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OPTIMIZATION OF STIFFENED PANEL FATIGUE LIFE BY USING FINITE ELEMENT ANALYSIS

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OPTIMIZATION OF STIFFENED PANEL FATIGUE LIFE BY USING FINITE ELEMENT ANALYSIS

By

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OPTIMIZATION OF STIFFENED PANEL FATIGUE LIFE BY USING FINITE ELEMENT ANALYSIS

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July 2020

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Aluminum Al 2024-T351 and titanium Ti–6Al–4V are widely used in aircraft components such as wings, fuselage, steam turbines and heat exchangers are prone to failure due to fatigue. In design, a range of operating temperatures, fluctuating working loads, duration and manufacturing processes are important and that due to these design factors the load-carrying capability of the structural members can be significantly affected. A comprehensive method of analysis combining experimental and simulation approaches in order to predict the fatigue life of structural members were carried out in this research. The experimental analyses were conducted for tensile and fatigue tests at several stress levels. The frequency of 10 Hz and the load ratio of 0.1 was selected during the fatigue tests. The tests were conducted in controlled elevated and low temperatures. The effect of temperature on the yield strength, ultimate strength, elastic modulus and deformation were discussed. Finite element analysis (FEA) was validated with the experimental work to verify the precision of the results. The overall data showed a good agreement between experimentally observed and computationally predicted data. The single edge notched tension specimen was used to calculate the fracture toughness of a material. The stress intensity factor and critical length were analytically calculated and compared with the numerical results. Several crack growth models such as NASGRO, Forman, Broek & Schijve and Paris were applied to the calculated data in order to predict the fatigue life and cycles to crack initiation. The Paris model was observed to be the closest results to the numerical model. A range of stiffened panels consisted of stiffeners that were fastened to the skin as used in aircraft wings and fuselage structures were simulated and analyzed. Three optimization methods: screening, multi-objective genetic algorithm and adaptive multi-objective algorithm were adopted in this study. The screening approach that is the random sampling

method was able to select design points close to the objective. The multi-objective genetic algorithm which selects the design points based on Pareto optimal design combined with the adaptive multi-objective algorithm method which uses an optimal space-filling was shown to be efficient for time limitation and budget. The results of the multi-objective genetic algorithm method confirmed the possibility of archive improvement in fatigue life, even with the decrease in stress and mass simultaneously.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGOPTIMUMAN KEHIDUPAN STRUKTUR PANEL YANG DIKUKUHKAN DENGAN MENGGUNAKAN ANALISIS ELEMEN TERHINGGA

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Aluminium Al 2024-T351 dan titanium Ti – 6Al – 4V digunakan secara meluas dalam komponen pesawat seperti sayap, pesawat, turbin wap dan penukar haba terdedah kepada kegagalan kerana keletihan. Dalam reka bentuk, pelbagai suhu operasi, beban kerja yang berubah-ubah, jangka masa dan proses pembuatan adalah penting dan kerana faktor reka bentuk ini, keupayaan membawa anggota struktur dapat dipengaruhi dengan ketara. Kaedah analisis yang komprehensif yang menggabungkan pendekatan eksperimen dan simulasi untuk meramalkan keletihan kehidupan anggota struktur dilakukan dalam penyelidikan ini. Analisis eksperimen dilakukan untuk ujian tegangan dan keletihan pada beberapa tahap tekanan. Kekerapan 10 Hz dan nisbah beban 0.1 dipilih semasa ujian keletihan. Ujian dilakukan dalam suhu tinggi dan rendah yang terkawal. Kesan suhu pada kekuatan hasil, kekuatan tertinggi, modulus elastik dan ubah bentuk telah dibincangkan. Analisis elemen hingga (FEA) disahkan dengan kerja eksperimen untuk mengesahkan ketepatan hasilnya. Keseluruhan data menunjukkan kesepakatan yang baik antara data yang diperhatikan secara eksperimen dan data yang diramalkan. Spesimen tegangan berlekuk tepi tunggal digunakan untuk mengira ketahanan patah bahan. Faktor intensiti tekanan dan panjang kritikal dikira secara analitik dan dibandingkan dengan hasil berangka. Beberapa model pertumbuhan retak seperti NASGRO, Forman, Broek & Schijve dan Paris diterapkan pada data yang dihitung untuk meramalkan keletihan hidup dan kitaran untuk memulakan permulaan. Model Paris diperhatikan sebagai hasil terdekat dengan model berangka. Rangkaian panel yang diperkuat terdiri dari pengeras yang diikat pada kulit seperti yang digunakan pada sayap pesawat dan struktur pesawat disimulasikan dan dianalisis. Tiga kaedah pengoptimuman: penyaringan, algoritma genetik pelbagai objektif dan algoritma multi-objektif adaptif diadopsi dalam kajian ini. Pendekatan saringan yang merupakan kaedah persampelan rawak dapat memilih titik reka bentuk yang hampir dengan objektif. Algoritma genetik

