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Practical PID Control
Antonio Visioli

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Tao Liu • Furong Gao

Industrial Process Identification and Control Design

Step-test and Relay-experiment-based Methods

Springer

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To my mother—Zuqin Zhu, and my wife—Ying Zhou

献给我的母亲—朱祖琴，和我的妻子—周颖

Tao Liu (刘涛)

Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies . . . , new challenges. Much of this development work resides in industrial reports, feasibility study papers and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

A common engineering approach to complex problems is to look for a set of simple characterising features and then construct an engineering paradigm based on a parsimonious analysis that succinctly and efficiently captures the identified characteristics. In control engineering, a good example is the use of first-order-plus-dead-time (FOPDT) and second-order-plus-dead-time (SOPDT) models to represent the key features of a range of process responses. The elements of this model class have just a few parameters (time constants, second-order model parameters, delay time, zero positions) that are able to depict a wide set of process dynamics.

This particular control engineering approach links model identification to the use of process step responses or to relay experiment data. The simplicity of these two test procedures and their interrelation to the tuning rules for proportional-integral-derivative (PID) controllers has led to an extensive literature that is still developing today, despite the fact that the tuning rules of Ziegler and Nichols were devised over 60 years ago. A modern version of this idea is to widen the class of controllers chosen, to accept that the model representation is not accurate and use robust methods to ensure the fidelity of the control design. This is one of the paths followed in the monograph being introduced here.

A good demonstration of the ingenuity that can be brought to these basic ideas is found in this *Advances in Industrial Control* monograph entitled *Industrial Process*

Identification and Control Design: Using a Step/Relay Test by Tao Liu and Furong Gao. The two questions posed by the authors are:

1. How can we identify models from the FOPDT and SOPDT model class using step response and relay experiment data for stable, integrating and unstable processes?
2. How can we exploit the parsimonious FOPDT/SOPDT model structure in control system designs for: SISO processes, two degree of freedom controllers, cascade control systems, multiloop control, decoupling control and batch process control?

The monograph is divided into two parts that pursue these two questions. Part I (Chaps. 1–6) deals with the identification issues and Part II (Chaps. 7–12) explores the six control design topics of the question above; one topic per chapter. Closing the monograph is a summary chapter (Chap. 13) that looks again at the outcomes of the authors' extensive and comprehensive research and goes on to discuss and list some remaining unresolved issues.

The step test and relay experiment results follow an analytical route that brings rewards in the enhanced clarification of the possible outcomes for the two identification methods when used with different types of processes. The comprehensive set of results presented by the authors look ideal for further use in a possible industrial process identification toolbox.

The sequence of chapters in Part II uses the internal model control (IMC) framework to investigate the six control system design problems. IMC is modified for the various control structures and objectives. In the batch process control chapter, the iterative learning control (ILC) method is used. Inherent within these study topics is the use of the FOPDT/SOPDT class of process models, robust methods to overcome model inaccuracy and PID controllers for implementation where feasible. Each chapter is comprehensive in its coverage of such issues as setpoint tracking, disturbance rejection, robustness and noise rejection, and presents comparative examples to demonstrate performance.

This monograph follows previous *Advances in Industrial Control* monographs for this and the related process identification field, notably the volumes *Identification of Continuous-Time Models from Sampled Data* edited by H. Garnier and L. Wang (ISBN 978-1-84800-160-2, 2008), *Practical Grey-box Process Identification: Theory and Applications* by T. Bohlin (ISBN 978-1-84628-402-1, 2006) and *Autotuning of PID Controllers: Relay Feedback Approach* by C.C. Yu (ISBN 978-3-540-76250-8, 1999 (second edition ISBN 978-1-84628-036-8, 2006)) There have also been *Advances in Industrial Control* volumes on PID and related control aspects including, *Practical PID Control* by A. Visioli (ISBN 978-1-84628-585-1, 2006), *Structure and Synthesis of PID Controllers* by A. Datta, M.-T. Ho and S.P. Bhattacharyya (ISBN 978-1-85233-614-1, 1999) and *Advances in PID Control* by K.K. Tan, Q.-G. Wang and C.C. Hang with T.J. Hägglund (ISBN 978-1-85233-138-2, 1999).

