To Professors Graham Goodwin and Mogens Blanke,

who guided me unfailingly during my first steps into research.
Preface

Motion control systems have a significant impact on the performance of ships and marine structures allowing them to perform tasks in severe sea states and during long periods of time. Ships are designed to operate with adequate reliability and economy, and in order to achieve this, it is essential to control the motion. For each type of ship and operation performed (transit, landing a helicopter, fishing, deploying and recovering loads, etc.), there are not only desired motion settings, but also limits on the acceptable (undesired) motion induced by the environment. The task of a ship motion control system is therefore to act on the ship so it follows the desired motion as closely as possible.

This book provides an introduction to the field of ship motion control by studying the control system designs for course-keeping autopilots with rudder roll stabilisation and integrated rudder-fin roll stabilisation. These particular designs provide a good overview of the difficulties encountered by designers of ship motion control systems and, therefore, serve well as an example driven introduction to the field.

The idea of combining the control design of autopilots with that of fin roll stabilisers, and the idea of using rudder-induced roll motion as a sole source of roll stabilisation seems to have emerged in the late 1960s. Since that time, these control designs have been the subject of continuous and ongoing research. This ongoing interest is a consequence of the significant bearing that the control strategy has on the performance and the issues associated with control system design. The challenges of these designs lie in devising a control strategy to address the following issues: underactuation, disturbance rejection with a non-minimum phase system, input and output constraints, model uncertainty, and large unmeasured stochastic disturbances. To date, the majority of the work reported in the literature has focused strongly on some of the design issues whereas the remaining issues have been addressed using ad hoc approaches. This has provided an additional motivation for revisiting these control designs and looking at the benefits of applying a contemporary
design framework, which can potentially address the majority of the design issues.

**Intended Audience**

The book has been written for students, researchers and practitioners of both control engineering and marine technology. Because of the mixed intended audience, much effort has been put into balancing the level of the presentation of topics of control and marine technology. Nevertheless, the reader is assumed to have some background knowledge in linear systems and state-space models, as covered in standard undergraduate control courses.

**How Does the Book Fit in with the Related Literature?**

With respect to the pioneering books on marine control systems by Prof. Thor I. Fossen [? , ?], this book provides a deeper coverage of hydrodynamic aspects related to control, wave-induced motion modelling and roll stabilisation. In addition, it addresses the fundamental issues of constrained control system design and performance-limitation analysis. Therefore, this book complements [?, ?]. This book also includes extensive references to the literature of ship roll stabilisation of the last 30 years with, plus a complete benchmark example vessel with both manoeuvring and seakeeping model parameters.

**Numerical Simulations and Software Support**

Throughout the book numerical simulations are used to illustrate the main concepts and results. These simulations have been performed by the author using the *Marine GNC Toolbox*, which is part of the *Marine System Simulator (MSS)* developed at NTNU. This is a *Matlab®/Simulink®* based toolbox specially developed for rapid prototyping and evaluation of marine control systems. For further details and free-download versions see [http://www.cesos.ntnu.no/mss](http://www.cesos.ntnu.no/mss)

**Book Overview**

The key ingredients for a successful control system design are

- A mathematical model of the system to be controlled,
- Understanding of how performance will be assessed,
- Knowledge of fundamental limitations that may prevent any design achieving the desired performance.
The book is thus organised in four parts; the first three parts deal with the above ingredients, and the fourth addresses control system design:

**Part I—ship modelling for control.** This part introduces the models used to describe environmental disturbances and ship dynamics for control system design. Chapter 2 introduces concepts of related to modelling and simulation of ocean waves. It discusses the principal characteristics of waves relevant to the ship motion control system design and presents different modelling and simulation techniques. The modelling of a marine vehicle is then considered in three parts. Chapter 3 describes the geometrical aspects of ship motion (kinematics): variables, reference frames and transformations of variables. Chapter 4 presents the equations of motion (kinetics); it discusses how these equations are formulated in different theories of ship motion study (manoeuvring and seakeeping), and how the different models are linked to obtain both comprehensive models for control testing and simplified models for control system design. This chapter introduces a novel state-space model for manoeuvring in a seaway, which is believed to be the basis for a new generation of model-based ship motion control systems. Simulation aspects of ship motion are also discussed. Chapter 5 reviews the characteristics and models of actuators: lifting surfaces and the forces and moments they generate. This includes rudders, fins and their associated machinery.

**Part II—introduction to ship roll stabilisation.** Chapter 6 provides an overview of the roll stabilisation techniques commonly used, and discusses the advantages and disadvantages of each technique. Chapter 7 reviews the methods commonly employed in the marine environment to assess the motion performance of the ship. These methods provide a basis for obtaining control system specifications in agreement with performance assessment methods.

