NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

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STO TECHNICAL REPORT **TR-AVT-275**

Continuing Airworthiness of Aging Systems

(Navigabilité continue des systèmes vieillissants)

Final report on best practices and lessons learned for aircraft structural, propulsion, and mechanical systems safety and reliability. The report Annex, STO-TR-AVT-275-A, contains Chapters 10, 23, and 29.

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The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

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The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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Table of Contents

	Page
List of Figures	**xiii**
List of Tables	**xix**
List of Acronyms	**xxi**
Acknowledgements	**xxiii**
AVT-275 Membership List	**xxiv**
Executive Summary and Synthèse	**ES-1**
Part 1: Continuing Airworthiness Policies and Approaches	**1-i**
Chapter 1 – Continuing Airworthiness Policies (United States)	**1-1**
1.1 United States	1-1
1.1.1 Continuing Airworthiness	1-1
1.1.2 Risk Management	1-1
1.2 References	1-2
Chapter 2 – Continuing Airworthiness Program of the Royal Canadian Air Force (RCAF)	**2-1**
2.1 Introduction	2-1
2.2 Continuing Airworthiness (CAW)	2-1
2.3 In-Service Monitoring Program	2-1
2.4 Aging Aircraft Structural Assessment	2-2
2.5 Aging Aircraft Systems	2-2
2.6 Record of Airworthiness Risk Management (RARM)	2-3
2.7 Lessons Learned from the RCAF CAW Practice	2-5
2.8 References	2-5
Chapter 3 – Lessons from Aging Aircraft Systems Audits	**3-1**
3.1 Introduction	3-1
3.2 Aging Aircraft Regulatory Issues	3-2
3.2.1 Definition of Aging	3-2
3.2.2 Definition of the Aims of an Aging Aircraft Programme	3-2
3.2.3 Audit or Programme?	3-2
3.2.4 Streamlining the AAA Approach	3-2
3.2.5 Guidance for the Conduct of Aging Aircraft Programmes	3-2
3.2.6 The Requirement for On-Aircraft Condition Surveys	3-3
3.2.7 Safety Management Systems Foundations for Supporting an AAA	3-3
3.2.8 Validation of Emergency Systems Performance	3-3
3.2.9 Validation of Design and Usage Assumptions	3-4

3.3 Aging Aircraft Programme Conduct Issues 3-4
3.3.1 Pan-Organisation Support 3-4
3.3.2 Systems Sampling 3-4
3.3.3 Identification of Target Systems and Zones with Limited A Priori Information 3-5
3.3.4 System Performance Assessment 3-5
3.3.5 System Interconnection Issues 3-6
3.3.6 Risk-Based Reporting 3-6
3.4 Wider Airworthiness Issues 3-6
3.4.1 Electrical Wiring and Interconnection Systems (EWIS) Integrity 3-6
3.4.2 Fault Reporting and Corrective Action Systems 3-7
3.4.3 Configuration Control Systems 3-7
3.4.4 Corrosion of Systems Components 3-7
3.4.5 Polymer Degradation 3-8
3.5 Conclusions 3-8
3.6 Acknowledgements 3-8
3.7 References 3-9

Chapter 4 – European Union and NATO Military Aircraft Airworthiness Policy 4-1

4.1 Introduction 4-1
4.2 European Defence Agency (EDA) Military Airworthiness Policy 4-1
4.3 NATO Airworthiness Policy 4-3
4.3.1 NATO Airworthiness Policy Implementation Roadmap 4-4
4.4 Concept of Airworthiness Regulation for the NE-3A Fleet 4-6
4.4.1 Background of the Programme 4-6
4.4.2 NATO Airborne Early Warning and Control (NAEW&C) Airworthiness System 4-6
4.5 Summary 4-9
4.6 References 4-10

Chapter 5 – European Military Airworthiness Maintenance Requirements 5-1

5.1 Introduction 5-1
5.2 Continuing Airworthiness Responsibilities Related with Maintenance 5-1
5.2.1 Case 1 5-2
5.2.2 Case 2 5-2
5.2.3 Case 3 5-3
5.3 Aircraft Maintenance Programme (AMP) 5-5
5.4 Occurrence Reporting 5-9
5.5 Identification of Sources of Potential Problems Related to the Maintenance Process After the Implementation of EMAR 5-10
5.6 Conclusions 5-11
5.7 References 5-12

