Chapter 2 studies the multiplicative or relative approximation problem here the purpose is to find a reduced order model $\hat{G}$ for a given full order model G so that the multiplicative error $\|G^{-1}(G-\hat{G})\|_\infty$ or the relative error $\|\hat{G}^{-1}(G-\hat{G})\|_\infty$ is small. There are essentially three known techniques for solving this problem: balanced stochastic truncation (BST), frequency weighted balanced truncation, and multiplicative Hankel norm approximation. This chapter introduces the BST and multiplicative Hankel norm approximation methods. It is shown in the next chapter that the frequency weighted balanced truncation can give the same results as that of BST when it is applied to this special frequency weighted problem.

It should be pointed that model reduction itself is probably not the ultimate goal for developing model reduction techniques in control. The real purpose is to use them for designing lower order controllers, i.e., for controller reductions. Chapter 3 proposes some lower order controller design methods by formulating the lower order controller design problems as various frequency weighted controller or plant model order reduction problems in order to preserve some closed-loop properties. Two types of weighting functions are commonly used: closed-loop stability preserving weighting functions and closed-loop performance preserving weighting functions. The stability preserving weighting functions are easy to calculate but the resulting reduced order controllers may not give desired closed-loop performance. On the other hand, the performance preserving weighting functions are usually much harder to calculate since they are either involving the reduced order controllers themselves (which is approximated in the book) or involving complicated calculations (which are not described in the book and only references are given). Since the reduced order controller design problems are now formulated as frequency weighted model reduction problems. The frequency weighted balance truncation technique and the frequency weighted Hankel norm approximation method are described in detail together with some error bounds and computational algorithms. The sampled-data controller reduction problems are also considered using lifting techniques. And finally, a numerical example is presented.

The final chapter, Chapter 4, presents yet another reduced order controller design technique by formulating the reduced order controller design problem as either a coprime factor reduction problem or a weighted coprime factor reduction problem. First of all, the concept of coprime factorization and the state space factorization formulas are introduced. Next, various closed-loop performance bounds are derived in terms of the controller coprime factor reduction errors. Finally, a general H_∞ performance preserving controller reduction technique is described using weighted coprime factor reduction method. The most conspicuous advantage of this coprime factor performance preserving controller reduction technique is that the weighting function is very easy to calculate and furthermore the method seems to be very effective by the reviewer's experience. This is probably a somewhat pleasant surprise to those who have initially proposed the coprime factor controller reduction method since the initial motivation for considering the reduced order controller design problem using coprime factors is probably to avoid the problems faced in those previous methods when the controllers themselves are unstable.

In conclusion, this is an excellent reference on model and controller reduction techniques and anyone who has interests on these topics should have one on their shelves.

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About the reviewer

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Essentials of robust control

Kemin Zhou, John C. Doyle; Prentice-Hall, Englewood Cliffs, NJ, 1998, ISBN: 0-13-790874-1

Among the handful of expository books on $\mathscr{H}_\infty$ based robust control, the book under review and (Vidyasagar, 1985; Francis, 1987; Maciejowski, 1989; Green & Limebeer, 1995; Zhou, Doyle, & Glover, 1996), two are coauthored by Zhou and Doyle. The authors mastering of the subject, carefulness in material selection, skill in exposition, and rigor of reasoning have made the books masterpieces. This book can be considered as a watered down version of (Zhou, Doyle, & Glover, 1996), intended as a textbook instead of research monograph. As such, examples, exercises and MATLAB instructions are added. Nevertheless, it also offers something new in technical contents. It is the only textbook so far containing the beautiful and successful theory of $\mathscr{H}_\infty$ loop shaping and the optimal gap metric (or ν-gap metric) robust control theory. This is said with no disregard to the two excellent monographs on these topics (McFarlane & Glover, 1990; Vinnicombe, 1999).