**Part III—performance limitations in feedback control with application to ship roll stabilisers.** Using the models introduced in Part I, this part addresses the fundamental issue of performance limitations for the particular problems of rudder and fin roll stabilisation. Chapter 8 reviews the fundamental performance limitations of the closed-loop system due to the dynamic characteristics of the ship. A study quantifying the limitations due to the non-minimum phase dynamics and underactuation characteristics of the system is presented. Chapter 9 incorporates the limitations imposed by the limited authority of the actuators into the study and discusses the role of the different limiting factors under different sailing conditions. The material presented in this part contributes to a deeper understanding of the main design issues and provides a method to estimate a benchmark performance prior to the design.

**Part IV—control system design for autopilot with RRS and fin stabilisers.** Chapter 10 presents a comprehensive review of the previous work on
control of rudder and fin stabilisers. Chapter 11 provides an introduction to constrained control system design, with emphasis on techniques based on optimization; in particular model predictive control. Chapter 12 discusses the constituting parts of contemporary course-keeping autopilots (guidance system, wave filters and controller), and concentrates on control design. Chapter 13 addresses the control system design for fin-based roll stabilisers. It discusses a non-linear phenomena due unsteady hydrodynamics, which appears to affect the performance of stabilisers in moderate to rough sea states. A control strategy based on constrained control is then proposed to address the design issues. Finally, the problem combined rudder-fin stabilisation is discussed.
Acknowledgements

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Trondheim, Norway

Tristan Perez

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## Contents

1 **Introduction to Ship Motion Control** .......................... 1  
  1.1 The Fundamental Problem of Ship Motion Control .......... 2  
  1.2 Ship Motion Control Problems and Control Designs  
   Addressed in this Book ........................................ 4  
  1.3 Mathematical Models for Control .............................. 5  
  1.4 State-space and Input-output Models Revisited .............. 6  
   1.4.1 State-Space Models .................................... 8  
   1.4.2 Laplace-Transform Models ............................... 10  
  1.5 Computer-Controlled Systems .................................. 11  
  1.6 The Road Ahead ............................................. 13

Part I Ship Modelling for Control

2 **Environmental Disturbances** ................................. 17  
  2.1 Basic Hydrodynamic Assumptions ............................. 17  
   2.1.1 Fluid Flow and Continuity ............................... 17  
   2.1.2 Material Derivative ..................................... 18  
   2.1.3 Navier-Stokes Equations ................................ 19  
  2.2 Regular Waves in Deep Water ................................ 20  
  2.3 Encounter Frequency ......................................... 23  
  2.4 Ocean Waves and Wave Spectra ............................... 25  
   2.4.1 Statistics of Wave Period ............................... 27  
   2.4.2 Statistics of Maxima .................................... 27  
   2.4.3 A Note on the Units of the Spectral Density .......... 30  
  2.5 Standard Spectrum Formulae .................................. 31  
  2.6 Linear Representation of Long-crested Irregular Seas ...... 34  
  2.7 The Encounter Spectrum ..................................... 36  
  2.8 Short-crested Irregular Seas ................................ 36  
  2.9 Long-term Statistics of Ocean Waves ........................ 38
3 Kinematics of Ship Motion .......................................... 45
  3.1 Reference Frames .............................................. 45
  3.2 Vector Notation ................................................ 48
  3.3 Coordinates Used to Describe Ship Motion ................. 48
    3.3.1 Manoeuvring and Seakeeping ......................... 48
    3.3.2 Manoeuvring Coordinates and Reference Frames .... 49
    3.3.3 Seakeeping Coordinates and Reference Frames ...... 50
    3.3.4 Angles About the z-axis ............................. 52
  3.4 Velocity Transformations ................................... 53
    3.4.1 Rotation Matrices ...................................... 53
    3.4.2 Kinematic Transformation Between the b- and the n-frame ............................................ 54
    3.4.3 Kinematic Transformation Between the b- and the h-frame ........................................... 55

4 Ship Kinetics .......................................................... 59
  4.1 An Overview of Ship Modeling for Control ............... 59
  4.2 Seakeeping Theory Models .................................. 62
    4.2.1 Equations of Motion and Hydrodynamic Forces in the h-frame ........................................... 63
    4.2.2 Wave Force Response Amplitude Operator (Force RAO) ................................................. 66
    4.2.3 Motion Response Amplitude Operator (Motion RAO) ..................................................... 67
    4.2.4 Ship Motion Spectra and Statistics of Ship Motion .................................................... 71
    4.2.5 Time-series of Ship Motion using Seakeeping Models .................................................. 73
  4.3 Manoeuvring Theory Models ................................ 79
    4.3.1 Rigid Body Dynamics in the b-frame ................. 79
    4.3.2 Manoeuvring Hydrodynamics ............................ 82
    4.3.3 Nonlinear Manoeuvring State-space Models ........ 83
    4.3.4 Linear Manoeuvring State-space Models ............ 85
  4.4 A Force-superposition Model for Slow Manoeuvring in a Seaway ......................................... 86
    4.4.1 Time Domain Seakeeping Models in the h-frame ... 86
    4.4.2 Seakeeping Model in the b-frame ..................... 89
    4.4.3 A Unified Nonlinear State-space Model .............. 91

