

Contents

1	Introduction	1
1.1	Necessity for the Fault Diagnosis and Condition Monitoring of Liquid Rocket Engine	1
1.2	History and Development of LRE Fault Diagnostics Technology	4
1.3	Development Trend of the LRE Fault Diagnosis	8
2	Failure Pattern and Corresponding Mechanism Analysis of LRE	11
2.1	Introduction	11
2.2	Structure of LRE	12
2.3	Failure Pattern Analysis of the LRE	12
2.4	Failure Mechanism Analysis of the LRE	14
2.4.1	Thrust Chamber and Gas Generator	14
2.4.2	Turbo Pump	17
2.4.3	Seal Components	26
2.5	Standard Failure Pattern of the LRE	28
3	Analysis Methods of Failure Model for LRE	37
3.1	Introduction	37
3.2	Working Process of LRE	38
3.3	Model of Steady State Process for LRE	39
3.3.1	Analysis of Liquid Flow in the Pipeline	39
3.3.2	Working Characteristic Equation of Engine Parts	40
3.3.3	Parameter Balance Model of Engine	46
3.3.4	Fault Characteristic Equation of Engine Components [55, 62–64]	48
3.3.5	Steady State Model of the First-Stage Engine	54
3.3.6	Steady State Model of the Second-Stage Engine	54
3.4	Dynamic Model of LRE [55, 62–64]	55
3.4.1	Thrust Chamber	55
3.4.2	Gas Generator	57

3.4.3	Turbine Pump System	58
3.4.4	Liquid Pipeline System	60
3.4.5	Autogenous Pressurization System	64
3.4.6	Dynamic Model of the First-Stage Engine	69
3.4.7	Dynamic Model of the Second-Stage Engine	69
4	Fault Characteristic Analysis of LRE	71
4.1	Characteristic Analysis of Failure Patterns in Steady State	71
4.1.1	Numerical Solution of the Steady State Model	72
4.1.2	Simulation Analysis of Steady State Feature	73
4.1.3	The Numerical Method Based on the Hopfield Neural Nets	75
4.1.4	Analysis of Engine Steady State Fault	78
4.1.5	Secondary Engine Steady State Fault Analysis Based on Ant Colony Algorithm	81
4.1.6	Analysis of Engine Fault Feature Based on Evolutionary Calculation	85
4.1.7	Acquisition of Engine Steady State Failure Mode	99
4.2	Analysis of Dynamic Failure Mode	100
4.2.1	The Numerical Method for Solving the Dynamic Model of Engine	101
4.2.2	Analysis of Engine Dynamic Fault	102
4.3	Integrated Fault Analysis	116
4.4	Separability and Detectability of Fault	118
4.4.1	Separability of Fault	118
4.4.2	The Detectability and Diagnostic Ability of Fault	119
5	Fault Diagnosis of LRE Based on ANN	121
5.1	Theory of ANN	121
5.1.1	Basics of ANN	122
5.1.2	BP ANN and Improved Algorithm	123
5.2	Diagnostic Mechanism of ANN	127
5.3	Fuzzy Preprocessing of the Input Data for the ANN	129
5.4	Fault Diagnosis Method Based on BP ANN	130
5.5	Fault Diagnosis Method Based on RBF ANN	131
5.5.1	RBF ANN	138
5.5.2	Application Examples	142
5.5.3	Calculation Results and Analysis	147
5.6	Fault Diagnosis Method Based on Improved ART2 ANN	147
5.6.1	Selection of no Mentor Learning ANN Model	148
5.6.2	Basic Structure and Theory of ART ANN	150
5.6.3	Improved ART2 Algorithm	153
5.6.4	Implementation of Improved ART2 Algorithm	155
5.6.5	Fault Diagnosis Examples	157

