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# Time Series Modeling for Analysis and Control

## Advanced Autopilot and Monitoring Systems

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# Preface

The autopilot and main engine governor of a ship are typical examples of feedback systems that have a long history. Autopilot systems to maintain the heading angle of a ship in order to hold a desired course were developed by the Sperry Corporation in the 1910s, and since then helmsmen have become free from the arduous task of steering in course navigation. A governor mechanism to maintain the revolution rate of the engine shaft was invented much earlier than the autopilot system and can be traced back to the centrifugal governor invented by James Watt for regulating a steam engine in the eighteenth century. The classical control theory for designing these analog control systems has contributed to control in numerous mechanical systems.

In the latter half of the twentieth century, however, the circumstances of control engineering have changed rapidly due to dramatic developments in digital computers and microelectronics, and digital computers have overtaken analog systems in several fields. In the first stage of digital control, the analog control law was digitized to realize a digital control system. However, a more essential innovation in control system design was to apply the modern control theory based on the state-space model of the control system.

In the 1970s, modern control theory was also introduced, allowing innovations in ship autopilot systems. The critical problem in designing an autopilot system, however, is to obtain a model of the ship that can properly represent the complicated and inherently stochastic behavior of a ship at sea. Without a reasonable model of the control system, it is not possible to apply modern control theory, which is a bottleneck when applying modern control theory to complicated large systems with strong disturbance noise.

As a practical solution to this problem, Dr. Hirotugu Akaike proposed the use of the autoregressive (AR) model in the analysis and control of complicated systems. The crucial problem in statistical modeling was the identification of the model, including the selection of variables, model type, and model orders, and the estimation of unknown parameters. For this problem, he proposed final prediction errors (FPE) for identifying the stochastic behaviors of a cement rotary kiln system using a multivariate autoregressive (MAR) model, and generalized FPE to the

Akaike information criterion (AIC) for evaluating a more general statistical model. Many successful applications of analysis and control of complicated stochastic systems through statistical modeling based on AIC have appeared in the literature.

The purpose of this book is to present an appropriate time series modeling method for the analysis and control of complicated systems, for which it is difficult to obtain a precise model that can express the behavior of a controlled system based on the theory of the domain. Throughout this book, we will use multivariate autoregressive modeling with exogenous variables based on AIC. However, we will also consider a nonstationary version and a nonlinear version of the model to cope with real problems. A special feature of this book is to consider modeling, analysis, and control of a real ship's behavior at sea, and we herein develop various types of autopilot systems. We present not only the results of simulation studies, but also many results of actual sea tests. Although we treat only applications related to ships, we hope that the readers of this book will gain a deeper general knowledge and useful tools for the analysis and control of complicated systems and will be able to apply these methods to solve problems in their own fields.

This book is the result of long and intensive collaboration of three researchers who have different research fields. Kohei Ohtsu's research interests include the analysis, monitoring, and control of ship motions at sea using time series modeling techniques. He developed a novel autopilot system using an autoregressive model in cooperation with Genshiro Kitagawa in the 1970s. Hui Peng's research interests include nonlinear system modeling, nonlinear optimization, and optimal control. He developed a practical modeling technique for nonlinear time series using a radial bases function ARX model and, together with the two other authors of this book, recently succeeded in developing tracking control of a ship using this model. Genshiro Kitagawa's primary interests are in statistical modeling, nonstationary time series analysis, and optimal control of stochastic systems. He developed a Monte Carlo filter technique for a nonlinear state-space model which is now referred to as a "particle filter".

The authors would like to thank the numerous people who have supported our research in its various stages. In particular, we would like to express our sincere thanks to the late Dr. Hirotugu Akaike, former Director General of the Institute of Statistical Mathematics, Japan, for his guidance and valuable suggestions regarding our research. We are also grateful to Prof. Michio Horigome, Dr. Hiroyuki Oda, Dr. Jun Wu, the crew members of Shioji-Maru, and numerous other people for their collaboration and contributions to our research. Finally, we would like to thank Ms. Michiko Oda for her help in editing this book.

Tokyo, Japan, January 2015 Kohei Ohtsu
Changsha, China Hui Peng
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# Contents

# Chapter 1
# Introduction

**Abstract** In the following, the necessity of statistical modeling for analysis and control of complex, large systems with large disturbances and the aim of this book are first presented. We then present the basic concepts of ship motion and course keeping control problems, which are the primary applications of the time series modeling treated in this book. A brief explanation of the real ships that were used in actual sea tests is then presented. Finally, the organization of this book is described.

**Keywords** Ship motion · Statistical modeling · Autopilot · Ship propelling · Outline of chapters

## 1.1 Necessity of Statistical Modeling for Complex, Large Systems

In the identification of ship motion on the ocean, it is important to adopt a statistical model because external disturbances caused by wind, waves, and the motion of the hull itself in response to such oceanic disturbances are intrinsically irregular. Moreover, the dynamic range of the external disturbances is very wide, from mirror-like calm seas to rough seas with violent storms. Thus, changes of ship motions are so large that they would not be imaginable in other vehicles. A method of practical analysis of such irregular phenomena has been established in the frequency domain (Blackman and Tukey 1959; Isobe 1960), and the ship motion under disturbances has also been dealt with as a stochastic process in the field of ship-building engineering.

