

# Contents

**Part I    Introduction, Basic Concepts and Preliminaries**

<b>1</b>	<b>Introduction</b>	3
1.1	Basic Concepts of Fault Diagnosis Technique	4
1.2	Historical Development and Some Relevant Issues	8
1.3	Notes and References	10
<b>2</b>	<b>Basic Ideas, Major Issues and Tools in the Observer-Based FDI Framework</b>	13
2.1	On the Observer-Based Residual Generator Framework	13
2.2	Unknown Input Decoupling and Fault Isolation Issues	14
2.3	Robustness Issues in the Observer-Based FDI Framework	15
2.4	On the Parity Space FDI Framework	16
2.5	Residual Evaluation and Threshold Computation	17
2.6	FDI System Synthesis and Design	18
2.7	Notes and References	18
<b>3</b>	<b>Modelling of Technical Systems</b>	21
3.1	Description of Nominal System Behavior	22
3.2	Coprime Factorization Technique	23
3.3	Representations of Systems with Disturbances	25
3.4	Representations of System Models with Model Uncertainties	25
3.5	Modelling of Faults	27
3.6	Modelling of Faults in Closed-Loop Feedback Control Systems	29
3.7	Case Study and Application Examples	31
3.7.1	Speed Control of a DC Motor	31
3.7.2	Inverted Pendulum Control System	34
3.7.3	Three-Tank System	38
3.7.4	Vehicle Lateral Dynamic System	41
3.7.5	Continuous Stirred Tank Heater	46
3.8	Notes and References	49

<b>4</b>	<b>Fault Detectability, Isolability and Identifiability</b>	<b>51</b>
4.1	Fault Detectability	51
4.2	Excitations and Detection of Multiplicative Faults	56
4.3	Fault Isolability	57
4.3.1	Concept of System Fault Isolability	57
4.3.2	Fault Isolability Conditions	58
4.4	Fault Identifiability	65
4.5	Notes and References	67

## **Part II Residual Generation**

<b>5</b>	<b>Basic Residual Generation Methods</b>	<b>71</b>
5.1	Analytical Redundancy	72
5.2	Residuals and Parameterization of Residual Generators	75
5.3	Issues Related to Residual Generator Design and Implementation	78
5.4	Fault Detection Filter	79
5.5	Diagnostic Observer Scheme	81
5.5.1	Construction of Diagnostic Observer-Based Residual Generators	81
5.5.2	Characterization of Solutions	82
5.5.3	A Numerical Approach	91
5.5.4	An Algebraic Approach	96
5.6	Parity Space Approach	98
5.6.1	Construction of Parity Relation Based Residual Generators	98
5.6.2	Characterization of Parity Space	101
5.6.3	Examples	102
5.7	Interconnections, Comparison and Some Remarks	103
5.7.1	Parity Space Approach and Diagnostic Observer	104
5.7.2	Diagnostic Observer and Residual Generator of General Form	108
5.7.3	Applications of the Interconnections and Some Remarks	111
5.7.4	Examples	113
5.8	Notes and References	115
<b>6</b>	<b>Perfect Unknown Input Decoupling</b>	<b>117</b>
6.1	Problem Formulation	117
6.2	Existence Conditions of PUIDP	119
6.2.1	A General Existence Condition	119
6.2.2	A Check Condition via Rosenbrock System Matrix	120
6.2.3	An Algebraic Check Condition	122
6.3	A Frequency Domain Approach	126
6.4	UIFDF Design	128
6.4.1	The Eigenstructure Assignment Approach	129
6.4.2	Geometric Approach	133
6.5	UIDO Design	141
6.5.1	An Algebraic Approach	141
6.5.2	Unknown Input Observer Approach	142