5 Control Surfaces (Actuators) ...................................... 93
  5.1 Geometry of Fin and Rudder Hydrofoils .................. 93
  5.2 Hydrodynamic Forces Acting on a Foil .................... 93
  5.3 Unsteady Hydrodynamics .................................... 97
  5.4 Forces and Moments Acting on the Hull ................... 101
    5.4.1 Rudder .................................................... 102
  5.5 Rudder-Propeller Interaction .............................. 104
    5.5.1 Fins ..................................................... 106
  5.6 Hydraulic Machinery ........................................... 108
### Part II Introduction to Ship Roll Stabilisation

#### 6 Ship Roll Stabilisation
- 6.1 Effects of Roll Motion on Ship Performance 113
- 6.2 Damping or Stabilising Systems? 113
- 6.3 Ship Roll Stabilisation Techniques 115
  - 6.3.1 Gyroscopes 116
  - 6.3.2 Bilge Keels 116
  - 6.3.3 Anti-rolling Tanks 117
  - 6.3.4 Active Fin Stabilisers 119
  - 6.3.5 Rudder Roll Stabilisation RRS 120
- 6.4 A Note on the Early Days of Ship Roll Stabilisation 122

#### 7 Ship Motion Performance
- 7.1 Seakeeping Indices Affected by Roll
  - 7.1.1 Lateral Force Estimator—LFE 136
  - 7.1.2 Motion-induced Interruptions—MII 138
  - 7.1.3 Motion Sickness Incidence—MSI 140
- 7.2 Implications for Stabiliser Control System Design 141
- 7.3 Part II Summary and Discussion 142

### Part III Performance Limitations in Feedback Control with Application to Ship Roll Stabilisers

#### 8 Linear Performance Limitations
- 8.1 Introduction to Fundamental Limitation in Feedback Control Systems 146
- 8.2 Non-minimum Phase Dynamics in Ship Response 150
- 8.3 Deterministic SISO Performance Limitations of RRS 154
  - 8.3.1 Sensitivity Integrals—Frequency Domain Approach 155
  - 8.3.2 Performance Trade-offs of Non-adaptive Feedback Controllers for RRS 159
- 8.4 Stochastic SISO Performance Limitations of RRS 161
  - 8.4.1 Limiting Optimal Control Performance Limitations 161
  - 8.4.2 Stochastic SISO Results and RRS 164
- 8.5 Optimal Roll Reduction vs. Yaw Interference Trade-off 165
  - 8.5.1 SITO Control Problems in the Frequency Domain 165
8.5.2 Limiting Stochastic LQR ................................. 167
8.6 Comments on the Applicability of Rudder Stabilisers .... 171
8.7 NMP Dynamics in Fin Stabilizers ....................... 175

9 Constrained Performance Limitations ...................... 177
  9.1 Input Constraints and Saturation Effects ............... 177
  9.2 Input Constraints and Performance at a Single Frequency .... 178
      9.2.1 Magnitude Limitations ....................... 179
      9.2.2 Rate Limitations ............................ 180
  9.3 Application to Rudder-Based Stabilizers ............... 181
  9.4 Stochastic Approach: Variance Constraints ............. 182
      9.4.1 IVC Optimal Control Problem Formulation ........ 182
      9.4.2 IVC Application to RRS ....................... 185
  9.5 Part III Summary and Discussion ..................... 188

Part IV Control System Design for Autopilot with Rudder Roll Stabilisation and Fin Stabilisers

10 Previous Research in Control of Rudder Roll Stabilisation and Fin Stabilisers ......................... 193
  10.1 Rudder Roll Stabilisation in the 1970s ................. 193
  10.2 Rudder Roll Stabilisation in the 1980s ................. 196
  10.3 Rudder Roll Stabilisation in the 1990s ................. 201
  10.4 Rudder Roll Stabilisation from 2000 to 2004 .......... 203
  10.5 Work on Fin and Combined Rudder and Fin Stabiliser Control 204
  10.6 Main Issues Reported in Previous Work ............... 204

