

CONTENTS

VOLUME 1

NONLINEAR SYSTEM PARAMETER ESTIMATION

Preface	xv
Glossary	xvii
1. Nonlinear Dynamic Process Models	1
1.1 INTRODUCTION.....	1
1.2 NONPARAMETRIC POLYNOMIAL DYNAMIC MODELS.....	4
1.2.1 The Volterra series model.....	4
1.2.2 Wiener model using Laguerre functions and Taylor series.....	14
1.2.3 Wiener model using Laguerre and Hermite functions.....	19
1.2.4 The orthogonal Wiener series model.....	20
1.2.5 Other nonparametric models.....	24
1.3 BLOCK ORIENTED MODELS.....	28
1.3.1 Classification according to the number of the multipliers.....	29
1.3.2 Quadratic block oriented models.....	32
1.3.3 Cascade systems.....	37
1.3.4 Description of systems with polynomial nonlinearities by parallel channels of different nonlinear degree.....	39
1.3.5 The S_M and the factorable Volterra models.....	39
1.3.6 Nonlinear systems having only one nonlinear term and feedback and/or feedforward paths.....	40
1.4 THE GENERALIZED HAMMERSTEIN AND THE PARAMETRIC VOLTERRA MODELS.....	43
1.4.1 The generalized Hammerstein model.....	43
1.4.2 The parametric Volterra model.....	45
1.4.3 The generalized and extended parametric Volterra models.....	47
1.5 PARAMETRIC DISCRETE TIME MODELS LINEAR-IN-PARAMETERS.....	48
1.5.1 Polynomial difference equations.....	48
1.5.2 Recursive rational difference equation.....	49
1.5.3 Output-affine difference equations.....	51
1.5.4 Recursive polynomial difference equations.....	52
1.5.5 Classification of the polynomial difference equations.....	56
1.5.6 Calculation of the Volterra kernels.....	61
1.6 QUASI-LINEAR MODELS HAVING SIGNAL DEPENDENT PARAMETERS.....	67
1.6.1 Physical meaning.....	67
1.6.2 Continuous time description of continuous time models with signal dependent parameters.....	71
1.6.3 Discrete time description of continuous time models with signal dependent parameters.....	73
1.6.4 Discrete time models with signal dependent parameters.....	82
1.6.5 The effect of changing the parameters of the continuous time models to the parameters of the discrete time equivalent description.....	85
1.6.6 The effect of changing the parameters of the discrete time models to the parameters of the continuous time equivalent	

	description	98
1.7	GATE FUNCTION MODELS	102
1.7.1	Static models.....	103
1.7.2	Nonparametric dynamic models.....	105
1.7.3	Parametric spatial model.....	106
1.7.4	The elementary gate function model and the linear multi-model	106
1.8	TYPES OF NONLINEAR STATIC TERMS	110
1.9	REFERENCES.....	114
2.	Test Signals for Identification.....	119
2.1	INTRODUCTION	119
2.2	RANDOM SIGNAL WITH NORMAL (GAUSSIAN) DISTRIBUTION	132
2.3	PSEUDO-RANDOM MULTI-LEVEL SIGNALS (PRMS-S) WITH MAXIMAL LENGTH.....	136
2.3.1	Generating PRMS-s by multi-level shift registers.....	136
2.3.2	Generating PRMS-s by solving difference equations.....	142
2.3.3	Generating PRMS-s by polynomial division.....	145
2.3.4	Mapping PRMS-s to centered signals.....	147
2.3.5	A FORTRAN subroutine for generating PRMS-s.....	150
2.4	TIME FUNCTIONS OF PRMS-S WITH MAXIMAL LENGTH.....	154
2.4.1	Two-level signals.....	154
2.4.2	Three-level signals.....	154
2.4.3	Five-level signals.....	154
2.4.4	Properties of the signals	154
2.5	AUTO-CORRELATION FUNCTIONS OF PRMS-S WITH MAXIMAL LENGTH.....	165
2.5.1	Relation between the continuous and the discrete time auto- correlation functions	165
2.5.2	Two-level signals.....	168
2.5.3	Three-level signals.....	170
2.5.4	Five-level signals.....	171
2.5.5	Properties of the first-order auto-correlation functions.....	172
2.5.6	Properties of the higher-order auto-correlation functions.....	186
2.6	POWER DENSITY SPECTRA OF PRMS-S WITH MAXIMAL LENGTH.....	186
2.6.1	Two-level signals.....	188
2.6.2	Three-level signals.....	189
2.6.3	Five-level signals.....	191
2.6.4	Properties of the power density spectra	192
2.7	CHOICE OF THE PARAMETERS OF THE PRMS GENERATORS.....	194
2.8	REFERENCES.....	197
3.	Parameter Estimation Methods.....	199
3.1	INTRODUCTION.....	199
3.2	STOCHASTIC MODELS.....	200
3.2.1	Recursive polynomial difference equation.....	201
3.2.2	Recursive rational difference equation.....	202
3.2.3	Output-affine difference equation.....	203
3.3	METHODS FOR RESIDUAL MODELS LINEAR-IN-	