pelbagai objektif yang memilih titik-titik reka bentuk berdasarkan reka bentuk optimum Pareto digabungkan dengan kaedah algoritma multi-objektif adaptif yang menggunakan pengisian ruang yang optimum terbukti berkesan untuk had masa dan anggaran. Hasil kaedah algoritma genetik pelbagai objektif mengesahkan kemungkinan peningkatan arkib dalam kehidupan keletihan, walaupun dengan penurunan tekanan dan jisim secara serentak.

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TABLE OF CONTENTS

		Page
ABSTRACT		i
ABSTRAK		iii
ACKNOWLEDGEMENTS		v
APPROVAL		vi
DECLARATION		viii
LIST OF TABLES		xiii
LIST OF FIGURES		xiv
LIST OF ABBREVIATIONS		xx
LIST OF APPENDICES		xxi
CHAPTER		
1	**INTRODUCTION**	1
	1.1 Background	1
	1.2 Problem Statement	2
	1.3 Research Objectives	3
	1.4 Scope of Study	3
	1.5 Thesis Layout	4
2	**LITERATURE REVIEW**	5
	2.1 Introduction	5
	2.2 Fatigue of Metals	5
	2.3 Fatigue at Different Temperature	10
	2.3.1 Elevated Temperature	10
	2.3.2 Low Temperature	12
	2.3.3 Environmental effect	15
	2.4 Stiffened Panel	17
	2.5 Numerical simulations	22
	2.6 Design Optimization by Finite Element Analysis (FEA)	24
	2.6.1 Response Surface Optimization	25
	2.6.2 Goal-Driven Optimization (GDO)	25
	2.7 Summary	27
3	**METHODOLOGY**	32
	3.1 Introduction	32
	3.2 Tensile Test	36
	3.2.1 Controlled Temperature	36
	3.2.2 Elevated Temperature	37
	3.2.3 Low Temperature	38
	3.3 Fatigue Test	39
	3.3.1 Controlled Temperature	41
	3.3.2 Elevated Temperature	42

3.3.3 Low Temperature 42
3.4 Numerical Simulation 43
3.4.1 Specimen Design 44
3.4.2 Stiffened Panel 45
3.5 Fatigue Analysis with ANSYS Workbench 46
3.6 Single Edge Notch Tension Specimen 53
3.6.1 Finding the critical length 54
3.6.2 Crack Initiation Life and Total Life Estimation 55

3.7 Optimization 56
3.7.1 Screening Method 58
3.7.2 Multi-Objective Genetic Algorithm (MOGA) 59
3.7.3 Adaptive Multi-Objective (AMO) 61

3.8 Limitation of Fabrication of the Stiffened Panel 63
3.9 Summary 64

4 RESULTS AND DISCUSSION 65
4.1 Introduction 65
4.2 Tensile Test 65
4.2.1 Controlled Temperature 65
4.2.2 Elevated Temperature 67
4.2.3 Low Temperature 70
4.2.4 Summary of Mechanical Properties at Various Temperature 71
4.3 Fatigue Test 76
4.3.1 Controlled Temperature 76
4.3.2 Elevated Temperature 78
4.3.3 Low Temperature 81
4.3.4 Summary of Fatigue Life at Various Temperatures 83
4.4 Validation with ANSYS Workbench Results 85
4.4.1 Aluminum Al 2024-T351 85
4.4.2 Titanium Ti–6Al–4V 88
4.5 Optimization using ANSYS Workbench 90
4.5.1 Screening method 90
4.5.2 Multi-objective genetic algorithm method 93
4.5.3 Adaptive multi-objective method 96
4.6 Analysis Results of SENT Specimen and Fatigue Life 99

