general framework developed in Chapter 6, it is known that the global robust output regulation problem for a given nonlinear system can be converted into the global robust stabilization problem for an augmented system. The framework has been applied to two typical classes of nonlinear systems, i.e. output feedback systems and lower triangular systems, respectively. A small gain theory-based robust control method is developed to solve the robust stabilization problem for the two respective augmented systems.

- *Output Regulation for Singular Systems*: Output regulation problem for singular nonlinear systems is studied in Chapter 8. Results obtained for both the output regulation problem and the robust output regulation problem have been extended to singular nonlinear systems.
- *Output Regulation for Discrete-time Systems*: Output regulation problem and the robust output regulation problem for discrete-time nonlinear systems are considered in Chapter 9. A set of results and design techniques parallel to Chapters 3–6 are obtained.

In addition, two appendices are included. Appendix A describes the solution of the Sylvester equations and Appendix B introduces the ITAE prototype design method. A section entitled 'Notes and References' gives general comments on the references of this topic, which are informative and helpful for further study.

The organization of the book is quite cohesive. It basically covers all important scenarios of the output regulation problem except for the emerging adaptive output regulation problem. The book should be of interest to both university professors, and graduate students in systems and control area. It is also a useful reference for control engineers. It is a valuable addition to the literature of nonlinear control systems.

The book can be used as a graduate textbook for graduate students interested in nonlinear control systems. Although Chapter 2 provides the necessary background for pursuing this topic, a certain degree of familiarity with such topics as stability theory and normal form in the level of Isidori's book [2] or Khalil's book [3] should be very helpful.

The readability of the book could be further enhanced particularly for engineers if the author can provide more engineering and/or numerical examples and supply each chapters by some exercises.

Finally, I was recently informed by the author that the book now has a website (http://www2.acae.cuhk.edu.hk/˜jhuang/OutputRegulation/). In particular, an updated errata list can be found from the website by opening the file errata.pdf.

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DAIZHAN CHENG
Institute of Systems Science,
Chinese Academy of Sciences,
Beijing 100080, People's Republic of China
E-mail: dcheng@iss.ac.cn

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PID CONTROLLERS FOR TIME-DELAY SYSTEMS, Guillermo J. Silva, Aniruddha Datta and S. P. Bhattacharyya, Birkhäuser, Boston, 2005, 330pp., US$ 79.95, ISBN 0-8176-4266-8

1. INTRODUCTION

In the last two decades there has been renewed interest in PID controllers. According to

Bennett [1], in just the last decade of the last century, the number of papers on PID control has exceeded the total number of papers published before 1990. Recent books (e.g. References [2, 3]) present several methods for tuning PID controller parameters, the main objective being the compensated system performance rather than the details of establishing stabilizing conditions before designing the PID compensators. Although the design techniques presented in the literature usually lead to PID controllers that stabilize the closed-loop system, mainly when the plant is already stable, closed-loop stability is not guaranteed in advance.

On the other hand, other control design techniques (e.g. H_∞ robust control [4, 5]), takes a different approach to controller design: first, closed-loop stability is guaranteed in advance by ensuring that the controller belongs to the class of stabilizing controllers, which is done in terms of the Youla–Jabr–Bongiorno–Kučera (YJBK) parameterization, and in the sequel, the degrees of freedom left in the parameterization are used to design optimal controllers, i.e. controllers which minimize certain H_∞ costs. Such an approach is not usual in dealing with PID controllers, since up to now it has not been possible to obtain an analytical characterization of the class of PID controllers. This is apparently the motivation for the writing of the book under review as well as the previous one by two of the same authors [6]. However, instead of presenting an analytic characterization of all stabilizing controllers, this book presents algorithms for the computation of the entire set of PID controllers which achieve closed-loop stability.