6.5.3	A Matrix Pencil Approach to the UIDO Design . . . . .	146
6.5.4	A Numerical Approach to the UIDO Design . . . . .	150
6.6	Unknown Input Parity Space Approach . . . . .	152
6.7	An Alternative Scheme—Null Matrix Approach . . . . .	153
6.8	Discussion . . . . .	154
6.9	Minimum Order Residual Generator . . . . .	154
6.9.1	Minimum Order Residual Generator Design by Geometric Approach . . . . .	155
6.9.2	An Alternative Solution . . . . .	157
6.10	Notes and References . . . . .	160
<b>7</b>	<b>Residual Generation with Enhanced Robustness Against Unknown Inputs . . . . .</b>	<b>163</b>
7.1	Mathematical and Control Theoretical Preliminaries . . . . .	164
7.1.1	Signal Norms . . . . .	165
7.1.2	System Norms . . . . .	167
7.1.3	Computation of $\mathcal{H}_2$ and $\mathcal{H}_\infty$ Norms . . . . .	169
7.1.4	Singular Value Decomposition (SVD) . . . . .	171
7.1.5	Co-Inner–Outer Factorization . . . . .	171
7.1.6	Model Matching Problem . . . . .	174
7.1.7	Essentials of the LMI Technique . . . . .	175
7.2	Kalman Filter Based Residual Generation . . . . .	177
7.3	Robustness, Fault Sensitivity and Performance Indices . . . . .	180
7.3.1	Robustness and Sensitivity . . . . .	181
7.3.2	Performance Indices: Robustness vs. Sensitivity . . . . .	182
7.3.3	Relations Between the Performance Indices . . . . .	182
7.4	Optimal Selection of Parity Matrices and Vectors . . . . .	184
7.4.1	$S_{f,+}/R_d$ as Performance Index . . . . .	184
7.4.2	$S_{f,-}/R_d$ as Performance Index . . . . .	188
7.4.3	$J_{S-R}$ as Performance Index . . . . .	190
7.4.4	Optimization Performance and System Order . . . . .	192
7.4.5	Summary and Some Remarks . . . . .	193
7.5	$\mathcal{H}_\infty$ Optimal Fault Identification Scheme . . . . .	196
7.6	$\mathcal{H}_2/\mathcal{H}_2$ Design of Residual Generators . . . . .	198
7.7	Relationship Between $\mathcal{H}_2/\mathcal{H}_2$ Design and Optimal Selection of Parity Vectors . . . . .	201
7.8	LMI Aided Design of FDF . . . . .	208
7.8.1	$\mathcal{H}_2$ to $\mathcal{H}_2$ Trade-off Design of FDF . . . . .	208
7.8.2	On the $\mathcal{H}_-$ Index . . . . .	213
7.8.3	$\mathcal{H}_2$ to $\mathcal{H}_-$ Trade-off Design of FDF . . . . .	221
7.8.4	$\mathcal{H}_\infty$ to $\mathcal{H}_-$ Trade-off Design of FDF . . . . .	223
7.8.5	$\mathcal{H}_\infty$ to $\mathcal{H}_-$ Trade-off Design of FDF in a Finite Frequency Range . . . . .	225
7.8.6	An Alternative $\mathcal{H}_\infty$ to $\mathcal{H}_-$ Trade-off Design of FDF . . . . .	226
7.8.7	A Brief Summary and Discussion . . . . .	229

7.9	The Unified Solution . . . . .	230
7.9.1	$\mathcal{H}_i/\mathcal{H}_\infty$ Index and Problem Formulation . . . . .	230
7.9.2	$\mathcal{H}_i/\mathcal{H}_\infty$ Optimal Design of FDF: The Standard Form . . . . .	231
7.9.3	Discrete-Time Version of the Unified Solution . . . . .	234
7.9.4	A Generalized Interpretation . . . . .	235
7.10	The General Form of the Unified Solution . . . . .	238
7.10.1	Extended CIOF . . . . .	239
7.10.2	Generalization of the Unified Solution . . . . .	241
7.11	Notes and References . . . . .	244
<b>8</b>	<b>Residual Generation with Enhanced Robustness Against Model Uncertainties . . . . .</b>	<b>249</b>
8.1	Preliminaries . . . . .	250
8.1.1	LMI Aided Computation for System Bounds . . . . .	250
8.1.2	Stability of Stochastically Uncertain Systems . . . . .	251
8.2	Transforming Model Uncertainties into Unknown Inputs . . . . .	252
8.3	Reference Model Based Strategies . . . . .	254
8.3.1	The Basic Idea . . . . .	254
8.3.2	A Reference Model Based Solution for Systems with Norm-Bounded Uncertainties . . . . .	254
8.4	Residual Generation for Systems with Polytopic Uncertainties . . . . .	261
8.4.1	The Reference Model Scheme Based Scheme . . . . .	262
8.4.2	$\mathcal{H}_-$ to $\mathcal{H}_\infty$ Design Formulation . . . . .	266
8.5	Residual Generation for Stochastically Uncertain Systems . . . . .	267
8.5.1	System Dynamics and Statistical Properties . . . . .	268
8.5.2	Basic Idea and Problem Formulation . . . . .	269
8.5.3	An LMI Solution . . . . .	270
8.5.4	An Alternative Approach . . . . .	277
8.6	Notes and References . . . . .	280
<b>Part III Residual Evaluation and Threshold Computation</b>		
<b>9</b>	<b>Norm-Based Residual Evaluation and Threshold Computation . . . . .</b>	<b>285</b>
9.1	Preliminaries . . . . .	286
9.2	Basic Concepts . . . . .	288
9.3	Some Standard Evaluation Functions . . . . .	289
9.4	Basic Ideas of Threshold Setting and Problem Formulation . . . . .	291
9.4.1	Dynamics of the Residual Generator . . . . .	292
9.4.2	Definitions of Thresholds and Problem Formulation . . . . .	293
9.5	Computation of $J_{th,RMS,2}$ . . . . .	296
9.5.1	Computation of $J_{th,RMS,2}$ for the Systems with the Norm-Bounded Uncertainty . . . . .	296
9.5.2	Computation of $J_{th,RMS,2}$ for the Systems with the Polytopic Uncertainty . . . . .	300
9.6	Computation of $J_{th,peak,peak}$ . . . . .	302
9.6.1	Computation of $J_{th,peak,peak}$ for the Systems with the Norm-Bounded Uncertainty . . . . .	302

