## Contents

*Preface*  page xiii  
*List of symbols*  xv  

### 1 INTRODUCTION
1.1 Operational limits  6  
1.2 Hydrodynamic optimization  10  
1.3 Summary of main chapters  10  

### 2 RESISTANCE AND PROPULSION
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
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

5 SURFACE EFFECT SHIPS 141
  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

6 HYDROFOIL VESSELS AND FOIL THEORY 165
  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
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

8 SLAMMING, WHIPPING, AND SPRINGING 286
  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
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.3.5 Steady-state turning</td>
<td>401</td>
</tr>
<tr>
<td>10.3.6 Multihull vessels</td>
<td>402</td>
</tr>
<tr>
<td>10.3.7 Automatic control</td>
<td>403</td>
</tr>
<tr>
<td>10.4 Linear ship maneuvering at moderate Froude number in finite water depth</td>
<td>403</td>
</tr>
<tr>
<td>10.5 Linear ship maneuvering in deep water at high Froude number</td>
<td>403</td>
</tr>
<tr>
<td>10.6 Nonlinear viscous effects for maneuvering in deep water at moderate speed</td>
<td>406</td>
</tr>
<tr>
<td>10.6.1 Cross-flow principle</td>
<td>406</td>
</tr>
<tr>
<td>10.6.2 2D+t theory</td>
<td>410</td>
</tr>
<tr>
<td>10.6.3 Empirical nonlinear maneuvering models</td>
<td>415</td>
</tr>
<tr>
<td>10.7 Coupled surge, sway, and yaw motions of a monohull</td>
<td>416</td>
</tr>
<tr>
<td>10.7.1 Influence of course control on propulsion power</td>
<td>417</td>
</tr>
<tr>
<td>10.8 Control means</td>
<td>419</td>
</tr>
<tr>
<td>10.9 Maneuvering models in six degrees of freedom</td>
<td>421</td>
</tr>
<tr>
<td>10.9.1 Euler’s equation of motion</td>
<td>421</td>
</tr>
<tr>
<td>10.9.2 Linearized equation system in six degrees of freedom</td>
<td>425</td>
</tr>
<tr>
<td>10.9.3 Coupled sway-roll-yaw of a monohull</td>
<td>426</td>
</tr>
<tr>
<td>10.10 Exercises</td>
<td>431</td>
</tr>
<tr>
<td>10.10.1 Course stability of a ship in a canal</td>
<td>431</td>
</tr>
<tr>
<td>10.10.2 Nonlinear, nonlifting and nonviscous hydrodynamic forces and moments on a maneuvering body</td>
<td>432</td>
</tr>
<tr>
<td>10.10.3 Maneuvering in waves and broaching</td>
<td>432</td>
</tr>
<tr>
<td>10.10.4 Linear coupled sway-yaw-roll motions of a monohull at moderate speed</td>
<td>433</td>
</tr>
<tr>
<td>10.10.5 High-speed motion in water of an accidentally dropped pipe</td>
<td>433</td>
</tr>
</tbody>
</table>

APPENDIX: Units of Measurement and Physical Constants | 435

References | 437

Index | 451