	4.7 Summary	101
5	**CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH**	103
	5.1 Introduction	103
	5.2 Conclusion	103
	5.3 Recommendation For Future Work	104
REFERENCES		105
APPENDICES		116
BIODATA OF STUDENT		204
LIST OF PUBLICATIONS		205

LIST OF TABLES

Table		Page
2.1	The capabilities of each method in ANSYS Workbench	27
2.2	The summary table of literature review	28
3.1	Alignment setting of MTS 810	39
3.2	Load Tuning for Both Materials	40
3.3	Number of Elements and Nodes For All Models	50
3.4	Input and Output Parameters	58
4.1	Optimization Results in the Screening Method	93
4.2	Optimization results for the multi-objective genetic algorithm method	96
4.3	Optimization results for the adaptive multi-objective method	99

LIST OF FIGURES

Figure		Page
2.1	Phrases in fatigue	6
2.2	Crack modes of failure	7
2.3	Fatigue crack growth with the transition from tensile to shear mode	7
2.4	Stable (below) and unstable (above) crack growth regions	8
2.5	Duplex (bimodal) structure of Titanium 6Al-4V which light structures represent α grains and dark structures represent α+β lamellar grains	8
2.6	Basket weave structure of Titanium 6Al-4V	9
2.7	SEM surface cracks initiation Titanium 6Al-4V	9
2.8	Facet structure of Titanium 6Al-4V	10
2.9	Mechanical Properties at Elevated Temperature	11
2.10	Comparison of tensile curves for aluminum 2024-T3	11
2.11	Fatigue test of aluminum 2024-T3 at (a) 20°C (b) 100°C (c) 200°C (d)300°C	12
2.12	Fatigue surface fracture of aluminum 2024-T3 at -60 C	13
2.13	Fracture surface at; a) Controlled temperature b) low temperature	13
2.14	Grain size of aluminum 2024-T3 (a) Before test (b) After test	14
2.15	Stress strain graph of manganese steel at room and low temperature	14
2.16	S-N curve of aluminum at; a) controlled temperature b) low temperature	15

2.17	Fatigue striation of Aluminum 7075 at room temperature T6	16
2.18	Dimple from crack initiation area of Aluminum 7075 T6 at room temperature	16
2.19	Comparison deflection between integrally and riveted stiffened panels	17
2.20	Comparison of maximum stress between integrally and riveted stiffened	18
2.21	Comparison of mass between integrally and riveted stiffened panels	18
2.22	Duration of crack growth in riveted and integral panel skin from initial skin crack between intact stringers	19
2.23	Full scale stiffened panel fatigue testing	20
2.24	Stiffened panel with grip design	20
2.25	Stiffened panel with bolted grips	21
2.26	Composite I stiffened panel with a steel plate as the base	21
2.27	Stiffened panel with a steel plate at both ends	22
2.28	Metal plate at both ends of the stiffened panel	22
2.29	Fatigue life prediction for UIC 54	23
2.30	Response surface of radius and thickness variables of landing gear	26
3.1	Flow chart of experimental and simulation of aluminum Al 2024-T351 and titanium Ti–6Al–4V	33
3.2	The flow chart of the optimization of the stiffened panel	34
3.3	The flow chart of single edge notched tension (SENT) and application of crack model	35

