Handbook of

MARINE CRAFT HYDRODYNAMICS AND MOTION CONTROL

Thor I. Fossen

Second Edition

WILEY

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This book is dedicated to my parents Gerd Kristine and Ole Johan Fossen, and my family Heidi, Sindre and Lone Moa who have always been there for me.

Thor I. Fossen

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About the Author

Professor Thor I. Fossen received an MSc degree in Marine Technology in 1987 and a PhD in Engineering Cybernetics in 1991, both from the Norwegian University of Science and Technology (NTNU). Fossen's academic background, besides cybernetics, is computer science, robotics, cybersecurity, aerospace engineering, marine technology and inertial navigation systems. He studied flight control as a Fulbright Scholar at the University of Washington, Seattle. He was appointed professor of guidance, navigation and control at NTNU at age 30. He has been visiting professor at University of California, San Diego (UCSD), University of California, Santa Barbara (UCSB), Aalborg University, Denmark and the Technical University of Denmark (DTU). Professor Fossen has been elected to the Norwegian Academy of Technological Sciences (1998) and elevated to IEEE Fellow (2016). He is one of the founders of the company Marine Cybernetics (2002), which was acquired by DNV GL in 2014. He is also one of the founders of the company SCOUT Drone Inspection (2017).

Professor Fossen is the author of the Wiley textbooks:

Fossen, T. I (2021). *Handbook of Marine Craft Hydrodynamics and Motion Control*, 2nd ed. John Wiley & Sons, Ltd. Chichester, UK

Fossen, T. I (2011). *Handbook of Marine Craft Hydrodynamics and Motion Control*, 1st edition. John Wiley & Sons, Ltd. Chichester, UK

Fossen, T. I (1994). *Guidance and Control of Ocean Vehicles*, John Wiley & Sons, Ltd. Chichester, UK

and co-author of the editorials:

Fossen, T. I, K. Y. Pettersen and H. Nijmeijer (2017). *Sensing and Control for Autonomous Vehicles*, Springer Verlag

Fossen, T. I and H. Nijmeijer (2012). *Parametric Resonance in Dynamical Systems*, Springer Verlag

Nijmeijer, H. and T. I. Fossen (1999). *New Directions in Nonlinear Observer Design*, Springer Verlag.

Professor Fossen has been instrumental in the development of several industrial autopilot, path-following and dynamic positioning (DP) systems. He also has experience in state estimators for marine craft and automotive systems as well as strapdown GNSS/INS navigation systems for ships and aerial vehicles. He received the Automatica Prize Paper Award in 2002 for a concept for weather optimal positioning control of marine craft. In 2008 he received the Arch T. Colwell Merit Award at the SAE 2008 World Congress.

He is currently professor of guidance, navigation and control in the Department of Engineering Cybernetics, NTNU.

Preface

The main motivation for writing the second edition of this book was to include new results on guidance, navigation and control (GNC) and hydrodynamic modeling of marine craft. In addition, the book has been reorganized into 16 chapters to improve readability.

The Wiley book from 1994 was the first attempt to bring hydrodynamic modeling and control system design into a unified notation for modeling, simulation and control. My first book also contains state-of-the-art linear and nonlinear design methods for ships and underwater vehicles up to 1994. In the period 1994–2011 a great deal of work was done on nonlinear control of marine craft. This work resulted in many useful results and lecture notes, which have been collected and included in the *Handbook of Marine Craft Hydrodynamics and Motion Control*. The first edition was published in 2011 and it was used as the main textbook in my course on “Guidance, Navigation and Control of Vehicles” at the Norwegian University of Science and Technology (NTNU) until 2020. Then it was replaced by this edition, which contains many new chapters and sections, general improvements, recent results and MATLAB scripts, which can be downloaded from a GitHub repository. The new chapters of the second edition cover autopilot models, models for underwater vehicles, control forces and moments, model-based navigation systems, Kalman filtering and inertial navigation systems.

Accompanying MATLAB Software

In 2019 the Marine Systems Simulator (MSS), which is an open source MATLAB toolbox, was migrated to GitHub in order to improve version control and support incremental software updates. The MATLAB software accompanying the book can be downloaded from the repository:

MSS toolbox: https://github.com/cybergalactic/MSS

The second edition of the book is fully compliant with the new features of the MSS toolbox and the book contains many examples using the MSS toolbox.

Preview of the Book

Part I of the book covers maneuvering and seakeeping theory and it is explained in detail how the equations of motion can be derived for both cases using both frequency- and time-domain formulations. This includes transformations from the frequency to the time domain and the explanation of fluid-memory effects. Great effort has been made in the development of kinematic equations for effective representation of the equations of motion in seakeeping, body, inertial and geographical coordinates. This is very confusing in the existing literature on hydrodynamics and the need to explain this properly motivated me to find a unifying notation for marine and mechanical systems. This was done in the period 2002–2010 and it is inspired by the elegant formulation used in robotics where systems are represented in a matrix-vector notation. The unified notation dates back to my PhD thesis, which was published in 1991.