PARAMETERS.....	205
3.3.1 Least squares method.....	206
3.3.2 Extended least squares method.....	207
3.3.3 Suboptimal least squares method.....	207
3.3.4 Instrumental variable method.....	208
3.3.5 Parametric correlation method.....	209
3.3.6 Prediction error method.....	215
3.3.7 Orthogonal parameter estimation.....	216
3.4 METHODS FOR RESIDUAL MODELS NONLINEAR-IN- PARAMETERS.....	221
3.4.1 Classification of prediction models of the output signal.....	221
3.4.2 Different minimization algorithms.....	224
3.4.3 Handling restrictions to the parameters.....	228
3.5 GATE FUNCTION METHOD.....	231
3.6 TWO-STEP METHOD: FITTING THE BEST MODEL LINEAR-IN- PARAMETERS AND IDENTIFICATION OF THE ESTIMATED SIMULATED MODEL.....	234
3.7 ESTIMATION OF THE VOLTERRA KERNELS.....	237
3.7.1 Computing the kernels from pulse and step responses.....	237
3.7.2 Correlation method using Gaussian white noise input.....	242
3.7.3 Correlation technique using exponentially filtered Gaussian white noise input.....	245
3.7.4 Least squares based parameter estimation methods.....	247
3.7.5 Least squares method using Laguerre filters.....	250
3.7.6 Correlation method using Laguerre filters.....	251
3.7.7 Two-step method: fitting a Wiener series model and computing the Volterra kernels.....	252
3.7.8 Two-step method: fitting a parametric model linear-in-parameters and computing the Volterra kernels.....	252
3.8 ESTIMATION OF THE WIENER KERNELS.....	253
3.8.1 Multi-dimensional correlation technique.....	253
3.8.2 Multi-dimensional spectral density method.....	259
3.8.3 Orthogonal estimation of the coefficients of the Wiener model built from Laguerre and Hermite series.....	262
3.9 METHODS APPLIED TO THE SIMPLE HAMMERSTEIN MODEL.....	267
3.9.1 Non-iterative method starting with the estimation of the steady state characteristic.....	268
3.9.2 Non-iterative method starting with the estimation of the parameters of the linear dynamic term.....	269
3.9.3 Correlation method.....	272
3.9.4 Using a process model linear-in-parameters.....	273
3.9.5 Using a process model linear-in-parameters with limitations.....	276
3.9.6 Using a process model nonlinear-in-parameters.....	276
3.9.7 Iterative parameter estimation technique using the inverse of the linear model.....	277
3.9.8 Iterative parameter estimation technique without using the inverse of the linear model.....	280
3.9.9 Gate function method.....	283
3.9.10 Identification by graphical plotting.....	283