Chapter 1 gives a guided tour of the book. Chapters 2 and 3 are brief introductions on linear algebra and elementary linear system theory, respectively. Chapter 4 defines $\mathscr{H}_2$ and $\mathscr{H}_\infty$ spaces for signals and systems. It also gives the relationship between these spaces, as well as the state-space methods for the computation of the $\mathscr{H}_2$ and $\mathscr{H}_\infty$ norms of a system. Chapter 5 is on the stability theory of feedback systems. It defines the internal stability of feedback systems, gives its state-space test (in an exercise problem), introduces the extremely useful concept of coprime factorizations, and describes its role in the study of stability and its connection with state-space realizations.

Chapter 6 explains how usual performance specifications can be cast as requirements in the weighted $\mathscr{H}_2$ or $\mathscr{H}_\infty$ norms of certain closed loop transfer functions, such as sensitivity and complimentary sensitivity functions. These functions cannot be assigned arbitrarily. They are limited, as indicated in this chapter, by some simple open loop characteristics such as plant unstable zeros and nonminimum phase zeros. This is why $\mathscr{H}_2$ and $\mathscr{H}_\infty$ optimization comes into play.

The theme of Chapter 7 is model reduction. It is not intended to be exhaustive, but gives an account of model reduction by truncating the balanced realization of the system.

Chapter 8 further motivates $\mathscr{H}_\infty$ optimization from robust control point of view. It discusses various ways to describe system uncertainties in the frequency domain. The celebrated small gain theorem is then used to establish the connection of system robust stability with the $\mathscr{H}_\infty$ norm of certain closed loop transfer function. Robust performance issue is also mentioned.

Chapter 9 briefly introduces the linear fractional transformation (LFT) and the associated star product, which turn out to be handy tools in describing feedback connections, system uncertainties and controller parameterization. The popularization of LFT is one of the major advances of systems control theory in the 1980s.

Chapter 10 introduces μ analysis and synthesis. The motivation is to model and treat general structured multiple sources of uncertainties. Hence, they have important implications in applications. Issues in stability robustness analysis and robust controller synthesis under structured uncertainties are discussed. The robust control synthesis is connected to the $\mathscr{H}_\infty$ optimization.

Chapter 11 examines the set of all stabilizing controllers for a plant. The fact that this set can be parameterized in terms of an LFT of an arbitrary stable system Q and any closed loop transfer function is an affine function of this Q is one of cornerstones of modern control theory and it revolutionized our thinking of linear optimal control. The chapter gives a beautiful presentation of this gem of control theory.

Chapter 12 studies the algebraic Riccati equation (ARE), which is a main mathematical tool in solving the optimal $\mathscr{H}_2$ control problem and the $\mathscr{H}_\infty$ control problem. A method in finding the stabilizing solution is presented. The connections between ARE and several transfer function factorization problems (coprime factorization, spectral factorization, inner–outer factorization) are examined (mostly in the exercise problems).

Chapters 13 and 14 form the core of this book. They present the solutions to the standard $\mathscr{H}_2$ optimal control and $\mathscr{H}_\infty$ control problems. They also address some related problems, such as the linear quadratic regulator (LQR) problem, $\mathscr{H}_2$ and $\mathscr{H}_\infty$ integral control for constant reference tracking and disturbance rejection, and $\mathscr{H}_\infty$ filtering. Probably a better understanding of the material can be made by consulting the first part of the accompanying solution manual (Zhou, 1998), which gives alternative formulations and derivations of $\mathscr{H}_2$ and $\mathscr{H}_\infty$ control problems and solutions. The alternative derivations exhibit more clearly the separation feature of the solutions in terms of a state feedback and a state estimation.

Chapter 15 concerns controller order reduction. The materials here are related to the model reduction in Chapter 7 but the difference is that closed loop effect consideration is emphasized here.