3.4	Dimension of Specimen (mm)	36
3.5	Tensile test with Instron 3382	37
3.6	Tensile test MTS 810 equipped with heating holder	38
3.7	Tensile test with a cooling holder	39
3.8	Fatigue test with MTS 810	42
3.9	ANSYS Workbench fatigue analysis approach	44
3.10	A complete 3D specimen	44
3.11	The basic design of the stiffened panel	45
3.12	3D model of the stiffened panel	45
3.13	The stiffened panel integrated with grip	46
3.14	Selection of analysis system in toolbox	46
3.15	Static Structural workflow for ANSYS Workbench	47
3.16	Engineering Data outline	46
3.17	Geometry selection	46
3.18	Project outline inside ANSYS Workbench	49
3.19	a) The 3D specimen b) Meshed specimen	49
3.20	The mesh convergence.a) Aluminium b)Titanium c)Stiffened Panel	51
3.21	Selection of boundary condition of the flat specimen: a) Fixed support b) Force	52
3.22	a) Sketching the crack b) Extruding the sketch	53
3.23	Defining pre-meshed crack in ANSYS Workbench	53
3.24	Boundary condition and loading of the model; a) Fixed support b) Pressure	54

3.25	Project outline after selection of parameters	57
3.26	The workflow of MOGA method	60
3.27	The workflow of AMO method	62
3.28	Fabricated stiffened panel using AISI 200	63
4.1	Stress strain curve of aluminium at controlled temperature	66
4.2	Stress-strain curve of titanium at controlled temperature	66
4.3	Stress-strain curve of aluminium at 100°C	67
4.4	Stress-strain curve of aluminium at 200°C	68
4.5	Stress-strain curve of titanium at 200°C	69
4.6	Stress-strain curve of titanium at 500°C	69
4.7	Stress-strain curve of aluminium at - 30°C	70
4.8	Stress-strain curve of titanium at - 30°C	71
4.9	The effect of temperature on the yield strength of aluminium 2024-T3	72
4.10	The effect of temperature on the ultimate strength of aluminium 2024-T3	72
4.11	The effect of temperature on the elastic modulus of aluminium 2024-T3	73
4.12	The effect of temperature on the deformation of aluminium 2024-T3	73
4.13	The effect of temperature on the yield strength of titanium 6Al-4V	74
4.14	The effect of temperature on the ultimate strength of titanium 6Al-4V	74
4.15	The effect of temperature on the elastic modulus of titanium 6Al-4V	75

4.16	The effect of temperature on the deformation of titanium 6Al-4V	75
4.17	S-N curve of aluminium at room temperature	76
4.18	S-N curve of titanium at room temperature	77
4.19	S-N curve of aluminium at 100°C	79
4.20	S-N curve of aluminium at 200°C	79
4.21	S-N curve of titanium at 200°C	80
4.22	S-N curve of titanium at 500°C	81
4.23	S-N curve of aluminium at - 30°C	82
4.24	S-N curve of titanium at - 30°C	82
4.25	Comparison of fatigue life at various temperatures for aluminium 2024-T3	84
4.26	Comparison of fatigue life at various temperatures for titanium 6Al-4V	84
4.27	ANSYS and experimental result at room temperature for aluminium	85
4.28	ANSYS and experimental result at 100°c for aluminium	86
4.29	ANSYS and experimental result at 200°c for aluminium	86
4.30	ANSYS and experimental result at -30°C for aluminium	87
4.31	ANSYS and experimental result at room temperature for titanium	88
4.32	ANSYS and experimental result at 200°C for titanium	89
4.33	ANSYS and experimental result at 500°C for titanium	89
4.34	ANSYS and experimental result at -30°C for titanium	90

4.35	Sensitivity analysis results of screening method	91
4.36	Tradeoff chart for screening method; a) Stress versus life b) Mass versus life c) Stress versus mass	92
4.37	Sensitivity analysis by multi-objective genetic algorithm method	94
4.38	Tradeoff chart of the multi-objective genetic algorithm method; a) Stress versus life b) Mass versus life c) Stress versus mass	95
4.39	Sensitivity analysis by adaptive multi-objective method	97
4.40	Tradeoff chart of the adaptive multi-objective method; a) Stress versus life b) Mass versus life c) Stress versus mass	98
4.41	Stress intensity factor versus crack length	100
4.42	Cracks length versus fatigue life	101

LIST OF ABBREVIATIONS

ASME	American Society of Mechanical Engineers
CAD	Computer Aided Design
CNC	Computer Numerical Control
DOE	Design of Experiment
FCG	Fatigue Crack Growth
FEA	Finite Element Analysis
GB	Gigabyte
GDO	Goal Driven Optimization
LEFM	Linear Elastic Fracture Mechanic
MIL-HDBK	Military Handbook
MTS	Material Testing Machine
RAM	Random Access Memory
RSO	Response Surface Optimization
SENT	Single Edge Notch Tension
SIF	Stress Intensity Factor