11 Constrained Control via Optimisation ..................... 207
  11.1 Constraint Classification .......................... 208
  11.2 Different Approaches to Constrained Control Problems ... 208
  11.3 Finite-horizon Sequential-decision Problems .......... 209
  11.4 Infinite Horizons and Receding-horizon Implementation ... 210
  11.5 Model Predictive Control .......................... 211
  11.6 Constrained Linear Systems ......................... 213
  11.7 Explicit and Implicit Implementations of QP-MPC ....... 216
  11.8 Stability of Model Predictive Control ................ 217
  11.9 Constrained Control of Uncertain Systems ............ 219

12 Control System Design for Autopilots with Rudder Roll Stabilisation ........................................... 221
  12.1 Overview of Autopilot Functions and their Influence on Control Design ......................................... 221
  12.2 RRS: A Challenging Control Problem .................... 223
  12.3 Control System Architecture .......................... 224
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4 Control Design Models</td>
<td>225</td>
</tr>
<tr>
<td>12.4.1 Control to Motion Model</td>
<td>226</td>
</tr>
<tr>
<td>12.4.2 Wave-induced Motion Model</td>
<td>228</td>
</tr>
<tr>
<td>12.5 Disturbance Parameter Estimation and Forecasting</td>
<td>229</td>
</tr>
<tr>
<td>12.6 Observer Design: State Estimation and Wave Filtering</td>
<td>233</td>
</tr>
<tr>
<td>12.7 Autopilot Control System Design</td>
<td>237</td>
</tr>
<tr>
<td>12.8 Autopilot Control Problem and Assumptions for the Design</td>
<td>237</td>
</tr>
<tr>
<td>12.9 A Model Predictive Control Solution</td>
<td>240</td>
</tr>
<tr>
<td>12.10 Performance of Model Predictive RRS</td>
<td>242</td>
</tr>
<tr>
<td>12.10.1 Choosing the Prediction Horizon</td>
<td>243</td>
</tr>
<tr>
<td>12.10.2 Penalising Roll Acceleration in the Cost</td>
<td>243</td>
</tr>
<tr>
<td>12.10.3 Case A: Beam Seas at the Top of Sea State 4</td>
<td>244</td>
</tr>
<tr>
<td>12.10.4 Case B: Quartering Seas at the Top of Sea State 5</td>
<td>245</td>
</tr>
<tr>
<td>12.10.5 Case C: Bow Seas at the Top of Sea State 5</td>
<td>246</td>
</tr>
<tr>
<td>12.10.6 The Role of Adaptation</td>
<td>246</td>
</tr>
<tr>
<td>12.10.7 A Comment About the Simulation Results</td>
<td>248</td>
</tr>
<tr>
<td>13 Constrained Control of Fin Stabilisers</td>
<td>251</td>
</tr>
<tr>
<td>13.1 Performance and Control of Rudder and Fins</td>
<td>251</td>
</tr>
<tr>
<td>13.2 A Model for Fin Stabilizer Control Design</td>
<td>252</td>
</tr>
<tr>
<td>13.3 Output Constraints to avoid Dynamic Stall</td>
<td>254</td>
</tr>
<tr>
<td>13.4 A MPC Fin-Stabiliser Controller</td>
<td>256</td>
</tr>
<tr>
<td>13.5 Numerical Simulations</td>
<td>258</td>
</tr>
<tr>
<td>13.6 Integrated Control of Rudder and Fins</td>
<td>263</td>
</tr>
<tr>
<td>13.7 Summary and Discussion</td>
<td>263</td>
</tr>
<tr>
<td>A Observers and Kalman Filtering</td>
<td>265</td>
</tr>
<tr>
<td>A.1 State Estimation via Observers</td>
<td>265</td>
</tr>
<tr>
<td>A.2 Kalman Filtering</td>
<td>266</td>
</tr>
<tr>
<td>A.3 Optimality of Kalman Filters</td>
<td>268</td>
</tr>
<tr>
<td>A.4 Correlated Disturbances</td>
<td>269</td>
</tr>
<tr>
<td>A.5 Practical Kalman Filter: Tuning</td>
<td>270</td>
</tr>
<tr>
<td>A.6 Steady State Kalman filter</td>
<td>270</td>
</tr>
<tr>
<td>A.7 Implementation Issues</td>
<td>271</td>
</tr>
<tr>
<td>B A Benchmark Example: Naval Vessel</td>
<td>273</td>
</tr>
<tr>
<td>B.1 Hull Shape</td>
<td>274</td>
</tr>
<tr>
<td>B.2 Adopted Reference frames</td>
<td>275</td>
</tr>
<tr>
<td>B.3 Principal Hull Data and Loading Condition</td>
<td>276</td>
</tr>
<tr>
<td>B.4 Rudder, Fins and Bilge Keels</td>
<td>277</td>
</tr>
<tr>
<td>B.5 Manoeuvring Coefficients and Motion RAO</td>
<td>279</td>
</tr>
</tbody>
</table>