Readers from the engineering disciplines of the process industries and academics and postgraduate students from the control field will find this monograph of new results and ideas by Tao Liu and Furong Gao an invaluable companion to these previous volumes.

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Preface

In the process industries, model-based control strategies are well known to result in superior system performance in set-point tracking and load disturbance rejection. Accordingly, control-oriented model identification methods have been increasingly explored in recent years. Among various excitation signals used for system identification, the step response test is most widely practised owing to its implementation simplicity and economy. To prevent the process output from drifting too far away from the set-point, closed-loop identification methods from relay feedback tests have been developed on an ad hoc basis in the past two decades. For pioneering works, see Atherton (1982), Tsypkin (1984), Åström and Hägglund (1984) and Luyben (1987). Recent monographs concerned with relay feedback identification can be seen in Wang et al. (2003), Yu (2006) and Sung et al. (2009).

Motivated by the above observation, a series of model identification methods have recently been developed by the authors based on the use of a step response test or relay feedback test. This monograph summarises these results into a systematic identification methodology based on a typical classification of open-loop response characteristics for various industrial processes: stable, integrating and unstable. The low-order model structures of first-order-plus-time-delay (FOPDT) and second-order-plus-time-delay (SOPDT) are mainly studied here, owing to the fact that such models are most widely used for control system design and controller tuning in industrial engineering practice. A few higher-order model identification algorithms are also given to facilitate advanced control design for industrial processes with special requirements. Moreover, identification methods for estimating the process frequency response from a step or relay test are provided, including robust estimation algorithms against measurement noise, in particular for the low-frequency range which is of primary concern for control design and tuning in engineering practice.

In a coherent manner, a series of model-based control methods also developed by the authors are subsequently integrated into this monograph for practical applications – single-input-single-output (SISO) processes, cascade control processes, multiple-input-multiple-output (MIMO) processes and batch processes. These control methods are developed based on the internal model control (IMC) theory (Morari and Zafiriou 1989), robust control theory (Zhou et al. 1996; Skogestad and Postlethwaite 2005) and iterative learning control (ILC) theory (Moore 1993). A common feature of these control methods is that all controllers in these control schemes are analytically derived in the form of design formulae. Each of these formulae, intuitively or essentially, has only a single adjustable parameter that can be monotonically tuned to meet the best trade-off between the control performance and robustness (robust stability), thereby facilitating the control implementation in practical applications.

For ease of reading, the technical development of the proposed identification and control methods are presented in a self-contained manner. Readers are only assumed to have a basic knowledge of linear algebra and complex analysis. Illustrative examples and experimental applications are given for all the proposed methods in an easy-to-follow manner. It is believed that the monograph should be of interest to control engineers and researchers in the process industries, and could also be used for undergraduate and graduate students in control engineering, process system engineering, chemical engineering, mechanical engineering, electrical engineering, biomedical engineering and industrial automation engineering.

The book is divided into two parts – Part I: Process Identification (Chaps. 1–6) and Part II: Control System Design (Chaps. 7–12). Part I provides a basis for applying the control methods presented in Part II. In fact, both parts are self-contained and can be read independently by readers with different demands. A quick preview of the contents is given below:

Chapter 1, the first chapter in Part I, provides an introduction to the scope and objective of process identification, the excitation signals commonly used for open-loop and closed-loop identification tests and the model fitting criteria.

Chapter 2 presents step response identification methods for open-loop stable processes using an open-loop or closed-loop step test. A frequency response estimation method is given. The model structures chosen for identification are FOPDT, SOPDT and a higher-order model with time delay. A robust identification method is proposed for practical applications subject to unsteady initial process conditions and unexpected load disturbance. Moreover, a piecewise model identification method is given for simultaneously identifying the process model and the deterministic (inherent) load disturbance model from a step test.