LIST OF APPENDICES

Appendix		Page
A1	Tensile test results for aluminum 2024-T3	116
A2	Tensile test results for titanium 6Al-4V	117
B1	Example of Fatigue worksheet	118
B2	Fatigue test results at different temperature for aluminum 2024-T3	121
B3	Fatigue test results at different temperature for titanium 6Al-4V	144
C1	Fatigue simulation results aluminum 2024-T3	162
C2	Fatigue simulation results of titanium titanium 6Al-4V	166
D1	Specimen fracture after fatigue testing of aluminum 2024-T3	169
D2	Specimen fracture after fatigue testing of titanium 6Al-4V	176
E1	Raw optimisation data for screening	181
E2	Raw optimisation data for MOGA	184
E3	Raw optimisation data for AMO	188
F1	Drawing of aluminum 2024-T3 specimen	194
F2	Drawing of titanium 6Al-4V specimen	195
F3	Drawing of stiffened panel	196
F4	Drawing of SENT specimen	197
G1	Calculation of SIF and critical length	198
G2	Calculation of fatigue life based on crack growth model	202

CHAPTER 1

INTRODUCTION

1.1 Background

The fatigue damage mechanisms for structural components are influenced by temperature, fluctuating loads, time and manufacturing process (Bedowski, 2014; Batchelor, Lam, & Chandrasekaran, 2002). About 70% to 90% of mechanical failures during their operations are related to fatigue (Stephens et al., 2000). However, it is extremely rare for a fatigue failure incident in the aerospace industry (Weiss & Lavi, 2016). This is because, during the designing stage, finite element analysis (FEA) software is used to simulate real-life situations in whole or certain parts of aircraft structures. The conventional experimental method to obtain the fatigue life of the components takes quite the amount of time (Hussain, Abdullah, & Nuawi, 2016). FEA software is a tool that helps designers in solving mathematical and engineering problems numerically. The software covers the area of structural, fluid flow, heat transfer and electronics.

The service life of structures at elevated and low temperature is a major concern for researchers and industries. Components that are exposed to elevated temperature during fatigue loading changes the material behaviour (Szusta & Seweryn, 2018). The wear process speeds up and causes an increase in crack propagation. Also, the strength parameter decreases as the temperature increases (Tomczyk, Seweryn & Grądzka-Dahlke, 2018). In the meantime, at low temperature the fatigue crack growth rate decreases compared to room temperature (Zhao et al., 2020). The tensile properties of metal also improved at low temperature (Li et al., 2015; Nayan et al., 2014).
The stiffened panel consists of stiffeners reinforced to the plate. The structure can be manufactured by riveted, bonded joints or machining from thick plates into the shape (Michalcova & Ruzek, 2016). The panels subjected to various levels of loading and condition to investigate the service life (Sepe et al., 2015) and damage to discover the crack initiation (Giglio & Manes, 2008). The fatigue life can also be predicted from stress, strain data, fracture toughness and stress intensity factor (Cordes, 2001). In addition, the FEA method able to estimate the fatigue life when a certain crack length is introduced (Grbovic & Rasuo, 2012). The single edge notched tension specimen is one of the considerations in finding the fracture toughness and stress intensity factor (Moore & Hutchison, 2016; John, 2013).

For the past decades, varieties of optimization techniques have been developed in improving the fatigue life of aircraft structures. Different structural optimization problems are influenced by shape, size and topology as a design objective. The optimization that focuses on improving performance is more into modifying the shape of a structure or parameters that affect the shape (Bang et al., 2008). On the other hand, sizing optimization focuses on reducing weight, stress, and displacement of the structure. Selection of suitable types of structures for operating condition or problem faced is based on topology optimization (Zargham et al., 2016)

1.2 Problem Statement

The components in an engine are exposed to working condition related to fatigue and elevated temperature. The properties of high fatigue strength are required for the combined effects under this condition (Sivananth & Vijayarangan, 2015; Kamal & Rahman, 2015). The piston, heat exchanger and cylindrical head are components that experience these effects (Zhu et al., 2006). The mechanical failure linked to these components may affect the aircraft, safety of the crews and passengers (Krstic et al., 2016). Also, the fatigue analysis of different temperature is important as the collected data to be used in design and simulation to ensure structural safety in engineering application (Yarullin & Ishtyryakov, 2016).