Statistical methods for analyzing time series obtained from model tests conducted in irregular waves or using records of actual-sea tests in the frequency domain have been established by 1960s (Yamanouchi 1961). However, there are few rigorous statistical methods by which to fit a model in the time domain (Åström and Wittenmark 1984). A breakthrough came with the development of objective model evaluation criteria, such as the final prediction error, FPE, and the Akaike information criterion, AIC, proposed by Akaike (Akaike 1971, 1974; Nakamura and Akaike 1988; Akaike and Nakagawa 1988; Konishi and Kitagawa 2008), which enables identification of a multivariate time series model for real data. The AIC was a useful tool for identifying the actual irregular data observed onboard a ship and for controlling ship motions.



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The present authors have worked to identify actual onboard data and design a marine control system similar to an autopilot or main engine governor. The purpose of this book is to discuss a statistical approach by which to identify a time series model, in particular, a multivariate autoregressive model of observed onboard data, and to control ship motion and main engine behavior using statistical models. Since the models of a ship's autopilot and engine governor discussed herein are typical feedback systems, the authors hope that the readers of this book will be able easily understand the proposed method and apply it in solving problems in their own fields.

## 1.2 Model of Ship Motion and Main Engine

Before discussing the problems treated herein, we briefly explain a model of the ship motion and main engine. The ship considered herein is a conventional vessel. Thus, special vessels including high-speed launches are not considered herein. As shown in Fig. 1.1, a ship navigating on the sea can be described as moving with six degrees of freedom (Fossen 1994; Lewis 1988).

Roll, pitch, and heave are motions that have restoring forces, whereas sway, surge, and yaw are motions having no restoring force. A ship generally installs with a propeller to control surge motion. Moreover, it is usually not necessary to control sway motion for maneuvering the ship at ocean. However, it is important to maintain and settle her course into a desired one. Thus, a ship is generally equipped with an autopilot system in order to appropriately control yaw. The primary role of autopilot system is to control yaw by rudder and steer the ship to directly follow a desired course. The motion induced by such steering is referred to as a course keeping motion. In this book, the heading deviation from the desired course is referred to as yaw. The secondary role of the autopilot is to alter the course so as to follow another desired course. Course-keeping motions require small-deviation control,

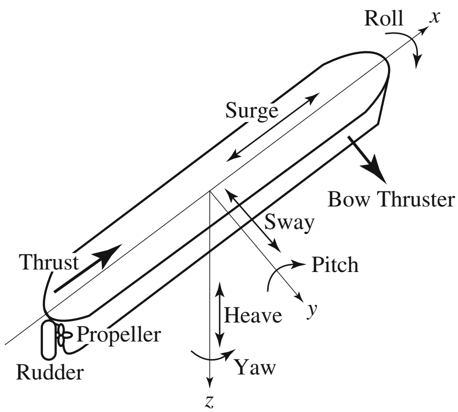


**Fig. 1.1** Terms used to describe ship motion

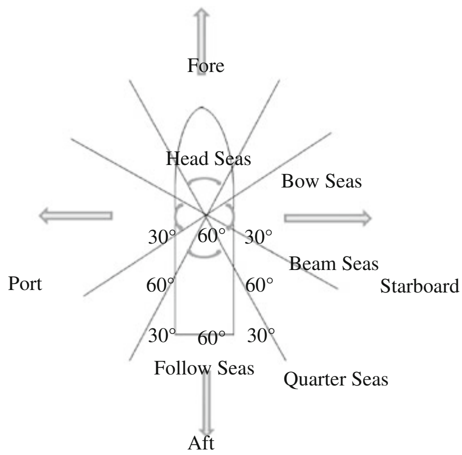


**Fig. 1.2** Terms used to describe directions at sea

whereas course-changing motions require large-deviation control. Another role of the autopilot system is to maintain a ship's trajectory along a desired track. Recently, research on a ship's tracking system has been conducted. We also discuss the tracking system in this book.

A ship receives strong disturbances, especially, by wind and waves, from the sea. The scale of the wind force is classified according to the Beaufort scale. However, a general measurement instrument by which to measure the wave height and direction has not yet been standardized. Figure 1.2 shows the terms used in described directions at sea.

On the other hand, the thrusting force of ship is generally generated through the propeller. The rotating force of the propeller is generated by the main engine (Fig. 1.1). The rotation of the propeller cannot maintain a set rotational frequency unless a regulator is properly applied. The engine governor is a device for regulating the amount of fuel supplied to the engine (so that the propeller can maintain the desired rotational frequency). At present, centrifugal governors, which have been widely used as governors in ships, have been gradually replaced by electronic governors because of rapid progress in electronic equipment.

## 1.3 Experimental Ships and Outline of Topics Discussed in Remaining Chapters

In the following, we use various actual sea test data for modeling and designing autopilot systems. The data were obtained primarily through experiments conducted on "Shioji-Maru II" and "Shioji-Maru III", training ships of Tokyo University of Mercantile Marine. The principal dimensions and main engine specifications of both ships are listed in Table 1.1. Figure 1.3 shows a photograph of T.S. Shioji-Maru III.