Chapter 3 presents step response identification methods for integrating and unstable processes using an open-loop or closed-loop step test. Identification algorithms for obtaining the most widely used FOPDT and SOPDT models are detailed, followed by a practical application to the start-up heating control of barrel temperature for an industrial injection moulding machine.

Chapter 4 presents closed-loop identification methods for stable processes using a relay feedback test. The implementation of a relay test of biased or unbiased type is briefly introduced, followed by the guidelines for model structure selection together with a list of different relay response shapes for reference. Analytical relay response expressions are subsequently derived for the most widely used FOPDT and SOPDT models, along with the corresponding model identification algorithms. Furthermore, based on developing a frequency response estimation algorithm, a generalised relay identification method for obtaining a model of any order with time delay is presented, which can be used to identify the process static gain independent of the choice of biased or unbiased relay.

Chapter 5 presents relay feedback identification methods for integrating processes. By deriving analytical relay response expressions for the widely used FOPDT and SOPDT models, the existence of the limit cycle in the use of a relay test is clarified. Based on the developed relay response expressions, the corresponding model identification algorithms are subsequently presented, followed by a practical application to the barrel temperature maintenance for an industrial injection moulding machine.

Chapter 6 presents relay feedback identification methods for unstable processes. A limiting condition to forming steady oscillation under a relay test is revealed by deriving the analytical relay response expressions for a FOPDT model. Identification algorithms for obtaining the widely used FOPDT and SOPDT models are detailed.

Chapter 7, the first chapter in Part II, provides an introduction of control engineering specifications in both the time and frequency domains, along with the closed-loop robust stability criteria used here. Based on a brief review of the IMC design, an enhanced IMC design for improving load disturbance rejection is proposed. The corresponding proportional-integral-derivative (PID) tuning formulae for the use of the unity feedback control structure are given to facilitate practical application.

Chapter 8 presents advanced two-degrees-of-freedom (2DOF) control methods for the separate optimisation of set-point tracking and load disturbance rejection for stable, integrating and unstable processes.

Chapter 9 presents two 2DOF control schemes for open-loop stable cascade processes, and a 3DOF control scheme for open-loop unstable cascade processes.

Chapter 10 provides an introduction of the selection criteria for the input-output pairing of multivariable control, along with the multi-loop structure controllability. An IMC-based multi-loop PID tuning method for the economic operation of such control systems is proposed.

Chapter 11 presents advanced decoupling control methods for multiple-input-multiple-output (MIMO) processes. An IMC-based control scheme is proposed for two-input-two-output (TITO) processes with time delays. An analytical decoupling control design for MIMO processes with time delays is presented in the framework of the unity feedback control structure. Moreover, a 2DOF control scheme for MIMO processes is proposed to improve decoupling regulation performance in both set-point tracking and load disturbance rejection for individual channels.

Chapter 12 provides an introduction to batch process control and the implementation requirements. An IMC-based ILC scheme for realising the perfect tracking of a desired output trajectory in the presence of process time delay and time-varying uncertainties is proposed.

Finally, Chap. 13 summarises the main contributions of this monograph, along with some suggestions and open issues for future research exploration.