3.9.11	Frequency method.....	284
3.10	METHODS APPLIED TO THE SIMPLE WIENER MODEL	287
3.10.1	Non-iterative method starting with the estimation of the steady state characteristic.....	288
3.10.2	Non-iterative method starting with the estimation of the parameters of the linear dynamic term.....	288
3.10.3	Correlation method.....	291
3.10.4	Estimation by the Volterra series and by the parametric Volterra model.....	292
3.10.5	Estimation by means of a process model linear-in-parameters.....	294
3.10.6	Estimation of the inverse process model by a model linear-in-parameters.....	296
3.10.7	Iterative estimation of the inverse process model	299
3.10.8	Using a process model nonlinear-in-parameters.....	301
3.10.9	Iterative parameter estimation technique using the inverse of the nonlinear static term	302
3.10.10	Iterative parameter estimation technique without using the inverse of the nonlinear static term	304
3.10.11	Gate function method.....	305
3.10.12	Identification by graphical plotting	306
3.10.13	Frequency method.....	306
3.11	METHODS APPLIED TO THE SIMPLE WIENER-HAMMERSTEIN MODEL.....	309
3.11.1	Estimation with a process model linear-in-parameters.....	310
3.11.2	Iterative parameter estimation	311
3.11.3	Using a process model nonlinear-in-parameters.....	312
3.11.4	Correlation method.....	313
3.11.5	Identification by repeated pulse excitations	317
3.11.6	Identification by graphical plotting	319
3.11.7	Frequency method.....	321
3.12	METHODS APPLIED TO THE S_M MODELS.....	325
3.12.1	Iterative estimation.....	326
3.12.2	Using a process model nonlinear-in-parameters.....	326
3.12.3	Separate identification of the parallel channels.....	328
3.12.4	Correlation method.....	328
3.12.5	Frequency method.....	330
3.13	METHODS APPLIED TO THE FACTORABLE VOLTERRA MODEL	331
3.13.1	Iterative estimation.....	331
3.13.2	Using a process model nonlinear-in-parameters.....	332
3.13.3	Correlation method.....	333
3.13.4	Frequency method.....	341
3.14	METHODS APPLIED TO OTHER BLOCK ORIENTED MODELS.....	343
3.15	IDENTIFICATION OF LINEAR AND NONLINEAR MULTI-MODELS	349
3.16	IDENTIFICATION OF QUASI-LINEAR MODELS WITH SIGNAL DEPENDENT PARAMETERS	354
3.16.1	Two-step method: fitting a signal dependent model to a linear multi-model.....	355

3.16.2	Identification of continuous time signal dependent models in a form linear-in-parameters	357
3.16.3	Identification of continuous time signal dependent models in the form nonlinear-in-parameters	369
3.16.4	Identification of discrete time signal dependent models in the form linear-in-parameters	370
3.17	IDENTIFICATION OF SPATIAL LINEAR AND NONLINEAR MODELS	373
3.18	ESTIMATION OF THE STEADY STATE CHARACTERISTIC OF A PROCESS.....	374
3.18.1	Evaluation of steady state measurements.....	375
3.18.2	Two-step method: fitting a model linear-in-parameters and the calculation the steady state relation	376
3.18.3	Evaluation of finite-length excitations.....	384
3.18.4	Correlation method.....	389
3.19	METHODS APPLIED TO SYSTEMS WITH NON-POLYNOMIAL NONLINEARITIES	391
3.20	REFERENCES.....	392

VOLUME 2

NONLINEAR SYSTEM STRUCTURE IDENTIFICATION

4. Nonlinearity Test Methods.....	399
4.1 INTRODUCTION	399
4.2 TIME DOMAIN AND STEADY STATE TESTS	401
4.3 TEST BASED ON THE NORMALIZED VARIANCE OF THE NOISE-FREE OUTPUT SIGNAL AROUND THE OUTPUT SIGNAL OF THE BEST FITTING LINEAR MODEL.....	404
4.4 AVERAGE VALUE TEST OF THE OUTPUT SIGNAL.....	410
4.5 GAUSSIAN DISTRIBUTION TEST OF THE OUTPUT SIGNAL.....	417
4.6 FREQUENCY METHOD.....	424
4.7 LINEAR SPECTRAL DENSITY METHOD.....	426
4.8 LINEAR CORRELATION METHOD.....	427
4.9 SECOND-ORDER (NONLINEAR) CROSS-CORRELATION METHOD.....	439
4.10 SECOND-ORDER (OUTPUT) AUTO-CORRELATION METHOD.....	450
4.11 SECOND-ORDER (OUTPUT) SPECTRAL DENSITY METHOD	452
4.12 DISPERSION METHOD.....	452
4.13 METHOD BASED ON THE COMPARISON OF THE VARIANCES OF THE NOISE-FREE MODEL OUTPUT SIGNALS OF THE IDENTIFIED BEST LINEAR AND OF AN ALTERNATIVE NONLINEAR MODEL.....	459
4.14 METHOD BASED ON THE IDENTIFICATION OF ORTHOGONAL SUBSYSTEMS.....	462
4.15 METHOD BASED ON THE IDENTIFICATION OF THE FIRST-ORDER URYSON MODEL.....	467
4.16 METHOD BASED ON PARAMETER ESTIMATION AND <i>F</i> -TEST OF LINEAR AND SIMPLE NONLINEAR STRUCTURES	472
4.17 METHOD BASED ON RESIDUAL ANALYSIS OF THE BEST	