9.6.2	Computation of $J_{th,peak,peak}$ for the Systems with the Polytopic Uncertainty . . . . .	305
9.7	Computation of $J_{th,peak,2}$ . . . . .	306
9.7.1	Computation of $J_{th,peak,2}$ for the Systems with the Norm-Bounded Uncertainty . . . . .	306
9.7.2	Computation of $J_{th,peak,2}$ for the Systems with the Polytopic Uncertainty . . . . .	309
9.8	Threshold Generator . . . . .	310
9.9	Notes and References . . . . .	312
<b>10</b>	<b>Statistical Methods Based Residual Evaluation and Threshold Setting . . . . .</b>	<b>315</b>
10.1	Introduction . . . . .	315
10.2	Elementary Statistical Methods . . . . .	315
10.2.1	Basic Hypothesis Test . . . . .	315
10.2.2	Likelihood Ratio and Generalized Likelihood Ratio . . . . .	318
10.2.3	Vector-Valued GLR . . . . .	320
10.2.4	Detection of Change in Variance . . . . .	322
10.2.5	Aspects of On-Line Realization . . . . .	323
10.3	Criteria for Threshold Computation . . . . .	325
10.3.1	The Neyman–Pearson Criterion . . . . .	325
10.3.2	Maximum a Posteriori Probability (MAP) Criterion . . . . .	326
10.3.3	Bayes’ Criterion . . . . .	327
10.3.4	Some Remarks . . . . .	328
10.4	Application of GLR Testing Methods . . . . .	328
10.4.1	Kalman Filter Based Fault Detection . . . . .	329
10.4.2	Parity Space Based Fault Detection . . . . .	335
10.5	Notes and References . . . . .	337
<b>11</b>	<b>Integration of Norm-Based and Statistical Methods . . . . .</b>	<b>339</b>
11.1	Residual Evaluation in Stochastic Systems with Deterministic Disturbances . . . . .	339
11.1.1	Residual Generation . . . . .	340
11.1.2	Problem Formulation . . . . .	341
11.1.3	GLR Solutions . . . . .	342
11.1.4	An Example . . . . .	345
11.2	Residual Evaluation Scheme for Stochastically Uncertain Systems . . . . .	346
11.2.1	Problem Formulation . . . . .	347
11.2.2	Solution and Design Algorithms . . . . .	348
11.3	Probabilistic Robustness Technique Aided Threshold Computation . . . . .	357
11.3.1	Problem Formulation . . . . .	357
11.3.2	Outline of the Basic Idea . . . . .	359
11.3.3	LMIs Used for the Solutions . . . . .	360
11.3.4	Problem Solutions in the Probabilistic Framework . . . . .	361
11.3.5	An Application Example . . . . .	363
11.3.6	Concluding Remarks . . . . .	365
11.4	Notes and References . . . . .	366