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Tao Liu
Furong Gao

Abbreviations and Symbols

Abbreviations

ARMAX	auto-regressive moving-average with eXogenous inputs
ARX	auto-regressive with eXogenous inputs
CSTR	continuous stirred tank reactor
DOF	degrees-of-freedom
DP	disturbance response peak
FIR	finite impulse response
FOPDT	first-order-plus-dead-time
GM	gain margin
IAE	integral-of-absolute-error
ILC	iterative learning control
IMC	internal model control
ISE	integral-of-squared-error
ITAE	integral-of-time-weighted-absolute-error
ITSE	integral-of-time-weighted-squared-error
IV	instrumental variables
LFT	linear fractional transformation
LHP	left-half-plane
LMI	linear matrix inequality
LS	least-squares
LTI	linear time invariant
MIMO	multiple-input-multiple-output
MP	minimum phase
MPC	model-based predictive control
MSE	mean square error
NMP	non-minimum phase
NSR	noise-to-signal ratio
P	proportional
PI	proportional-integral

PID	proportional-integral-derivative
PM	phase margin
PRBS	pseudo-random binary signal
RGA	relative gain array
RLS	recursive least-squares
SISO	single-input-single-output
SNR	signal-to-noise ratio
SOPDT	second-order-plus-dead-time
SP	Smith predictor
SVD	singular value decomposition
TITO	two-input-two-output
w.p.	with probability
w.r.t.	with respect to

General Symbols

$\Re$	field of real numbers
$\Re_+$	field of nonnegative real numbers
$\Re^n$	real vectors with a dimension of n
$\Re^{m\times n}$	$m \times n$ real matrices
$\mathbb{C}$	field of complex numbers
$\mathbb{C}_-\left(\bar{\mathbb{C}}_-\right)$	open (closed) left-half complex plane
$\mathbb{C}_+\left(\bar{\mathbb{C}}_+\right)$	open (closed) right-half complex plane
$\mathbb{C}^{m\times n}$	$m \times n$ complex matrices
∞	infinity
j	$\sqrt{-1}$
$\mathrm{j}\Re$	the set of imaginary numbers
$L_2(-\infty,\infty)$	time domain Lebesgue space (Hilbert space)
$L_\infty(\mathrm{j}\Re)$	the set of functions bounded on $\mathrm{Re}(s) = 0$ including at ∞ (Banach space)
$H_2(\mathrm{j}\Re)$	subspace of $L_2(\mathrm{j}\Re)$ with functions analytic in $\mathrm{Re}(s) > 0$
$H_2^\perp(\mathrm{j}\Re)$	subspace of $L_2(\mathrm{j}\Re)$ with functions analytic in $\mathrm{Re}(s) < 0$
$H_\infty(\mathrm{j}\Re)$	the set of $L_\infty(\mathrm{j}\Re)$ functions analytic in $\mathrm{Re}(s) > 0$
prefix R	real rational, e.g., RH_∞ and RH_2
$y(t)$	output response in time domain
$y_{\mathrm{sp}}(t)$	desired output trajectory in time domain (or the set-point profile)
$\widehat{y}(t)$	model output response in time domain
$\Delta y(t)$	output deviation to the input change
$\hat{y}(t)$	measured output response in time domain
$\zeta(t)$	measurement noise in time domain
$u(t)$	process input (control output) in time domain
$e(t)$	output error in time domain