Part II of the book covers guidance systems, navigation systems, state estimators and control of marine craft. This second part of the book focuses on state-of-the-art methods for feedback control such as PID control design for linear and nonlinear systems as well as control allocation methods. A chapter with more advanced topics, such as optimal control theory, backstepping, feedback linearization and sliding-mode control, is included for the advanced reader. Case studies and applications are treated at the end of each chapter. The control systems based on PID and optimal control theory are designed with a complexity similar to those used in many industrial systems. The more advanced methods using nonlinear theory are included so the user can compare linear and nonlinear design techniques before a final implementation is made. Many references to existing systems are included so control system vendors can easily find articles describing state-of-the art design methods for marine craft.

Acknowledgments

Most of the results in the book have been developed at NTNU in close cooperation with a large number of my former doctoral students. Our joint efforts have resulted in several patents, industrial implementations and spin-off companies.

The results on maneuvering and seakeeping are joint work with *Dr Tristan Perez*, who visited NTNU as a researcher in 2004–2007. The work with Dr Perez has resulted in several joint publications and I am grateful to him for numerous interesting discussions on hydrodynamic modeling and control.

I am particular grateful to *Professor Tor Arne Johansen* with whom I have co-authored a large number of my publications. Many of our joint results are included in the second edition of the book. *Dr Morten Breivik* and *Associate Professor Anastasios Lekkas* have contributed with many important results on guidance systems. *Professor Mogens Blanke* was instrumental in the development of the the sections on maneuvering, roll damping and propulsion theory. *Associate Professor Torleiv H. Bryne* should be thanked for important contributions on ship control and inertial navigation systems, while *Bjarne Stenberg* should be thanked for creating many of the graphical illustrations. Finally, *Stewart Clark* should be thanked for his assistance with the English language. The book project has been sponsored by the Norwegian Research Council through the author's affiliation as key scientist at the Center of Ships and Ocean Structures (2002–2012) and co-director of the Center of Autonomous Marine Operations and Systems since 2012.

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List of Tables

Part One

Marine Craft Hydrodynamics

De Navium Motu Contra Aquas

1

Introduction to Part I

The subject of this book is *motion control and hydrodynamics of marine craft*. The term marine craft includes ships, high-speed craft, semi-submersibles, floating rigs, submarines, remotely operated and autonomous underwater vehicles, torpedoes, and other propelled and powered structures, for instance a floating air field. Offshore operations involve the use of many marine craft, as shown in Figure 1.1. *Vehicles* that do not travel on land (ocean and flight vehicles) are usually called craft, such as watercraft, sailcraft, aircraft, hovercraft and spacecraft. The term vessel can be defined as follows:

> *Vessel*: "hollow structure made to float upon the water for purposes of transportation and navigation; especially, one that is larger than a rowboat."

The words *vessel, ship* and *boat* are often used interchangeably. In *Encyclopedia Britannica*, a ship and a boat are distinguished by their size through the following definition:

> *Ship*: "any large floating vessel capable of crossing open waters, as opposed to a boat, which is generally a smaller craft. The term formerly was applied to sailing vessels having three or more masts; in modern times it usually denotes a vessel of more than 500 tons of displacement. Submersible ships are generally called boats regardless of their size."

Similar definitions are given for submerged vehicles:

> *Submarine*: "any naval vessel that is capable of propelling itself beneath the water as well as on the water's surface. This is a unique capability among warships, and submarines are quite different in design and appearance from surface ships."
> *Underwater vehicle*: "small vehicle that is capable of propelling itself beneath the water surface as well as on the water's surface. This includes unmanned underwater vehicles (UUV), remotely operated vehicles (ROV), autonomous underwater vehicles (AUV) and underwater robotic vehicles (URV). Underwater vehicles are used both commercially and by the navy."

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Figure 1.1 Marine craft in operation. Source: illustration by B. Stenberg.

From a hydrodynamic point of view, marine craft can be classified according to their maximum operating speed. For this purpose it is common to use the *Froude number*

$$F_{\mathrm{n}} := \frac{U}{\sqrt{gL}} \tag{1.1}$$

where U is the craft speed, L is the overall submerged length of the craft and g is the acceleration of gravity. The pressure carrying the craft can be divided into *hydrostatic* and *hydrodynamic* pressure. The corresponding forces are:

- Buoyancy force due to the hydrostatic pressure (proportional to the displacement of the ship).
- Hydrodynamic force due to the hydrodynamic pressure (approximately proportional to the square of the relative speed to the water).

For a marine craft sailing at constant speed U, the following classifications can be made (Faltinsen 2005):

Displacement vessels ($F_n < 0.4$): The buoyancy force (restoring terms) dominates relative to the hydrodynamic forces (added mass and damping).

Semi-displacement vessel (0.4–$0.5 < F_n < 1.0$–1.2): The buoyancy force is not dominant at the maximum operating speed for a high-speed submerged hull type of craft.

Planing vessel ($F_n > 1.0$–1.2): The hydrodynamic force mainly carries the weight. There will be strong flow separation and the aerodynamic lift and drag forces start playing a role.