	FITTING LINEAR MODEL.....	476
4.18	CONCLUSIONS.....	480
4.19	REFERENCES.....	482
5.	Structure Identification	484
5.1	INTRODUCTION	484
5.2	SEPARATION OF THE SYSTEM'S RESPONSE TO PARALLEL CHANNELS OF DIFFERENT NONLINEAR DEGREE.....	485
5.3	CASCADE STRUCTURE IDENTIFICATION FROM PARALLEL CHANNELS OF DIFFERENT NONLINEAR DEGREE.....	497
5.4	STRUCTURE IDENTIFICATION OF SYSTEMS CONTAINING ONLY ONE NONLINEAR STATIC ELEMENT BY THE FREQUENCY METHOD.....	502
5.5	STRUCTURE IDENTIFICATION OF BLOCK ORIENTED MODELS	506
5.5.1	Method based on the estimated extended Wiener-Hammerstein cascade model.....	506
5.5.2	Method based on the estimated Volterra kernels.....	519
5.5.3	Frequency method.....	534
5.5.4	Evaluation of pulse and step responses	541
5.6	STRUCTURE IDENTIFICATION OF SIMPLE WIENER-HAMMERSTEIN CASCADE MODEL	543
5.6.1	Correlation analysis.....	544
5.6.2	Frequency method.....	555
5.6.3	Evaluation of pulse and step responses	558
5.7	STRUCTURE IDENTIFICATION AND PARAMETER ESTIMATION OF QUASI-LINEAR MODELS HAVING SIGNAL DEPENDENT PARAMETERS	561
5.7.1	Method using normal operating data.....	562
5.7.2	Evaluation of step responses.....	566
5.8	TWO-STEP STRUCTURE IDENTIFICATION METHOD: BEST INPUT-OUTPUT MODEL APPROXIMATION FROM NORMAL OPERATING DATA AND EVALUATION OF ITS STEP RESPONSES	567
5.9	SELECTION OF THE MOST SIGNIFICANT MODEL COMPONENTS OF MODELS LINEAR-IN-PARAMETERS.....	576
5.9.1	All possible regressions.....	576
5.9.2	Forward and backward regression	582
5.9.3	Stepwise regression	584
5.9.4	Regression analysis using orthogonal model components.....	590
5.9.5	Term clustering.....	599
5.9.6	Genetic algorithm.....	600
5.10	GROUP METHOD OF DATA HANDLING (GMDH)	600
5.11	REFERENCES.....	633
6.	Model Validity Tests	639
6.1	INTRODUCTION	639
6.2	TIME SEQUENCE PLOT OF THE COMPUTED MODEL OUTPUT SIGNAL.....	639
6.3	CHECKING THE MEAN VALUE OF THE RESIDUAL FOR ZERO VALUE	645
6.4	CHI-SQUARE TEST OF THE RESIDUALS.....	646

