

CONTENTS

PREFACE	xiii
ACKNOWLEDGMENTS	xv
OPERATORS AND NOTATIONAL CONVENTIONS	xvii
1. INTRODUCTION	1
1.1 Dynamical Systems	1
1.2 Models	3
1.3 The System Identification Procedure	7
1.4 Organization of the Book	8
1.5 Bibliography	10
 part i: systems and models	
2. TIME-INVARIANT LINEAR SYSTEMS	13
2.1 Impulse Responses, Disturbances and Transfer Functions	13
2.2 Frequency-domain Expressions	22
	vii

2.3	Signal Spectra	26
2.4	Single Realization Behavior and Ergodicity	34
	Results (*)	
2.5	Multivariable Systems (*)	35
2.6	Summary	36
2.7	Bibliography	37
2.8	Problems	38
	Appendix 2.A: Proof of Theorem 2.2	43
	Appendix 2.B: Proof of Theorem 2.3	45
	Appendix 2.C: Covariance Formulas	49
3.	SIMULATION, PREDICTION, AND CONTROL	51
3.1	Simulation	51
3.2	Prediction	52
3.3	Observers	59
3.4	Control (*)	62
3.5	Summary	65
3.6	Bibliography	65
3.7	Problems	66
4.	MODELS OF LINEAR TIME-INVARIANT SYSTEMS	69
4.1	Linear Models and Sets of Linear Models	69
4.2	A Family of Transfer-function Models	71
4.3	State-space Models	81
4.4	Distributed-Parameter Models (*)	90
4.5	Model Sets, Model Structures, and Identifiability: Some Formal Aspects (*)	93
4.6	Identifiability of Some Model Structures	101
4.7	Summary	106
4.8	Bibliography	106
4.9	Problems	108
	Appendix 4.A: Identifiability of Black-box Multivariable Model Structures	115
5.	MODELS FOR TIME-VARYING AND NONLINEAR SYSTEMS	127
5.1	Linear Time-varying Models	127
5.2	Nonlinear Models as Linear Regressions	130
5.3	Nonlinear State-space Models	132
5.4	Formal Characterization of Models (*)	134
5.5	Summary	137
5.6	Bibliography	138
5.7	Problems	138

part ii: methods

6. NONPARAMETRIC TIME- AND FREQUENCY-DOMAIN METHODS	141
6.1 Transient Response Analysis and Correlation Analysis	141
6.2 Frequency-response Analysis	143
6.3 Fourier Analysis	146
6.4 Spectral Analysis	151
6.5 Estimating the Disturbance Spectrum (*)	160
6.6 Summary	162
6.7 Bibliography	162
6.8 Problems	163
Appendix 6.A: Derivation of the Asymptotic Properties of the Spectral Analysis Estimate	167
 7. PARAMETER ESTIMATION METHODS	 169
7.1 Guiding Principles behind Parameter Estimation Methods	169
7.2 Minimizing Prediction Errors	171
7.3 Linear Regressions and the Least-squares Method	176
7.4 A Statistical Framework for Parameter Estimation and the Maximum Likelihood Method	181
7.5 Correlating Prediction Errors with Past Data	190
7.6 Instrumental-variable Methods	192
7.7 Summary	195
7.8 Bibliography	196
7.9 Problems	197
Appendix 7.A: Proof of the Cramér–Rao Inequality	206
 8. CONVERGENCE AND CONSISTENCY	 208
8.1 Introduction	208
8.2 Conditions on the Data Set	210
8.3 Prediction-error Approach	214
8.4 Consistency and Identifiability	218
8.5 Linear Time-invariant Models: A Frequency-domain Description of the Limit Model	224
8.6 The Correlation Approach	229
8.7 Summary	233
8.8 Bibliography	233
8.9 Problems	234

9.	ASYMPTOTIC DISTRIBUTION OF PARAMETER ESTIMATES	239
9.1	Introduction	239
9.2	The Prediction-error Approach: Basic Theorem	240
9.3	Expressions for the Asymptotic Variance	242
9.4	Frequency-domain Expressions for the Asymptotic Variance	248
9.5	The Correlation Approach	254
9.6	Use and Relevance of Asymptotic Variance Expressions	258
9.7	Summary	262
9.8	Bibliography	263
9.9	Problems	264
	Appendix 9.A: Proof of Theorem 9.1	266
	Appendix 9.B: The Asymptotic Parameter Variance	270
10.	COMPUTING THE ESTIMATE	274
10.1	Linear Regressions and Least Squares	274
10.2	Numerical Solution by Iterative Search Methods	282
10.3	Computing Gradients	285
10.4	Two-stage and Multistage Methods	288
10.5	Local Solutions and Initial Values	292
10.6	Summary	294
10.7	Bibliography	294
10.8	Problems	296
11.	RECURSIVE ESTIMATION METHODS	303
11.1	Introduction	303
11.2	The Recursive Least-squares Algorithm	305
11.3	The Recursive IV Method	311
11.4	Recursive Prediction-Error Methods	311
11.5	Recursive Pseudolinear Regressions	316
11.6	The Choice of Updating Step	318
11.7	Implementation	322
11.8	Summary	326
11.9	Bibliography	327
11.10	Problems	328
	Appendix 11.A: Techniques for Asymptotic Analysis of Recursive Algorithms	329

part iii: user's choices

12.	OPTIONS AND OBJECTIVES	339
12.1	Options	339
12.2	Objectives	341
12.3	Bias and Variance	345
12.4	Summary	347
12.5	Bibliography	347
12.6	Problems	347
13.	AFFECTING THE BIAS DISTRIBUTION OF TRANSFER-FUNCTION ESTIMATES	349
13.1	Some Basic Expressions	349
13.2	Heuristic Discussion of Transfer-function Fit in Open-loop Operation	350
13.3	Some Solutions to Formal Design Problems	354
13.4	Summary	356
13.5	Bibliography	356
13.6	Problems	357
14.	EXPERIMENT DESIGN	358
14.1	Some General Considerations	359
14.2	Informative Experiments	361
14.3	Optimal Input Design (*)	369
14.4	Optimal Experiment Design for High-order Black-box Models (*)	375
14.5	Choice of Sampling Interval and Presampling Filters	378
14.6	Pretreatment of Data	386
14.7	Summary	389
14.8	Bibliography	390
14.9	Problems	391
15.	CHOICE OF IDENTIFICATION CRITERION	394
15.1	General Aspects	394
15.2	Choice of Norm: Robustness	396
15.3	Variance: Optimal Instruments	402
15.4	Summary	405
15.5	Bibliography	406
15.6	Problems	406

16. MODEL STRUCTURE SELECTION AND MODEL VALIDATION	408
16.1 General Aspects of the Choice of Model Structure	408
16.2 A Priori Considerations	411
16.3 Model Structure Selection Based on Preliminary Data Analysis	413
16.4 Comparing Model Structures	416
16.5 Model Validation	424
16.6 Summary	430
16.7 Bibliography	431
16.8 Problems	431
 17. SYSTEM IDENTIFICATION IN PRACTICE	 434
17.1 The Tool: Interactive Software	434
17.2 A Laboratory-scale Application	440
17.3 Identification of Ship-steering Dynamics	449
17.4 What Does System Identification Have to Offer?	454
17.5 Bibliography	456
 APPENDIX I: Some Concepts from Probability Theory	 457
 APPENDIX II: Some Statistical Techniques for Linear Regressions	 461
 REFERENCES	 482
 AUTHOR INDEX	 505
 SUBJECT INDEX	 511