $U/\sqrt{gL}$
$F_{nB}$	beam Froude number
$F_{nD}$	draft Froude number
$F_{nh}$	depth or submergence Froude number
$F_{nT}$	transom draft Froude number
$FP$	forward perpendicular
$F_v$	volumetric Froude number
$g$	acceleration of gravity
$G(x,y,z;\xi,\eta,\zeta)$	Green function
$\overline{GM}$	transverse metacentric height
$\overline{GM}_L$	longitudinal metacentric height
$\overline{GZ}$	moment arm in heel (roll) about COG
$h$	water depth; submergence
$h_j$	height of the center of the jet at station $S_7$ (see Figure 2.54) above calm free surface
$H$	wave height; head
$H_{1/3}$	significant wave height
$i$	imaginary unit
$I_{jk}$	moment or product of inertia
$\mathbf{i}, \mathbf{j}, \mathbf{k}$	unit vectors along x, y and z-axis, respectively
IVR	inlet velocity ratio
$J$	advance ratio of propeller
$k$	wave number; roughness height; form factor
KC	Keulegan-Carpenter number
$k_f$	reduced frequency
$\overline{KG}$	height of COG above keel
$K_T$	thrust coefficient
$K_Q$	torque coefficient
$L$	length of ship; lift of a foil; hydrodynamic roll moment in maneuvering
$L_C$	chine wetted length
LCB	longitudinal center of buoyancy
l <sub>cg</sub>	longitudinal center of gravity measured from the transom stern
LCG	longitudinal center of gravity
$L_K$	keel wetted length
$L_{OA}$	length, overall
$L_{OS}$	length, overall submerged

$l_p$	longitudinal position of the center of pressure measured along the keel from the transom stern
$L_{PP}$	length between perpendiculars
$L_{WL}$	length of the designer's load waterline
$M$	mass; moment; hydrodynamic pitch moment in maneuvering
$\mathbf{M}$	fluid momentum vector
$m$	mass per unit length
$M_{jk}$	components of mass matrix
$n$	propeller revolutions per second
$\mathbf{n}$	surface normal vector positive into the fluid
$N$	normal force; hydrodynamic yaw moment in maneuvering
$O$	origin of coordinate system
$O(\varepsilon)$	order of magnitude of $\varepsilon$
$P$	power; pitch of propeller; probability
$p$	pressure; roll component of angular velocity; half of the distance between the center lines of the demihulls of a catamaran; stagger between foils
$p_a$	atmospheric pressure
$P_D$	delivered power
$p_o$	ambient pressure; static excess pressure
$p_v$	vapor pressure of water
$Q$	propeller torque; volume flux; source strength
$q$	pitch component of angular velocity
$r$	yaw component of angular velocity
$R$	radius; resistance
$R_{AA}$	added resistance in air and wind
$R_{AW}$	added resistance in waves
$r_{jj}$	radius of gyration in rigid body mode $j$
$RMS$	root mean square
$Rn$	Reynolds number
$R_R$	residual resistance
$R_S$	spray resistance
$R_T$	total resistance
$R_V$	viscous resistance
$R_W$	wave-making resistance
$s$	span length of foil
$S$	area of wetted surface; cross-sectional area
$S_B$	body surface
$S(\omega)$	wave spectrum
$t$	time; thrust-deduction coefficient; maximum foil thickness
$T$	period; propeller thrust
$T_0$	modal or peak period
$T_1$	mean wave period
$T_2$	mean wave period
$T_e$	encounter period
$T_n$	natural period
$T_S$	surface tension



xviii • List of symbols

$U$	forward velocity of vessel
$U_I$	mean velocity at the most narrow cross-section of the waterjet inlet
$U_S$	propeller slip stream velocity
$u$	x-component of vessel velocity
$v$	y-component of vessel velocity
$v_{cg}$	vertical distance between COG and the keel
$V_g$	group velocity
$V_p$	phase velocity
$v^*$	wall friction velocity
$V$	water entry velocity
$W$	weight
$w$	wake fraction; z-component of vessel velocity; vertical deflection
$W_n$	Weber number
$x, y, z$	Cartesian coordinate system. Moving with the forward speed in seakeeping analysis. Body-fixed in maneuvering analysis.
$X$	x-component of hydrodynamic force in maneuvering
$X_E, Y_E, Z_E$	Earth-fixed coordinate system
$x_T$	x-coordinate of transom
$x_s$	$L_K - L_C$
$Y$	y-component of hydrodynamic force in maneuvering
$Z$	z-component of hydrodynamic force in maneuvering

Greek symbols

$\alpha$	angle of attack
$\alpha_c$	Kelvin angle
$\alpha_f$	flap angle
$\alpha_i$	ideal angle of attack
$\alpha_0$	angle of zero lift
$\beta$	wave propagation angle; deadrise angle; drift angle
$\Gamma$	circulation; gamma function; dihedral angle
$\gamma$	vortex density; sweep angle; ratio of specific heat for air
$\delta$	boundary layer thickness; rudder angle; flap angle
$\delta^*$	displacement thickness
$\Delta$	vessel weight
$\varepsilon$	angle
$\zeta$	surface elevation
$\zeta_a$	wave amplitude
$\eta$	overall propulsive efficiency
$\eta_H$	hull efficiency
$\eta_J$	jet efficiency
$\eta_k$	wave-induced vessel motion response, where $k = 1, 2, 3, \dots, 6$ refers to surge, sway, heave, roll, pitch, and yaw, respectively
$\eta_p$	propeller efficiency; pump efficiency
$\eta_R$	relative rotative efficiency
$\eta_S$	sinkage
$\eta_T$	thrust power efficiency
$\theta$	pitch angle; momentum thickness

$\Lambda$	aspect ratio of foil
$\Lambda_L$	ratio between full scale and model length
$\lambda$	wavelength
$\lambda_w$	mean wetted length-to-beam ratio
$\mu$	dynamic viscosity coefficient
$\nu$	kinematic viscosity coefficient
$\xi$	ratio between damping and critical damping
$\rho$	mass density of fluid (water)
$\rho_a$	mass density of air
$\sigma$	cavitation number; source density; standard deviation
$\sigma_i$	cavitation inception index
$\sigma_o$	propeller cavitation number
$\sigma_{0.7}$	propeller cavitation number defined at 0.7 R
$\tau$	trim angle in radians; $\omega_e U/g$
$\tau_{deg}$	trim angle in degrees
$\tau_{ij}$	Newtonian stress relations
$\tau_w$	frictional stress on hull surface
$\phi$	heel (roll) angle
$\varphi$	velocity potential
$\psi$	yaw angle
$\omega$	circular frequency in radians per second
$\boldsymbol{\omega}$	vorticity vector; vector of rotational vessel motion
$\omega_n$	natural frequency
$\omega_e$	frequency of encounter
$\omega_o$	frequency of waves in an Earth-fixed coordinate system
$\boldsymbol{\Omega}$	vector of rotational vessel velocity
$\Omega$	volume

Special symbols

$\nabla$	displaced volume of water; vector differential operator
$\nabla^2$	$\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$