Chapters 16 and 17 are two closely related chapters. They first present a special $\mathscr{H}_\infty$ optimization problem with attractive features. This problem appears to be a general four-block $\mathscr{H}_\infty$ optimization problem, but is inherently a one-block problem and hence γ-iteration is not required in its solution. It corresponds to the robust stabilization problem with respect to general forms of uncertainties described possibly by the gap metric, the ν-gap metric, or the normalized coprime factorization. Then these chapters present an $\mathscr{H}_\infty$ loop shaping design procedure initiated by McFarlane and Glover (1990) and further developed by Vinnicombe (2001). In this new procedure, feedback controller design boils down to the selection of inside-of-the-loop weighting functions, which are to become part of the controller, so that the loop gain has a desired shape. The stability and robustness are taken care by designing the remaining part of the controller to solve the above mentioned $\mathscr{H}_\infty$ optimization problem.

In the "standard" feedback controller design using weighted $\mathscr{H}_\infty$ optimization, one difficulty is in the selection of the weighting functions from the design specifications, as briefly discussed in Chapter 6. These weighting functions are outside the control loop, hence are required to be stable, etc., and they have only loose relationship with the desired design specifications, whereas in this new loop shaping design procedure, the outside-of-the-loop weighting functions are replaced by inside-of-the-loop weighting functions. Clearer guidelines exist for their selection and they are less restrictive.

Chapter 18 is somewhat auxiliary. It briefly and selectively addresses two recent topics: robust model validation and robust stability analysis with structured uncertainty with possible mixed parametric and dynamic nature.

The exercise problems also contain quite a few robust control tools of general interest, such as normalized coprime factorization (Chapters 5 and 12), real stability radius (Chapter 8), Kharitonov theorem (Chapter 8), passivity theorem (Chapter 8), internal model control (Chapter 11).

This book is complemented by a solution manual (Zhou, 1998) and a website

URL: www.ece.lsu.edu/kemin/kemin.html

The solution manual contains, in addition to solutions to the exercise problems in the book, supplementary materials on $\mathscr{H}_2$ and $\mathscr{H}_\infty$ control, further streamlining the materials in Chapters 13 and 14. The website contains corrections, slides for lecturing purpose, as well as the solutions to the exercise problems.

The leanest graduate course based on this book could include at least Chapters 4 and 5, parts of Chapters 6 and 8, Chapters 9, 11–13, and part of Chapter 14. I would also strongly recommend Chapters 16 and 17 if time allows. The other chapters can be considered as either preparatory or supplementary.

The book shows the authors' meticulous effort in material selection and organization to make it accessible for entry level graduate students, practicing engineers, and users of the theory in other technical domains. Completeness is seen to give ways to conciseness. This book follows the philosophy of thinking in frequency domain and computing in the time domain, started since mid 1980s and exemplified in the book (Zhou, Doyle, & Glover, 1996). However, this book inclines more towards time domain state-space manipulations, because of its heavy emphasis on real design and computation. The role of coprime factorizations as well as other transfer function factorizations and decompositions, once the cradle of $\mathscr{H}_\infty$ control theory, is dramatically subdued. To our increasingly more pragmatic engineering community, this is a timely and worthy addition. On the other hand, for Ph.D. students and researchers in control area, the book (Zhou, Doyle, & Glover, 1996) does provide more connections with history and mathematics, reveal more insights and underlying ideas, and offer more depth and breadth.

Possible suggestions for a second edition of this book include adding more exercise problems to some chapters such as 17 and 18, expanding the notes and references sections to broaden the readers' exposures, streamlining the materials in Chapters 13 and 14 by putting the materials in the solution manual to the text, extending Chapter 18 to cover some more recent developments of general interest, and possibly adding a chapter to address the robust asymptotical tracking and rejection of persistent references and disturbances. The rationale for the last suggestion is because of the prominent role that robust tracking and disturbance rejection played in classical control theory (system type) and in early stage of robust control development (internal model principle). Although materials in Section 14.8 and the loop shaping design procedure in Chapter 16 provides possibility to address this issue, a more systematic treatment in the $\mathscr{H}_\infty$ spirit, such as the one in (Vidyasagar, 1985), seems plausible.

The beautiful Chinese calligraph in the cover, handwritten by the first author, gives his ingenious interpretation of $\mathscr{H}_\infty$, both phonetically and literally. Probably a reader will find understanding this calligraph equally rewarding as understanding the technical content.

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