The application of the stress-life (S-N) curve can be used to compare the results at various temperature levels (Hussain, Abdullah & Nuawi, 2016). It represents the applied stress and fatigue life which is widely used to study the behavior of the material. This curve is obtained from experimental method (Liu et al., 2007). However, the conventional method for collecting data for fatigue life is time consuming. FEA software makes it possible to plot the results of the S-N curve by using data stored in the database. Also, the critical areas leading to fatigue damage of the components can be predicted (Beden et al., 2010). As for the author's knowledge, there are limited studies related to predicting fatigue life at elevated and low temperature.

The single edge notched tension specimen can be used to determine the stress intensity factor and fracture toughness that points to the critical length. The presence of stress raisers comes from the manufacturing errors, fasteners holes and maintenance lead to the starts of crack initiation (Abdullah, Beden & Ariffin, 2011). The crack will propagate until it reaches the critical length and catastrophic failure occurs. Considering economic situations, not all components can be replaced when the cracks are detected. Hence, FEA software can be used to estimate the service life and replace the components on time.

The improvement of fatigue life of the stiffened panel is possible with the application of FEA software that comes with optimization features. The commonly used optimization methods in currently focused FEA software are screening, multi objective genetic algorithm and adaptive multi objective algorithm. The screening method is based on Hammersley algorithm that generate a large number of design points and sort them based on the objectives (Szweda & Poruba, 2010). The multi objective genetic algorithm is a much more refined approach as the design points evolve until the best Pareto set is formed. Still, the objectives involve a large number of functions and are expensive (Han & Zheng, 2020). The adaptive multiple objective algorithms may generate or use existing design points to approach the problem. This method does not analyze all design points but the results still closer than the screening method (Tho,Vu & Nghi, 2019). The experimental method consists of samples tested repeatedly under different groups and conditions. The simulation method is the recreation of an experimental procedure using numerical software. Hence, the development of combined experimental and simulation approaches to solve the arisen problem will be important in this research.

1.3 Research Objectives

Main objective

- ❖ To develop a combined experimental and simulation approach to predict fatigue life

Sub objectives

- ❖ To investigate the tensile properties of aluminium and titanium at controlled, elevated and low temperature
- ❖ To investigate the fatigue life of aluminium and titanium at controlled, elevated and low temperature
- ❖ To validate the fatigue life between experimental and simulation for aluminum and titanium

1.4 Scope of Study

The study focused on development of combined experimental and simulation approach to predict fatigue life. The tensile and fatigue test of aluminum Al 2024-T351 and titanium Ti–6Al–4V are conducted in controlled, elevated and low temperature. The fatigue tests will cover stress starting from 90% to 70% of the yield strength of both materials. The optimization methods of specific numerical software focusing on screening, multi-objective genetic algorithm and adaptive multi-objective algorithm to improve the fatigue life of the stiffened panel. The study will not cover the observation of the surface and scanning electron microscopy (SEM) of both materials. The thickness of the titanium Ti–6Al–4V specimen is different compared to Al 2024-T351 due to errors in the manufacturing process. The limitation to fabricate the stiffened panel is related to the connection between the stiffener and plate.

1.5 Thesis Layout

The thesis comprises five chapters. The first chapter is the introduction that includes background, problem statement, main and sub objectives and scope of the research. Chapter 2 is based on previous work of researchers from websites, journals, and books to find the lacking or contribution in the particular area. Chapter 3 consists of the methodology of the research and the steps taken to carry out the study. Chapter 4 focuses on the presentation of the raw results obtained from the experimental and numerical simulation. Discussions based on the findings are critically analyzed. Chapter 5 is the conclusion and recommendations for future work. The summary of the overall research, limitations, contribution and further improvements are written in this chapter.

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