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Preface

In many dynamical systems surrounding us, events often unfold with aftereffects. This is because it takes time for an event to take place upon being triggered by a stimulus. The duration of time between when a stimulus is applied and the onset of the event is the *time delay*. The effects of time delays on the behavior of dynamical and control systems form the main focus of this book.

The presence of delays as has been widely observed and studied draws attention to a number of interesting characteristics in dynamical and control systems in the way such systems evolve and interact with each other, and how decisions are formulated. In many cases such characteristics can be intriguing but difficult to assess, and can challenge one's intuition; this very likely explains the large body of literature on the topic spread across mathematics, engineering, physics, and economics. The presence of delays also brings about interesting philosophical questions regarding how events take place, how we perceive and react to them, how our past actions propagate through time and space, and how such actions may influence our current states.

In the context of dynamical and control systems, delays arise due to a number of reasons, including the time needed to transmit information between two physical points, to formulate complex decisions based on the information available, and to implement decisions/policies. Delays can arise in sensors and information infrastructure, in controllers, e.g., due to long computation times, and in actuators that do not instantaneously respond to input commands. In supply chain management one finds analogous observations, where supplies take time to displace between physical points, supply chain managers need time to evaluate certain factors before implementing key decisions, and such decisions when implemented can take time to take effect.

Numerous manuscripts, books, and conference proceedings have been published on the topic of *time delay systems*, with one primary topic of interest being *stability*. In the context of linear time-invariant (LTI) systems, stability analysis can be performed mainly under two well-recognized directions, namely, in the time domain and in the frequency domain. This book focuses on mastering frequency domain techniques for two main reasons, one being that the topic falls within the expertise of the author, and second, these techniques for time delay systems can be easily explained using the tools of classical control for systems without delays, e.g., in terms of eigenvalues, pole placement, complex analysis, root locus, and Nyquist stability criterion. Therefore this book is a convenient starting point, especially for readers new to the area and readers who would like to rapidly develop skills based on graduate level understanding of classical and modern control.

What inspired me the most to develop this book were the many questions I have received from colleagues regarding how to analyze the stability of various types of LTI systems with time delays. One other motivation was my desire to spread knowledge as clearly as possible not only to experts but also to readers willing to learn about the field but require some guidance at the beginning. In that regard, I hope this book achieves the purpose of disseminating key knowledge and can stimulate interest on the topic, expand the utilization of existing tools to new fields, become a valuable reference source, and help train graduate students.

Many years have gone into studying the literature, reading, and hands-on practice of the topic. This would not have been possible if I had not been introduced to the topic during my graduate studies at the University of Connecticut (2000–2005), where I worked with Professor Nejat Olgac on the stability analysis of LTI systems with single and multiple delays, and if I had not been guided in my postdoctoral position at HeuDiaSyC (CNRS) at Université de Technologie de Compiègne, France (2005–2006), where under a Chateaubriand postdoctoral fellowship of the French government I worked with Professor Silviu-Iulian Niculescu (currently at Ecole Centrale-Supelec (CNRS)) on time delay systems from supply chain management, car following dynamics and human reaction delays, and from the complex behavior arising due to the network infrastructure of coupled dynamical systems.

During my training, I was also fortunate to be exposed to studies in the areas of frequency domain techniques by, in no particular order, Gabor Stepan, Silviu-Iulian Niculescu, Jie Chen, Keqin Gu, Arild Thowsen, Zenonas V. Rekasius, Kenneth L. Cooke, Pauline van den Driessche, Richard F. Datko, Jack K. Hale, David Hertz, Ezra Zeheb, Eliahu I. Jury, John Chiasson, Edward W. Kamen, Chieh-Su Hsu, S. J. Bhatt, Fatihcan M. Atay, Zaihua Wang, Stephen Barnett, Wim Michiels, Dirk Roose, Nejat Olgac, Dimitri Breda, Stefano Masset, Rossana Vermiglio, Sabine Mondie, Elias Jarlebring, Tomas Vyhlidal, Yusuf Altintas, Hitay Ozbay, Dirk Helbing, Frank Allgower, and A. Galip Ulsoy. The list, as one may guess, is much much longer, but I have kept it brief to guide the reader to excellent research being conducted throughout the world on this topic.

With regard to what this book is about, I would note that it is slightly different in spirit and organization from traditional books. It is mainly focused on explaining in great detail a number of fundamental stability analysis techniques and how these techniques are implemented to solve problems. To serve this main purpose, these techniques are introduced and discussed in relation to other techniques to interweave them and establish connections, which are then followed by step-by-step solutions of numerical problems. The main reason for this was to help the reader to view the literature within a broader perspective to understand how key building blocks link with one another, and was to enable effective problem solving, which is rarely published in sufficient detail in archival journals inhibiting scientific progress and dissemination of knowledge. While preparing the book with this perspective, I also did my best in the introduction (Chapter 1) to provide sufficient background and a thorough list of key references. The main reason for this concise presentation was to avoid duplicating the work in excellent books already available in the literature, but instead to set the base for the subsequent discussions pertaining to the techniques and treatment of case studies.

