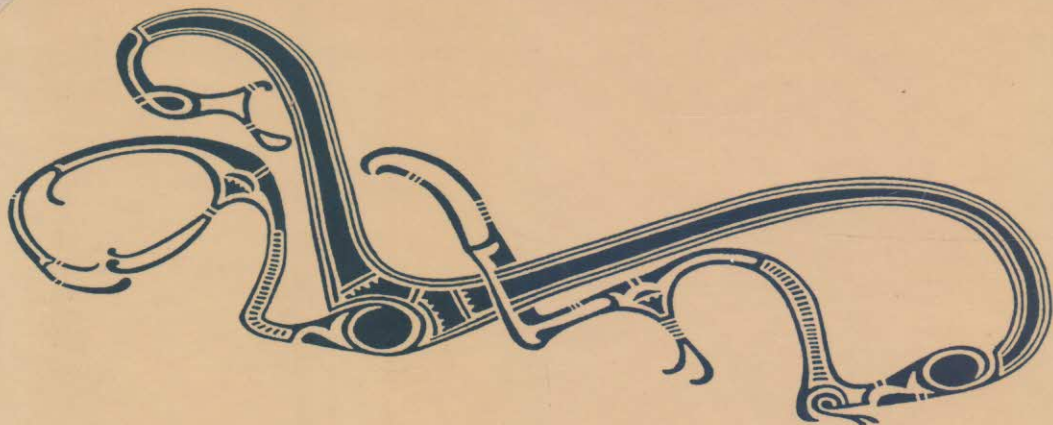


SYSTEM MODELING & IDENTIFICATION



ROLF JOHANSSON

PRENTICE HALL INFORMATION AND SYSTEM SCIENCES SERIES
Thomas Kailath, Series Editor

Contents

Preface	xi
1. Introduction	1
1.1 Why models?	1
1.2 Modeling	3
1.3 The purpose of identification	6
1.4 System and model complexity	7
1.5 The procedure of identification	10
1.6 Historical remarks and bibliography	13
2. Black box models	16
2.1 Introduction	16
2.2 Transient response analysis	17

2.3	Frequency response analysis	21
2.4	Application of frequency response analysis	29
2.5	Summary	30
2.6	Exercises	31
3.	Signals and systems	34
3.1	Introduction	34
3.2	Time-domain and frequency-domain transforms	35
3.3	Discretized data	36
3.4	The z-transform	38
3.5	Finite measurement time	39
3.6	The transfer function	43
3.7	Signal power and energy	45
3.8	Spectra and covariance functions	46
3.9	Correlation and coherence	47
3.10	Statistical characterization of disturbances	49
3.11	Exercises	51
4.	Spectrum analysis	53
4.1	The discrete Fourier transform	54
4.2	Power spectrum estimation	56
4.3	Spectral leakage and windowing	58
4.4	Transfer function estimation	66
4.5	Smoothing of spectra	69
4.6	Covariance estimates and 'correlation analysis'	71
4.7	Historical remarks	72
4.8	Bibliography	72
4.9	Exercises	73
5.	Linear regression	74
5.1	Introduction	74
5.2	Least-squares estimation	78
5.3	Optimal linear unbiased estimators	88
5.4	Linear regression in the frequency domain	90
5.5	Least-squares estimation with linear constraints	93
5.6	*A geometrical interpretation	95
5.7	*Multivariable system identification	97
5.8	Concluding remarks	100
5.9	Historical remarks and references	101
5.10	Exercises	102
6.	Identification of time-series models	104
6.1	Introduction	104

6.2	Model structures	105
6.3	Maximum-likelihood identification	113
6.4	Kalman filter	120
6.5	Instrumental variable method	121
6.6	Some aspects of application	125
6.7	Some remarks on convergence and consistency	129
6.8	Concluding remarks	131
6.9	Bibliography and references	131
6.10	Exercises	133
7.	Modeling	136
7.1	Introduction	136
7.2	Mechanical systems	137
7.3	Thermodynamic modeling	141
7.4	Compartment models	143
7.5	Principles of modeling	146
7.6	Physical parametrizations	149
7.7	Network models	152
7.8	Historical and bibliographical remarks	160
7.9	Exercises	162
8.	The experimental procedure	167
8.1	Introduction	167
8.2	The experimental condition	168
8.3	Identification and closed-loop control	168
8.4	Direct or indirect identification?	172
8.5	Choice of input	173
8.6	Parameter uncertainty and control	180
8.7	Planning and operation of experiments	183
8.8	Bibliography and references	186
8.9	Exercises	187
9.	Model validation	192
9.1	Introduction	192
9.2	Method prerequisites	194
9.3	Model order determination	200
9.4	Residual tests	207
9.5	Model and parameter accuracy	217
9.6	Classification with the Fisher linear discriminant	221
9.7	*The concept 'identifiability'	224
9.8	Concluding remarks	226
9.9	Bibliography and references	226