5.7	FTART ANN-based Fault Diagnosis Method.	158
5.7.1	FTART Structure and Basic Theory	159
5.7.2	Improvement and Its Mathematical Description of FTART ANN	160
5.7.3	Design of FTART ANN	162
5.7.4	Diagnosis Examples and Analysis for FRART ANN.	164
6	Fault Diagnosis Method Based on Wavelet Transform.	165
6.1	Theory of Wavelet Transform	165
6.1.1	Introduction.	165
6.1.2	Basic Theories of Wavelet Analysis [104].	167
6.2	Fault Diagnosis Based on Wavelet Analysis for LRE	176
6.2.1	Wavelet Packet Decomposition and Feature Extraction	176
6.2.2	Time-Series Analysis Method and Its Application	177
6.2.3	Harmonic Wavelet and Its Application	181
6.2.4	Abnormal Vibration Monitoring and Diagnosis of Turbo Pump	188
6.2.5	Sub-synchronous Precession Analysis of Turbo Pump Based on Wavelet Analysis.	189
6.2.6	Fault Diagnosis of LRE Based on Wavelet-ANN	189
7	Fault Diagnosis Method Based on Artificial Immune System	193
7.1	Artificial Immune System	193
7.1.1	Natural Immune System	193
7.2	Application of Negative Selection Principle to Fault Detection and Diagnosis of LRE	199
7.2.1	Negative Selection Algorithm	199
7.2.2	Case Study	201
7.3	Application of the Clone Selection Principle in Start-up Progress Simulation of LRE	209
7.3.1	Clone Selection Principle and Algorithm.	209
7.3.2	Case Study	212
8	Fault Diagnosis Method Based on Fuzzy Theory	219
8.1	Fuzzy Fault Diagnosis	219
8.1.1	Basic Theory of the Fuzzy	220
8.1.2	Fault Diagnosis Based on Fuzzy Theory	221
8.2	Fault Diagnosis Method Based on Fuzzy Theory	221
8.2.1	Basic Theory of the Fuzzy Pattern Recognition	222
8.2.2	Template Method-Based Membership Function Construction and the FPR	224
8.2.3	Multi-variable Membership Function and the FPR . . .	228

8.3	Fault Diagnosis Method Based on Fuzzy Clustering	232
8.3.1	Dynamic Clustering Method Based on the Fuzzy Equivalence Matrix	233
8.3.2	Clustering Method of Fuzzy ISODATA	235
8.3.3	Fuzzy Clustering Based on Max— $\odot$ Transitivity and Its Application	239
8.4	Fault Diagnosis Method Based on FNN	241
8.4.1	Fuzzy Neural Network	241
8.4.2	Fuzzy RBF ANN and Its Application in the Fault Diagnosis of LRE	246
9	Fault Analysis and Diagnosis Method Based on Statistical Learning Theory	255
9.1	Statistical Learning Theory and Support Vector Machine [136–140]	255
9.1.1	Machine Learning	257
9.1.2	Statistical Learning Theory	258
9.1.3	Support Vector Machine	260
9.1.4	Kernel Function and the Parameter Optimization	262
9.2	Application of the SVM in the Fault Diagnosis of LRE	266
9.2.1	Fault Character Analysis and Diagnosis of LRE in Steady State Based on SVM	266
9.2.2	Fault Diagnosis of LRE Based on GA—SVM	271
9.2.3	Fault Modeling and Analysis of LRE Based on SVM	272
10	Fault Diagnosis Method Based on Hidden Markov Model	279
10.1	Fault Diagnosis Method Based on HMM	279
10.1.1	Basic Ideology of HMM	280
10.1.2	Basic Algorithm of HMM	283
10.1.3	The Type of HMM	288
10.1.4	Improvement Measures of HMM in Practical Application	289
10.1.5	A Pump Fault Diagnosis Turbo Based on HMM	293
10.2	HMM-SVM Hybrid Fault Diagnosis Model and Its Application	303
10.2.1	SVM Training	304
10.2.2	HMM-SVM Fault Diagnosis Application Examples	304
11	Fault Prediction Methods of Liquid Rocket Engine (LRE)	307
11.1	Fault Prediction Method Based on Time Series Analysis	308
11.1.1	Time Series Analysis	308
11.1.2	Application and Analysis	316
11.2	Fault Prediction Method Based on Gray Model	317
11.2.1	Introduction of Gray Model	317
11.2.2	Basic Mechanism of Gray Model	317

11.2.3	Gray Prediction Method and Its Application in Fault Prediction of LRE	318
11.3	Rocket Engine Fault Prediction Method Based on Neural Network	327
11.3.1	Multistep Prediction Method for Dynamic Parameters of Rocket Engine Based on BP Network.	327
11.3.2	The Prediction Method for Dynamic of Rocket Engine Based on RBF Network.	331
11.3.3	The Prediction Method for Dynamic of Rocket Engine Based on Elman Network.	338
11.4	Rocket Engine Fault Prediction Based on SVM Method	348
11.4.1	The Regression Estimation Based on Support Vector Machine	349
11.4.2	Prediction Process and Evaluation Criteria Based on Support Vector Machine.	354
11.4.3	An Example of Liquid Rocket Engine Fault Prediction Based on SVM Method.	355
Appendix A: Steady State Fault Model of I-Level.		361
Appendix B: Steady State Fault Model of II-Level		377
Appendix C: Dynamic State Fault Model of I-Level		385
Appendix D: Dynamic State Fault Model of II-Level		389
References		395