2. BOOK OVERVIEW

The book deals with the problem of stabilizing a given plant with time-delay by PID controllers, i.e. the computation of the entire set of (k_p, k_i, k_d) values which make the closed-loop system stable. It is a continuation of previous books by the senior coauthor [6, 7] and, in particular, extends the results of Datta *et al.* [6] to time-delay systems.

The book is mainly concerned with establishing rigorous stability results for PID control of time-delay systems. Its great merit is that it does so with the minimum of fuss and in a fairly self-contained manner, providing complete proofs in appendices, as well as a short cut (Chapter 12, Sections 2–4) where all the results are summarized in algorithms for those who want to use all the results presented in the book without going through all the details. Even though the material covered in the book requires little background in control theory and mathematics, since the mathematical background is provided in the book, it is this reviewer's opinion that the book is more suitable for researchers and graduate students rather than undergraduate students, among other reasons because it presupposes familiarity with the stability theory of polynomials. The book presents a unified view of results originally presented in papers by Bhattacharyya and his collaborators and is a timely addition to the literature on this subject. On the downside, however, I should mention that the more practically inclined reader looking for a collection of PID tuning rules may be disappointed. In fact, PID controller design is only dealt with in two of the 12 chapters (9 and 12). Chapter 9 presents two design strategies: the first one for the design of non-fragile PID controllers, without any other control objective (apart from stability); the second one in which a controller is sought, among the members of the stabilizing set, in order to meet some performance specifications. The methods proposed in Chapter 12 are formulated in terms of H_∞ costs, and, as in Chapter 9, all the points in the stabilizing region are tested: the ones for which the PID controllers satisfy the H_∞ costs are chosen. The methods proposed in Chapters 9 and 12 are both parameter space sweeping (= brute force) methods, i.e. no optimization algorithm is used to reach the optimal value. In all other chapters, the main concern is with the computation of stabilizing regions.

3. BOOK DESCRIPTION AND ANALYSIS

A brief analysis of each Chapter is presented in the sequel.

As in all standard books on PID control, Chapter 1 starts with a brief introduction to PID controllers together with a qualitative justification for the need of integral action as a way to obtain zero steady-state error for step input reference signal. The authors next present a review of some well known PID tuning strategies, namely the Ziegler & Nichols step response and frequency response methods, the internal model controller (IMC) design technique and the Cohen–Coon method. At this stage of the book, it may not be clear to the readers why these particular methods have been chosen to illustrate PID design; this will become clear in Chapter 10, when these tuning strategies (together with the Chien, Hrones and Reswick (CHR) method) will be analysed as far as controller fragility is concerned. The justification is rather simple, i.e. these methodologies are based on modelling the plant as a first-order system with time-delay, which is the bread and butter of this book.

Chapter 2 revisits the Hermite–Biehler theorem and its generalization. Although it has already been presented in Reference [6], this is fundamental background for the results to be presented in the later chapters of the book.

Chapters 3 and 4 have also been presented in Reference [6]. They deal with the computation of k_p and (k_p, k_i) values (Chapter 3) and (k_p, k_i, k_d) values (Chapter 4) which make the closed-loop stable for a plant modelled as a linear time-invariant system with transfer function

$$G(s) = \frac{N(s)}{D(s)}$$

where $N(s)$ and $D(s)$ are polynomials in s. Although the constant gain stabilization problem may appear irrelevant at first glance, since it could be solved directly using the root-locus method, it plays an important role here. This is because the PI and PID stabilization problems are seen to have the same structure as the constant gain stabilization problem, as follows: (i) the PI stabilizing region is computed by sweeping over all real k_p which makes the closed-loop system stable and in the sequel solving, at each stage, a constant gain stabilization problem for k_i; (ii) the PID stabilizing region is computed by first defining the intervals of $k_p \in \mathbb{R}$ for which the closed-loop system is stable and, in the sequel, using the results of Chapter 2, for each stabilizing k_p value, the points (k_i, k_d) are computed as a solution of a linear programming problem.