Part 2: Aircraft Structural Systems 2-i

Chapter 6 – Airworthiness of Structures (United States) 6-1

6.1 Introduction 6-1
6.1.1 Initial Airworthiness 6-1
6.1.2 Continued Airworthiness for Operations Up To ~50% SLL 6-2
6.1.3 Continued Airworthiness for Operations Approaching SLL 6-2
6.1.4 Continued Airworthiness for Operations Beyond SLL 6-2
6.1.5 USAF Aircraft Structural Safety Experience 6-3
6.2 References 6-3

Chapter 7 – Approach to Structural Risk Analysis (USAF) 7-1

7.1 Risk Analysis Background 7-1
7.2 Overview of Input Data for Risk Analysis 7-1
7.2.1 Normalized Stress Intensity Factor 7-2
7.2.2 Fracture Toughness 7-3
7.2.3 Initial Crack Size Distributions 7-3
7.2.4 Crack Growth Life Curve 7-3
7.2.5 Maximum Stress Per Flight 7-4
7.2.6 Initial and Recurring Inspection Intervals 7-4
7.2.7 Probability of Detection Curves 7-5
7.2.8 Probability of Inspection 7-5
7.2.9 Repair Strategies 7-5
7.3 Probability of Failure Calculation 7-5
7.4 Risk Analysis Output Interpretation 7-7
7.4.1 Sensitivity Analysis 7-7
7.5 Summary 7-8
7.6 References 7-8

Chapter 8 – Continuing Airworthiness of Structures (Canada) 8-1

8.1 Introduction 8-1
8.2 Historical Perspective 8-1
8.3 Aircraft Structural Integrity Monitoring Requirements 8-2
8.4 ASIP Gap Analysis 8-4
8.5 Structural Usage Monitoring 8-4
8.6 Structural Condition Monitoring 8-4
8.7 Aging Aircraft Structural Assessment 8-5
8.8 Future Challenges 8-6
8.9 References 8-6

Chapter 9 – Australian Structural Integrity Approach 9-1

9.1 Introduction 9-1
9.2 Initial Airworthiness 9-2
9.3 Continuing Airworthiness 9-3

9.3.1 Continuing Airworthiness for Initial Operations 9-4
9.3.2 Continuing Airworthiness for Operations Approaching the SLL 9-4
9.3.3 Continuing Airworthiness for Operations Beyond Original SLL 9-4
9.4 Enhanced Teardowns 9-5
9.5 References 9-5

Chapter 10 – Enhanced Wing Teardown in Support of F-16 Structural Life Management[1] **10-1**

10.1 Introduction 10-1
10.2 Structural Life Management of the RNLAF F-16 fleet 10-1
10.2.1 History 10-1
10.2.2 SLM Framework 10-1
10.2.3 Examples of In-Country SLM Activities 10-2
10.2.3.1 Individual Aircraft Tracking 10-2
10.2.3.2 NDI Technology Evaluation 10-4
10.2.3.3 Mishap Investigations 10-5
10.2.3.4 Assessment of New Fastener System 10-6
10.2.3.5 Teardown Inspections 10-8
10.3 Enhanced F-16 Block 15 Wing Teardown 10-9
10.3.1 F-16 Block 15 Wing Teardown Inspection @ 4,200 FH 10-10
10.3.2 F-16 Block 15 Wing Damage Enhancement Test and Subsequent Teardown 10-13
10.3.2.1 Load Introduction 10-14
10.3.2.2 Test Setup 10-14
10.3.2.4 Marker Loads 10-18
10.3.2.5 Test Campaign 10-19
10.3.2.6 Apparent Fatigue Cracking During the Test 10-20
10.3.2.7 Post-WDET Teardown Inspection 10-21
10.3.2.8 Quantitative Fractography 10-22
10.3.2.9 Economic Service Life of the RNLAF F-16 Block 15 Wing 10-26
10.4 Conclusion 10-27
10.5 Outlook 10-28
10.6 References 10-29

Chapter 11 – Implementation of the Aircraft Structural Integrity Program Principles for PZL-130 "ORLIK" TC-II Trainer Aircraft **11-1**

11.1 Introduction 11-1
11.2 Operation Load Monitoring 11-2
11.3 Load Spectrum Development 11-3
11.4 Full-Scale Fatigue Test (Including NDI Program) 11-4
11.5 Teardown Inspection (TI) 11-7
11.6 Individual Aircraft Tracking Program 11-8
11.7 References 11-8

[1] Chapter 10, "Enhanced Wing Teardown in Support of F-16 Structural Life Management" is located in "Continuing Airworthiness of Aging Systems: Annex" (STO-TR-AVT-275-A).

