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Ship Motion Control

Course Keeping and Roll Stabilisation using Rudder and Fins

– Monograph –

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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`

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 stabilistion 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.

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Trondheim, Norway *Tristan Perez*
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