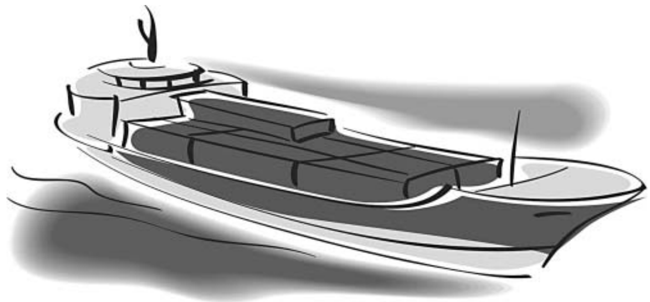

Figure 1.2 Displacement vessel.

In this book only displacement vessels are covered; see Figure 1.2.

The Froude number has influence on the hydrodynamic analysis. For displacement vessels, the waves radiated by different parts of the hull do not influence other parts of the hull. For semi-displacement vessels, waves generated at the bow influence the hydrodynamic pressure along the hull towards the stern. These characteristics give rise to different modeling hypotheses, which lead to different hydrodynamic theories.

For displacement ships it is widely accepted that two- and three-dimensional potential theory programs are used to compute the potential coefficients and wave loads; see Section 5.1. For semi-displacement vessels and planing vessels it is important to include the lift and drag forces in the computations (Faltinsen 2005).

Degrees of Freedom and Motion of a Marine Craft

In maneuvering, a marine craft experiences motion in six degrees of freedom (DOFs). The DOFs are the set of independent displacements and rotations that specify completely the displaced position and orientation of the craft. The motion in the horizontal plane is referred to as *surge* (longitudinal motion, usually superimposed on the steady propulsive motion) and *sway* (sideways motion). *Yaw* (rotation about the vertical axis) describes the heading of the craft. The remaining three DOFs are *roll* (rotation about the longitudinal axis), *pitch*(rotation about the transverse axis) and *heave* (vertical motion); see Figure 1.3.

Roll motion is probably the most influential DOF with regards to human performance, since it produces the highest accelerations and, hence, is the principal villain in seasickness. Similarly, pitching and heaving feel uncomfortable to people. When designing ship autopilots, yaw is the primary mode for feedback control. Stationkeeping of a marine craft implies stabilization of the surge, sway and yaw motions.

When designing feedback control systems for marine craft, reduced-order models are often used since most craft do not have actuation in all DOFs. This is usually done by decoupling the motions of the craft according to:

1-DOF models can be used to design forward speed controllers (*surge*), heading autopilots (*yaw*) and roll-damping systems (*roll*).

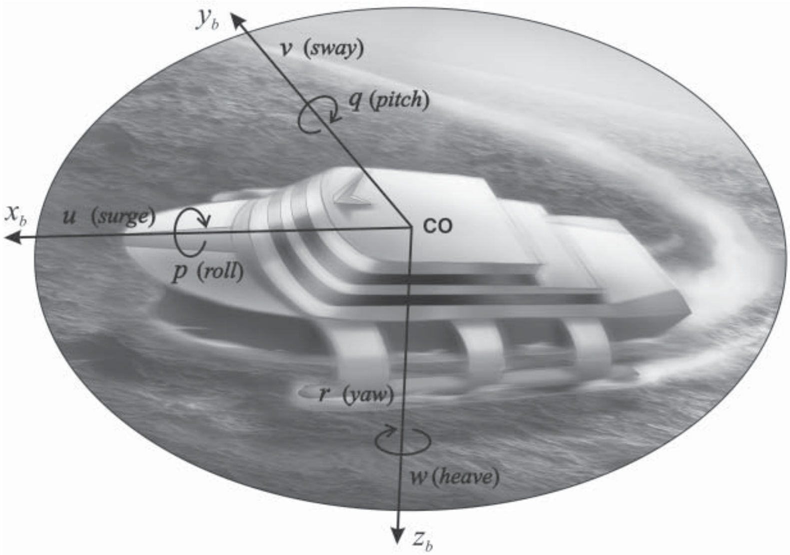

Figure 1.3 Motion in six degrees of freedom (DOFs).

3-DOF models are usually:

- Horizontal-plane models (*surge, sway* and *yaw*) for ships, semi-submersibles and underwater vehicles that are used in dynamic positioning systems, trajectory-tracking control systems and path-following systems. For slender bodies such as submarines, it is also common to assume that the motions can be decoupled into *longitudinal* and *lateral* motions.
- Longitudinal models (*surge, heave* and *pitch*) for forward speed, diving and pitch control.
- Lateral models (*sway, roll* and *yaw*) for turning and heading control.

4-DOF models (*surge, sway, roll* and *yaw)* are usually formed by adding the roll equation to the 3-DOF horizontal-plane model. These models are used in maneuvering situations where it is important to include the rolling motion, usually in order to reduce roll by active control of fins, rudders or stabilizing liquid tanks.

6-DOF models *(surge, sway, heave, roll, pitch* and *yaw*) are fully coupled equations of motion used for simulation and prediction of coupled vehicle motions. These models can also be used in advanced control systems for underwater vehicles that are actuated in all DOFs.

1.1 Classification of Models

The models in this book can be used for prediction, real-time simulation, decision-support systems, situational awareness as well as controller-observer design. The complexity and