Chapter 4 also addresses the discrete-time case in two steps: first by using a bilinear transformation and then by using a linear transformation $k_i = k_s - k_p$, to write the stabilization problems in the same form as those for the continuous-time case.

Chapters 5–8 represent the main contribution of the book. Chapter 5 presents a few results on the theory of time-delay systems which are essential for the derivation of the results to be presented in the following chapters. It starts with a brief study on the type of delays that may occur in feedback systems and its associated differential equation. In the sequel, by means of numerical examples, it is shown how the use of Padé approximation for a pure delays can lead to unreliable stability regions. Finally, a collection of results on the theory of quasi-polynomials is presented. The results are stated without proof (the readers are referred to more specialized books on the subject) and also without a motivation for its presentation. Readers might at first think that most of them are unnecessary, but they will prove essential in Chapters 6–8 and 11.

Chapter 6 considers the problem of finding the stabilizing gains for systems modelled as first and second orders with time-delay. Unstable first-order plants with time delay are also considered. Closed-form solutions to the constant gain stabilization problem, or equivalently, stabilization with a proportional controller, for the three cases above are presented as well as a necessary condition for stabilizing an unstable first-order system with time-delay with a proportional controller.

Chapter 7 deals with the problem of finding the stabilizing region for PI controllers. The results are derived only for stable and unstable plants modelled as first-order with time-delay. Closed-form solutions are obtained for both the proportional and the integral gains; the latter depends on the proportional gain that is being considered. The reading of this chapter is not straightforward but, in the end, the results are summarized in an algorithm.

Chapter 8 addresses the problem of computing the stabilizing region for PID controllers for stable and unstable plants that are represented by the same models as those of Chapter 7. Using similar arguments, closed-form solutions are obtained for the proportional gain. It is amazing how an apparently complicated problem can lead to stabilizing regions of (k_i, k_d) with the simple geometric shapes obtained in this chapter, namely, for a model

$$G(s) = \frac{k}{Ts+1}\,\mathrm{e}^{-Ls}, \quad k, T, L > 0 \qquad (1)$$

the stabilizing region of (k_i, k_d) is a trapezoid, for $-1/k < k_p < 1/k$; a triangle, for $k_p = 1/k$, and a quadrilateral for $1/k < k_p < k_u$, where

$$k_u = \frac{1}{k}\left[\frac{1}{L}\alpha_1 \sin(\alpha_1) - \cos(\alpha_1)\right]$$

with α_1 being the solution of the equation $\tan(\alpha) = -T\alpha/(T+L)$ in the interval $(0, \pi)$. A similar result is stated for the unstable case.

Chapter 9 considers initially the problem of computing all stabilizing P, PI and PID controllers for the family of plants with transfer function

$$G(s) = \frac{N(s)}{D(s)} = \frac{a_0 + a_1 s + a_2 s^2 + \cdots + a_m s^m}{b_0 + b_1 s + b_2 s^2 + \cdots + b_n s^n}$$

where $n \geqslant m$, $a_m b_n \neq 0$, and $a_i \in [\underline{a}_i, \bar{a}_i]$ and $b_i \in [\underline{b}_i, \bar{b}_i]$. The solution to this problem turns out to be simple and is obtained from the intersection of the stabilizing regions for the 16 plant transfer functions $G_{ij}(s)$, formed with all Kharitonov polynomials of the numerator and the denominator of $G(s)$, and computed in accordance with Chapters 3 and 4.

Another problem tackled in Chapter 9 is that of computing the stabilizing region for a plant modelled by (1) where $L \in [L_1, L_2]$. The simple result proved is that, if the controllers stabilize a plant where $L = L^{\star}$, then they stabilize all plants where $L \in [0, L^{\star}]$. This means, of course, that the problem reduces to that of finding the stabilizing regions for $L = L_2$.

Finally, in Chapter 9, two design problems are considered for first-order plus time-delay models: (i) the design of non-fragile PID controllers, leading to an algorithm for finding the centre of the largest ball that can be inscribed inside the stabilizing region, and (ii) a brute force method for finding PID controllers that satisfy performance specifications.