## Part IV Fault Detection, Isolation and Identification Schemes

<b>12 Integrated Design of Fault Detection Systems</b>	369
12.1 FAR and FDR	370
12.2 Maximization of Fault Detectability by a Given FAR	373
12.2.1 Problem Formulation	373
12.2.2 Essential Form of the Solution	374
12.2.3 A General Solution	376
12.2.4 Interconnections and Comparison	379
12.2.5 Examples	383
12.3 Minimizing False Alarm Number by a Given FDR	386
12.3.1 Problem Formulation	387
12.3.2 Essential Form of the Solution	388
12.3.3 The State Space Form	390
12.3.4 The Extended Form	392
12.3.5 Interpretation of the Solutions and Discussion	393
12.3.6 An Example	397
12.4 On the Application to Stochastic Systems	398
12.4.1 Application to Maximizing FDR by a Given FAR	399
12.4.2 Application to Minimizing FAR by a Given FDR	400
12.4.3 Equivalence Between the Kalman Filter Scheme and the Unified Solution	400
12.5 Notes and References	402
<b>13 Fault Isolation Schemes</b>	405
13.1 Essentials	406
13.1.1 Existence Conditions for a Perfect Fault Isolation	406
13.1.2 PFIs and Unknown Input Decoupling	408
13.1.3 PFIs with Unknown Input Decoupling (PFIUID)	411
13.2 Fault Isolation Filter Design	412
13.2.1 A Design Approach Based on the Duality to Decoupling Control	413
13.2.2 The Geometric Approach	416
13.2.3 A Generalized Design Approach	418
13.3 An Algebraic Approach to Fault Isolation	427
13.4 Fault Isolation Using a Bank of Residual Generators	431
13.4.1 The Dedicated Observer Scheme (DOS)	432
13.4.2 The Generalized Observer Scheme (GOS)	436
13.5 Notes and References	439
<b>14 Fault Identification Schemes</b>	441
14.1 Fault Identification Filter Schemes and Perfect Fault Identification	442
14.1.1 Fault Detection Filters and Existence Conditions	442
14.1.2 FIF Design with Measurement Derivatives	446
14.2 On the Optimal FIF Design	449
14.2.1 Problem Formulation and Solution Study	449
14.2.2 Study on the Role of the Weighting Matrix	451

14.3	Approaches to the Design of FIF . . . . .	456
14.3.1	A General Fault Identification Scheme . . . . .	457
14.3.2	An Alternative Scheme . . . . .	457
14.3.3	Identification of the Size of a Fault . . . . .	458
14.3.4	Fault Identification in a Finite Frequency Range . . . . .	460
14.4	Fault Identification Using an Augmented Observer . . . . .	461
14.5	An Algebraic Fault Identification Scheme . . . . .	463
14.6	Adaptive Observer-Based Fault Identification . . . . .	464
14.6.1	Problem Formulation . . . . .	464
14.6.2	The Adaptive Observer Scheme . . . . .	465
14.7	Notes and References . . . . .	468
<b>15</b>	<b>Fault Diagnosis in Feedback Control Systems and Fault-Tolerant Architecture . . . . .</b>	<b>471</b>
15.1	Plant and Control Loop Models, Controller and Observer Parameterizations . . . . .	472
15.1.1	Plant and Control Loop Models . . . . .	472
15.1.2	Parameterization of Stabilizing Controllers, Observers, and an Alternative Formulation of Controller Design . . . .	473
15.1.3	Observer and Residual Generator Based Realizations of Youla Parameterization . . . . .	475
15.1.4	Residual Generation Based Formulation of Controller Design Problem . . . . .	476
15.2	Residual Extraction in the Standard Feedback Control Loop and a Fault Detection Scheme . . . . .	478
15.2.1	Signals at the Access Points in the Control Loop . . . . .	478
15.2.2	A Fault Detection Scheme Based on Extraction of Residual Signals . . . . .	479
15.3	2-DOF Control Structures and Residual Access . . . . .	481
15.3.1	The Standard 2-DOF Control Structures . . . . .	481
15.3.2	An Alternative 2-DOF Control Structure with Residual Access . . . . .	483
15.4	On Residual Access in the IMC and Residual Generator Based Control Structures . . . . .	485
15.4.1	An Extended IMC Structure with an Integrated Residual Access . . . . .	485
15.4.2	A Residual Generator Based Feedback Control Loop . . . .	487
15.5	Notes and References . . . . .	488
	<b>References . . . . .</b>	<b>491</b>
	<b>Index . . . . .</b>	<b>499</b>

<http://www.springer.com/978-1-4471-4798-5>

Model-Based Fault Diagnosis Techniques

Design Schemes, Algorithms and Tools

Ding, S.

2013, XX, 504 p., Hardcover

ISBN: 978-1-4471-4798-5