

# Failure Characteristics Analysis and Fault Diagnosis for Liquid Rocket Engines

Wei Zhang

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國防工業出版社  
National Defense Industry Press



Springer

Wei Zhang  
Xi'an Research Institute of High-Tech  
Xi'an  
China

ISBN 978-3-662-49252-9                      ISBN 978-3-662-49254-3 (eBook)  
DOI 10.1007/978-3-662-49254-3

Jointly published with National Defense Industry Press

Library of Congress Control Number: 2016936646

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# Preface

Being composed of different components working with different programs, the liquid rocket engine (LRE) is a complex system that is widely used in the aerospace field. It can provide thrust for a vehicle outside of the atmosphere. However, the LRE is always working in execrable conditions with high temperatures and heavy corrosion. Therefore, it is necessary to monitor the condition of an LRE to enhance the reliability and safety of the thrust system and understand its working performance; it would also be useful to establish an advanced condition monitoring and fault diagnosis system for the LRE. Involving several disciplines and technologies, the core of LRE health monitoring is the technologies of fault detection and fault diagnosis. In recent decades, a special theory of fault detection and diagnosis was developed using digital computer technology, the theory of automatic control, signal processing, artificial intelligence, reliability theory, and engineering to provide a theoretical foundation for the development of fault detection and diagnosis in the LRE.

In this book, the mode, model, and characteristics of the LRE's fault are investigated. Then, the corresponding fault diagnosis methods, including methods based on the model, signal processing, and artificial intelligence are studied. Developed under the guidance of modern control theory and the modern optimization method, the model-based method carries out fault diagnosis by analyzing the residual obtained by the Luenberger observer, equivalent space equation, Kalman filter, parameter estimation, and identification based on the specialized criterion or threshold. It has attracted much attention because the model-based method can be closely combined with the control system and is a precondition of condition monitoring, fault tolerance control, system modification, and reconstruction.

By referring to the production of the residual, the model-based method can be divided into several methods, including the condition estimation method, parameter estimation method, and the equivalent space method. Comparatively, the method based on signal processing does not rely on an accurate model and has good suitability. Although most parts of signal processing-based methods are proposed

on the assumption that the system is linear, they are easily expanded to nonlinear systems. The methods involving Kullback information criterion, wavelet transform, time series analysis, and information fusion are included in the signal processing-based methods. With the development of the system, the system is becoming more and more complex and it is very difficult to establish an accurate model. In this instance, an artificial intelligence-based method, which does not rely on an accurate model, can be used for fault diagnosis. For example, the artificial neural net (ANN), expert system, pattern recognition, revolution algorithm, fuzzy logic method, and a combination of these methods are included in the intelligence-based method.

An LRE is a complex system involving high temperatures, high pressure, heavy corrosion, and strong power release. It is very difficult to establish an accurate model for the whole system, and the model-based method may be restricted in the engineering application. Comparatively, the signal processing-based method and the artificial intelligence-based method are advanced in the processing of the complex character of the object. In this instance, by combining the character and developing trends of the LRE fault diagnosis, wavelet transform, artificial intelligence, fuzzy logic, statistic learning theory, and gray theory are applied in the fault diagnosis of the LRE. This book concentrates on the subjects of monitoring technology of a healthy LRE, including its failure analysis, fault diagnosis, and fault prediction; several fault diagnosis methods have been investigated by combining the fault cases of LRE. We hope to have achieved the following characteristics in the writing of this book:

*Advanced.* The latest investigation achievements are summarized in this book and corresponding content is advanced and novel.

*Applicable.* As it is focused on the application of the fault character analysis and diagnosis technology in the LRE, this book can be used as the reference by researchers and engineers.

*Readable.* Although the theory is very complex, the content of this book, including the basic mechanisms, synthesis methods, and application cases, are logically arranged for the sake of understanding.

The content of this book is the culmination of research by our group. Many graduate students, including Tian Gan, Xu Zhi-gao, Yang Zheng-wei, Li Ming, Lin Xiang-jin, Gao Zheng-ming, Liu Chong-yang, Tian Lu, Xu Hai-bo, and Ming An-bo, worked on different parts of this book. All authors of references are appreciated because they provide rich material for the content in this book. We also thank the publishers for their help in the publishing process.

Because of restrictions in the knowledge of the authors, errors may appear in this book. All comments and corrections are cordially accepted!

# Contents

<b>1</b>	<b>Introduction</b> . . . . .	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
<b>2</b>	<b>Failure Pattern and Corresponding Mechanism Analysis of LRE</b> . . . . .	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
<b>3</b>	<b>Analysis Methods of Failure Model for LRE</b> . . . . .	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
<b>4</b>	<b>Fault Characteristic Analysis of LRE . . . . .</b>	<b>71</b>
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
<b>5</b>	<b>Fault Diagnosis of LRE Based on ANN . . . . .</b>	<b>121</b>
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
<b>9</b>	<b>Fault Analysis and Diagnosis Method Based on Statistical Learning Theory . . . . .</b>	<b>255</b>
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
<b>10</b>	<b>Fault Diagnosis Method Based on Hidden Markov Model . . . . .</b>	<b>279</b>
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
<b>11</b>	<b>Fault Prediction Methods of Liquid Rocket Engine (LRE) . . . . .</b>	<b>307</b>
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**

# Prologue

Astronautical technology is a type of synthesis engineering technology that aims to explore, develop, and use celestial bodies in outer space; it is an integrative sign of modern technology development. Moreover, military astronautical technology—an important part of the national defense industry—is very important for improvement in military information levels and national safety. However, the structure of an astronautical vehicle is very large and the environment of space flights is very complex. The launch and reclamation of the vehicle is very difficult. Furthermore, the demand for astronautical technology that carries people is increasing, while maintaining the safety and reliability of these vehicle faces great challenges.

Generally, a liquid rocket engine (LRE)—a kind of heat hydrodynamic system—is the main power source for space shuttles; its running condition is critical for the safety and reliability of the vehicle. Therefore, the investigation of the fault diagnosis and prediction of an LRE is very important for the improvement of astronautical activities. Using achievements in the areas of propulsion theory, signal processing, pattern recognition, artificial intelligence, sensor technology, and computer technology, the aim of the investigation of the fault diagnosis and prediction of an LRE is to enhance running reliability and flight safety. Recently, investigations on the fault diagnosis and prediction of LREs have achieved great improvements in China. The theoretical system of fault diagnosis and prediction was founded on the background of LREs and successfully applied in a ground test of space vehicle and military LREs. However, a systematical technical monograph on fault character and fault diagnosis technology has not yet been written in the area of military LREs. I am very pleased to see that this monograph on the basic theory and methods of the fault character, diagnosis, and prediction of military LREs summarizes the basis of the investigation and engineering practice of the past decades. This book is very significant for the improvement of military LRE fault diagnosis and engineering applications throughout the world.

Based on the LRE model with fault and characteristic analysis, the achievements on the fault characteristics and diagnosis technology of military LREs have been introduced. In particular, theoretical methods, including the artificial neural net, wavelet analysis, intelligence computing, fuzzy theory, statistic learning theory,

time series analysis, and the gray system model, are applied on the fault diagnosis and prediction of LREs and provide technological support for the novel design, scientific maintenance, and safe operation of weapons.

This book will help in the expansion and dissemination of fault diagnosis technology of military LREs and space vehicles. It will play an important role in the future of engineering.

Jinji Gao

Member of the China Engineering Academy

Vice President of the Equipment Management Association of China