$d_{\mathrm{i}}(t)$	load disturbance entering into the process from its input side
$d_{\mathrm{o}}(t)$	load disturbance entering into the process from its output side
$Y(s)$	Laplace transform of output response in frequency domain
$\Delta Y(s)$	Laplace transform of $\Delta y(t)$
$\widehat{Y}(s)$	Laplace transform of $\widehat{y}(t)$
$\hat{Y}(s)$	Laplace transform of $\hat{y}(t)$
$\xi(s)$	Laplace transform of $\zeta(t)$
$U(s)$	Laplace transform of process input in frequency domain
$E(s)$	Laplace transform of output error in frequency domain
$G(s)$	process transfer function
$\widehat{G}(s)$	model transfer function
$M_{\mathrm{T}}(s)$	maximal peak of the complementary sensitivity function
$M_{\mathrm{S}}(s)$	maximal peak of the sensitivity function
$s = \alpha + j\omega$	Laplace operator, α is the real part and ω is the imaginary part (frequency)
Δ_{A}	additive uncertainty
Δ_{M}	multiplicative uncertainty
λ	time scaling factor or a tuning parameter in IMC
e_s	steady-state offset
T_s	sampling period
t_{r}	the rise time of a step response
t_{set}	the settling time of a step response
t_N	the time corresponding to the N-th sampled data
k_{p}	process static (or proportional) gain
τ_{p}	process time constant
θ	process time delay
$\omega_{\mathrm{b}}(\mathrm{or}\ \omega_{\mathrm{BT}})$	closed-loop system bandwidth
ω_{c}	cutoff angular frequency
ω_{gc}	gain crossover frequency
ω_{rc}	referential cutoff angular frequency
ω_{π}	phase crossover frequency
σ_{ζ}^2	measurement noise variance
I_n	identity matrix of dimension $m \times n$
$\mathbf{0}_{m\times n}$	zero matrix of dimension $m \times n$
$A = \left[a_{ij}\right]_{m\times n}$	a $m \times n$ matrix with a_{ij} as the i–th row and j–th column element
$adj(A) = \left[A^{ij}\right]_{m\times n}^{T}$	adjoint matrix of a $m \times n$ matrix (A) with A^{ij} as the complement minor of a_{ij}
$diag\{a_i\}_{n\times n}$	a $n \times n$ diagonal matrix with a_i as the i–th diagonal element
$A > 0$	the matrix A is positive definite
$A \geq 0$	the matrix A is positive semi-definite
(A, B, C, D)	state-space realization of a transfer function
$\square$	end of proof
$\diamond$	end of remark

Operators and Functions

$:=$	defined as
$\approx$	approximately equal to
$\gg$	far greater than
$\ll$	far smaller than
$\angle$	angle
$\exists$	exist
$\forall$	to any (all)
$\in$	belong to
$\subset$	subset
$\rightarrow$	tend to
sup	supremum
inf	infimum
min	minimize
max	maximize
$\lvert a \rvert$	absolute value (magnitude) of $a \in \mathbb{C}$ or Euclidean norm ($\Vert a \Vert_2$) of $a \in \Re^n$
$\dot{y}(t)$	the first derivative of $y(t)$ in time domain
$\ddot{y}(t)$	the second derivative of $y(t)$ in time domain
$L[g(t)]$	Laplace transform of $g(t)$ in time domain
$\mathrm{Re}(G)$	real part of $G \in \mathbb{C}$
$\mathrm{Im}(G)$	imaginary part of $G \in \mathbb{C}$
$\deg(G)$	relative order of a rational transfer function $G \in RH_\infty$ (a order of the numerator over the denominator of G w.r.t. the Laplace operator, s)
$\langle , \rangle$	inner product
$\otimes$	Knonecker product
$\oplus$	direct product (Hadamard product)
$g * f$	convolution of $g(t)$ and $f(t)$ in time domain
$g \perp f$	orthogonality, i.e., $\langle g, f \rangle = 0$
A^T	matrix transpose
A^*	complex conjugate transpose of the matrix A
A^{-1}	inverse of the matrix A
A^+	pseudo inverse of the matrix A
$\det(A)$	determinant of the matrix A
$\mathrm{trace}(A)$	trace of the matrix A
$\lambda(A)$	eigenvalue of the matrix A
$\sigma(A)$	the set of spectrum (singular value) of the matrix A
$\bar{\sigma}(A)$	largest singular value of the matrix A
$\underline{\sigma}(A)$	smallest singular value of the matrix A
$\sigma_i(A)$	i–th singular value of the matrix A
$\Vert A \Vert$	spectral norm of matrix A: $\Vert A \Vert = \bar{\sigma}(A)$
$\Vert A \Vert_2$	2-norm of matrix $A \in L_2$
$\Vert A \Vert_\infty$	infinity-norm of $A \in L_\infty$
$F^{(n)}(s)$	the n-th order derivative of $F(s) \in H_\infty$ w.r.t. s