6.5	TIME SEQUENCE PLOT OF THE RESIDUALS	646
6.6	TIME SEQUENCE PLOT OF CERTAIN MEAN VALUES OF THE DATA TO THE ACTUAL TIME POINT.....	648
6.7	PLOTTING OF THE HISTOGRAM OF THE RESIDUALS.....	649
6.8	NORMALITY TEST OF THE RESIDUALS	650
6.9	FREQUENCY DOMAIN ANALYSIS OF THE RESIDUALS	651
6.10	RUN TEST OF THE RANDOMNESS OF THE RESIDUALS	651
6.11	DURBIN-WATSON TEST OF THE RESIDUALS.....	653
6.12	ANALYSIS OF THE AUTO-CORRELATION FUNCTION OF THE RESIDUALS	654
6.13	PLOT OF THE RESIDUALS AGAINST THE INPUT, OUTPUT AND PREVIOUS RESIDUAL VALUES	656
6.14	COMPUTATION AND PLOT OF THE CONDITIONAL MEAN VALUE OF THE RESIDUALS AGAINST THE INPUT, OUTPUT, AND THE PREVIOUS RESIDUAL VALUES.....	657
6.15	ANALYSIS OF THE CROSS-DISPERSIONAL FUNCTIONS OF THE RESIDUALS AND THE INPUT, OUTPUT, AND PREVIOUS RESIDUAL VALUES.....	661
6.16	ANALYSIS OF DIFFERENT CORRELATION FUNCTIONS OF THE RESIDUALS	662
6.17	CHECKING THE ESTIMATED PARAMETERS FOR SIGNIFICANCE.....	705
6.18	CHECKING THE IDENTIFIED MODEL FOR PHYSICAL INTERPRETATION.....	709
6.19	REFERENCES.....	710
7.	Case Studies on Identification of Real Processes.....	711
7.1	ELECTRICALLY EXCITED BIOLOGICAL MEMBRANE.....	711
7.1.1	Description of the process.....	711
7.1.2	Conclusions drawn from the measured records.....	712
7.1.3	Modeling by the simple Wiener model with signal dependent time constant.....	713
7.1.4	Modeling by a quasi-linear second-order lag with signal dependent gain and time constant.....	719
7.1.5	Conclusions	722
7.2	FERMENTATION PROCESS	724
7.2.1	Description of the process.....	724
7.2.2	Process identification and computation of the optimal control signals.....	724
7.2.3	Conclusions.....	725
7.3	ELECTRICALLY HEATED HEAT EXCHANGER	726
7.3.1	Description of the plant.....	726
7.3.2	Tuning the uncertainty factor in the theoretically derived model.....	729
7.3.3	Process identification by the grapho-analytical method.....	731
7.3.4	Discrete time identification of a linear model	735
7.3.5	Discrete time identification of a two-variable general quadratic model being linear in the parameters.....	736
7.3.6	Discrete time identification by means of stepwise regression.....	737
7.3.7	Discrete time identification of the parameters of a continuous time quasi-linear model with signal dependent	

	parameters.....	740
7.3.8	Discrete time identification of the parameters of a discrete time quasi-linear model with signal dependent parameters.....	741
7.3.9	Discrete time identification of the parameters of the theoretically derived model	742
7.3.10	Conclusions.....	743
7.4	STEAM HEATED HEAT EXCHANGER.....	745
7.4.1	Description of the plant.....	745
7.4.2	Process identification at changes in the steam flow	746
7.4.3	Conclusions.....	749
7.5	DISTILLATION COLUMN SEPARATING METHANOL-WATER MIXTURE.....	750
7.5.1	Description of the plant.....	750
7.5.2	Process identification at changes in the reflux flow	751
7.5.3	Process identification at changes in the distillate flow.....	753
7.5.4	Process identification at changes in the heating power	755
7.5.5	Conclusions.....	756
7.6	DISTILLATION COLUMN SEPARATING ETHANOL-WATER MIXTURE.....	756
7.6.1	Description of the plant.....	756
7.6.2	Process identification at step changes in the reflux rate	759
7.6.3	Process identification using pseudo-random binary excitation in the reflux flow	759
7.6.4	Process identification at changes in the heating power	767
7.6.5	Process identification at changes in the feed rate	768
7.6.6	Conclusions.....	769
7.7	FLOOD PROCESS OF RIVER CACHE.....	770
7.7.1	Description of the process.....	770
7.7.2	Process identification by Volterra series.....	770
7.7.3	Process identification by parametric models.....	772
7.7.4	Conclusions.....	773
7.8	FLOOD PROCESS OF RIVER SCHWARZA.....	773
7.8.1	Description of the process.....	773
7.8.2	Previous process identification results	774
7.8.3	Process identification by different nonlinear parametric models	775
7.8.4	Conclusions.....	776
7.9	OPEN-CIRCUIT CEMENT GRINDING MILL PILOT PLANT	777
7.9.1	Description of the plant.....	777
7.9.2	Process identification by the grapho-analytical method.....	779
7.9.3	Process identification by the least squares method at every input flow step separately	781
7.9.4	Conclusions drawn from the identification of the linear models in different working points.....	781
7.9.5	Discrete time process identification of the global valid nonlinear model	783
7.9.6	Conclusions.....	786
7.10	REFERENCES.....	786
Author Index	789
Subject Index	794