One critical point about this book is that various techniques are not necessarily covered in isolation from one another. First, this helps the reader to see how different techniques are interrelated, if any are, and enriches the discussions. Needless to say, all techniques are properly cited and approaches are credited. Second, this approach helps educate the reader on the philosophy of the techniques and enables the reader to see them from various perspectives. In this regard, this book is not a compilation of stand-alone techniques, but instead the presentation is optimized to make the most of the material when teaching it. In that sense, the presentation does not always flow linearly in chronological order but, when appropriate, pulls other relevant information together to make it more complete.

It is important to note that this book is provided as a reference resource to study and solve various problems, to be used as a refresher, and to train graduate students, but it is by no means complete in terms of references. One would appreciate the depth and richness of the literature, and I have done my best to present some key references to shed light on the problems studied. The book rather provides certain techniques and references therein as anchor points; it is therefore recommended that the reader utilize and connect these anchor points within their own literature reviews and research. In relation to this, it is important to note that the material presented should not be perceived as the first and/or the sole results on the topic, but rather a nucleation point from which to begin studying on the topic. Throughout the book, I have done my best not to insert any subjective opinions on the techniques since the goal here is to solve relevant problems, rather than champion a particular trend of approaches. In this sense, it is left to the reader to formulate a comprehensive understanding of the techniques and relevant literature when making comparisons between certain research trends. Nevertheless, I have still provided some objective ways to compare and contrast the approaches; whenever I did so, this was intended to provide the reader with a way to critically think, but not to diminish one approach over another.

To be able to comfortably follow this book, the reader should have graduate-level understanding of LTI systems, as well as classical and modern control. Specifically, knowledge of stability, root locus, the dominant pole concept, complex analysis, and stability-instability characterization in parameter space is needed as a foundation to easily extend to the understanding of how to analyze the stability of LTI systems with delays. While each chapter is self-contained and clearly organized into sections with headings, I would definitely recommend starting with the preliminaries in Chapters 2–4, and next examining Chapters 5–9, which are related to the fundamentals and treatment of single-delay cases. Once this is established, the reader can comfortably move on to the study of commensurate delay problems (Chapters 10–15) and followed by two-delay problems (Chapters 16–21). Moreover, the chapters are presented with interlinks to enable the reader to see how various techniques may have certain relationships; these cross references can guide the reader through various topics of interest.

The best way to learn is to practice. I would therefore strongly recommend that the reader reproduce the examples presented, comparing them side by side with the solutions provided, and next expand on more complex problems. Some solutions are also supported by MATLAB and MAPLE routines within the chapters and are marked as Algorithms to assist the reader with coding. While I am not a proficient coder, I hope that what I provide is sufficient to guide the exercises. I feel that once the reader solves the presented examples step by step, he/she will have gained a decent understanding in handling a variety of problems with time delays. To further assist the reader, some relevant MATLAB codes will be made available through the link

`www.siam.org/books/cs20`

All such current and future content is provided "as is"; neither SIAM nor the author are responsible for unfortunate errors in the online content.

Last but not least, I must mention that it was not possible to cover all possible problems; the focus is on those that have little ambiguity in their solution, including some degenerate cases. The interested reader can follow the most recent trends at conferences organized by IEEE, IFAC, and ASME. In particular, the IFAC Workshop on Time Delay Systems attracts a large group of researchers working on various aspects of time delay systems. Moreover, we see an increase in the number of edited volumes being published on the topic; a large collection can be found in the Springer Lecture Notes in Control and Information Sciences series and more recently in Springer Advances in Delays and Dynamics.

Before I close, I would like to express my sincere regards to SIAM, Executive Editor Elizabeth Greenspan, and the anonymous reviewers for their support and trust in me in providing this book for the community. I also would like to acknowledge the many opportunities I have had that enabled me to work on time delay systems, specifically through the support of the National Science Foundation and working with wonderful graduate students. None of this work would have been possible without a collegial and productive working environment. I am therefore indebted to the support of Northeastern University, College of Engineering, and the Department of Mechanical and Industrial Engineering. I also express my special thanks to Mr. Yanchao Wang, who provided valuable feedback on Parts I and II of this book.

And of course, none of this would be possible without support in one's life for the good days and the tough days; I cannot express in words how indebted I am to my wife Alix for her unlimited support and trust in what I do, and in what I love to do. As a tiny token of thanks, I dedicate this book to her and our eternal love.

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