9.10 Exercises	227
10. Model approximation	228
10.1 Introduction	228
10.2 Balanced realization and model reduction	231
10.3 Continued fraction approximation	239
10.4 Moment matching	243
10.5 The Padé approximation	245
10.6 Describing function analysis	246
10.7 Balanced model reduction in identification	252
10.8 Bibliography and references	256
10.9 Exercises	258
11. Real-time identification	260
11.1 Introduction	260
11.2 Recursive least-squares identification	263
11.3 Recursive instrumental variable methods	269
11.4 Pseudolinear regression	270
11.5 Stochastic gradient methods	272
11.6 The Levinson-Durbin algorithm	274
11.7 Spectral properties	278
11.8 Bibliography and references	278
11.9 Exercises	279
12. Continuous-time models	280
12.1 Introduction	280
12.2 Outline of the method	281
12.3 Model transformation	283
12.4 A noise model	291
12.5 Identification	293
12.6 Convergence and consistency	296
12.7 *State-space transformations	299
12.8 Signal processing filters	303
12.9 Concluding remarks	306
12.10 Bibliography and references	308
Appendix 12.1 — The Cramér-Rao lower bound	309
Appendix 12.2 — The Hessian Matrix	310
Appendix 12.3 — Proof of Theorem 12.1	311
12.11 Exercises	314
13. Multidimensional identification	316
13.1 Introduction	316
13.2 Two-dimensional transforms	318

13.3	Two-dimensional system analysis	319
13.4	Stability	320
13.5	Delay-differential systems	326
13.6	Two-dimensional spectra	330
13.7	Bibliography and references	335
14.	Nonlinear system identification	336
14.1	Introduction	336
14.2	Wiener models	338
14.3	Volterra-Wiener models	340
14.4	Power series expansions	346
14.5	Discussion and conclusions	358
14.6	References	358
14.7	Exercises	360
15.	Adaptive systems	361
15.1	Introduction	361
15.2	Heuristic control methods	364
15.3	Aspects on neural networks	368
15.4	Extremum control	371
15.5	Model-reference adaptive control	374
15.6	Multivariable direct adaptive control	388
15.7	Discussion and conclusions	394
15.8	Bibliography and references	396
	Appendix 15.1	398
A.	Appendix: Basic matrix algebra	402
A.1	Preliminaries	402
A.2	Matrix norms	409
A.3	Singular value decomposition	409
A.4	QR-factorization	411
A.5	Matrix differentiation	413
A.6	Polynomials and polynomial matrices	415
A.7	Bibliography and references	417
B.	Appendix: Statistical inference	418
B.1	Preliminaries	418
B.2	Convergence and consistency	420
B.3	Some important probability distributions	424
B.4	Conditional expectation	428
B.5	Statistical hypothesis testing	429
B.6	The Cochran theorem	432
B.7	References	434

C. Appendix: Numerical optimization	435
C.1 Introduction	435
C.2 Descent methods	436
C.3 Newton methods	437
C.4 Quasi-Newton methods	437
C.5 Conjugate gradient methods	438
C.6 Direct search methods	440
C.7 Parametric optimization	440
C.8 Bibliography and references	445
D. Appendix: Statistical properties of time series	447
D.1 Introduction	447
D.2 Stochastic processes	450
D.3 Difference equations	453
D.4 Autoregressive moving average models	460
D.5 Sample covariance functions and spectra	462
D.6 Nonstationary stochastic models	464
D.7 Prediction and reconstruction	466
D.8 The Kalman filter	468
D.9 Bibliography and references	470
E. Appendix: A case study	472
E.1 Introduction	472
E.2 Summary	473
E.3 Methods and materials	474
E.4 Modeling of posture control	474
E.5 Forces on the platform	478
E.6 A dynamic response classification	479
E.7 Experiments	479
E.8 Results of the experiments	481
E.9 Discussion	483
E.10 Conclusions	487
Appendix E.1 — Transfer function	488
Appendix E.2 — Force balances	489
Appendix E.3 — Calculations and analysis	491
Bibliography and references	497
Index	501