Chapter 10 appears to be weakest one in the book. In this chapter a study of the fragility of PID controllers tuned according to the Ziegler–Nichols step response method, the CHR method, the Cohen–Coon method, and the IMC design technique is carried out. These tuning methods have apparently been chosen because they are based on a first-order plus time-delay model for the plant. The problem with this chapter is that the fragility analysis is carried out based on the plant model, which may differ a great deal from the real system. The results of this chapter must be interpreted with caution.

Chapter 11 presents the generalization of the problem of computing PID stabilizing regions for time-invariant systems of any order with time-delay. Since the results of Chapter 5 do not generalize directly to this case, an alternative approach is followed, namely Tsypkin's generalization of the Nyquist stability criterion for systems with time-delay. The solution to this problem is obtained in two steps: (i) the computation of the stabilizing region for the delay-free plant $G_0(s)$, obtained according to Chapter 4, and (ii) the sets that must be excluded from the stabilizing region computed in (i) and correspond to those that make $C(s, \boldsymbol{k})G_0(s)$ improper, and the set of parameters for which there exist $L \in [0, L_0]$ and $\omega \in \mathbb{R}$ such that $C(\mathrm{j}\omega, \boldsymbol{k})G_0(\mathrm{j}\omega)\,\mathrm{e}^{\mathrm{j}\omega} = -1$.

There is a problem that has not been properly explained in Chapter 11. Example 11.4 re-examines the problem of stabilizing a plant modelled according to (1), where $L \in [0, L_0]$, using the technique presented in this chapter. However the stabilizing regions obtained in this example (Figure 11.12) do not match with those obtained in Chapter 8 (Figure 8.6). In spite of all the detailed calculation presented in Appendix C to justify the stabilizing regions of Figure 11.12, this reviewer felt the need for more explanation than that given in Remark 11.2 and suspects that the same may be true for the average reader of the book.

Chapter 12 is divided in two parts. The first part presents algorithms for finding the stabilizing regions for PID controllers for plants modelled as continuous and discrete-time rational transfer function of arbitrary order and continuous-time first-order transfer functions with time-delay. This part of the book should be read by those who want to use the results of Chapters 3, 4 and 8 without having to go into all the mathematical details necessary to obtain these results. The second part of Chapter 12 deals with PID controller design. Two controller problems are posed: the first one is the synthesis of H_∞ PID controllers for robust performance and the second one aims at finding PID controllers with guaranteed gain and phase margins. An important mathematical tool for the solution of the design problems formulated in this chapter is so-called complex PID stabilization algorithm, which consists in finding all stabilizing (k_p, k_i, k_d) values for which

$$c(s, k_p, k_i, k_d) = L(s) + (k_d s^2 + k_p s + k_i)M(s)$$

is Hurwitz, where $L(s)$ and $M(s)$ are two given complex polynomials (polynomials with complex coefficients). Writing $L(s)$ and $M(s)$ in terms of their real and imaginary decompositions, then the stabilization problem reduces to that of Chapters 3 and 4 with minor changes.

There are also three appendices (A–C) with all the proofs of Lemmas 8.3, 8.4, 8.5, 8.7 and 8.9 and with detailed analysis of Example 11.4.

4. CONCLUDING REMARK

In the preface, the authors write that they 'hope that (their) monograph acts as a catalyst to bridge the theory–practice gap in the control field as well as the classical–modern gap'. In this reviewer's opinion, despite the (minor) criticisms made above, the book succeeds admirably in its goal as a catalyst and is essential reading for researchers and practitioners in the area of PID controller design.

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JOÃO CARLOS BASILIO
UFRJ/COPPE,
Department of Electrical Engineering,
21949-900, Rio de Janeiro,
RJ, Brazil
E-mail: basilio@dee.ufrj.br

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