Chapter 12 – SU-22 Fighter-Bomber Aircraft Service Life Extension Programme Supported by Operational Load Monitoring Implementation 12-1

12.1 Introduction 12-1
12.2 Service Life Extension Program for SU-22 12-1
12.3 OLM System Design and Implementation On SU-22UM3K 12-3
12.4 In-Flight Load Determination 12-4
12.5 Summary 12-6
12.6 References 12-6

Chapter 13 – Aircraft Structural Integrity Management Activities in Finland 13-1

13.1 Introduction 13-1
13.2 In-Country Capabilities 13-1
13.3 ASIP Activities 13-2
13.4 Damage Tolerance and Lifing Policies 13-3
13.5 National R&D Activities 13-4
13.6 International Co-Operation 13-5
13.7 Conclusion 13-6
13.8 References 13-6

Part 3: Aircraft Propulsion Systems 3-i

Chapter 14 – Aircraft Propulsion Systems (United States) 14-1

14.1 Introduction 14-1
14.2 Historical Perspective 14-1
14.3 Advent of Propulsion System Integrity Program (PSIP) 14-2
14.4 Mechanical Integrity Requirements Overview 14-3
14.5 Continuing Airworthiness for USAF Propulsion 14-4
14.6 Summary 14-5
14.7 References 14-5

Chapter 15 – US Army Propulsion – Continuing Airworthiness 15-1

15.1 Executive Summary 15-1
15.2 Fundamental Approach 15-1
15.2.1 Drive Systems 15-3
15.2.2 Turboshaft Engines 15-3
15.2.3 T700 Life Management 15-4
15.3 Aviation Enterprise Programs 15-6
15.3.1 Quality Deficiency Report (QDR) 15-7
15.3.2 RIMFIRE 15-7
15.3.3 Engine Component Improvement Program (CIP) 15-8
15.3.4 Summary 15-8
15.4 References 15-8

Chapter 16 – Engine Structural Integrity Program (ESIP) 16-1
16.1 Introduction 16-1
16.2 Program Requirements 16-1
16.2.1 A Defined Program 16-1
16.2.2 At Regular Intervals 16-1
16.2.3 Reassess and Document Actual Usage Conditions 16-2
16.2.4 Compare Actual Usage Against Design Usage Conditions 16-2
16.2.5 Determine Life Consumption Based on Actual Usage (of Critical Components, as a Minimum) Accordingly 16-2
16.3 Other Requirements 16-3
16.3.1 Reliability Tracking 16-3
16.4 Outcomes 16-3
16.5 References 16-4

Chapter 17 – Aircraft Engine Structural Integrity Management Activities in Finland 17-1
17.1 Introduction 17-1
17.2 ENSIP Approach 17-1
17.3 Repair Development and Component Manufacturing 17-2
17.4 Experimental R&D Activities 17-2
17.5 Conclusion 17-4
17.6 References 17-5

Chapter 18 – Aging of Engine Structures 18-1
18.1 Engine Materials Failure Modes 18-1
18.2 Damage Tolerance Application Methodology for Aging Engines 18-5
18.3 References 18-9

Part 4: Aircraft Mechanical Systems, and Other Sub-Systems 4-i

Chapter 19 – Aircraft Mechanical Equipment and Subsystems 19-1
19.1 Introduction 19-1
19.2 Historical Perspective 19-1
19.3 Advent of Mechanical Equipment and Subsystems Integrity Program (MECSIP) 19-2
19.4 Mechanical Integrity Requirements Overview 19-3
19.4.1 Programmatic Issues 19-5
19.4.1.1 Aircraft Availability Cost 19-5
19.4.1.2 Database Accuracy 19-5
19.4.1.3 Serialized Component Tracking 19-5
19.4.2 Technical Issues 19-6
19.4.2.1 Life Prediction/History 19-6
19.4.2.2 Wiring Health 19-6
19.5 Maintenance/Sustainment for USAF Mechanical Equipment and Subsystems 19-6

19.6 Continuing Airworthiness for USAF Mechanical Equipment and Subsystems 19-7
19.7 Summary 19-7
19.8 References 19-7

Chapter 20 – Aircraft Mechanical Systems Integrity Program in Canada 20-1
20.1 Introduction 20-1
20.2 Historical Perspective 20-1
20.3 MSIP Overview and Applicable Systems 20-1
20.4 MSIP Methods of Compliance 20-2
20.4.1 Initial Aircraft Procurement Phase 20-2
20.4.2 In-Service Phase 20-3
20.4.3 ELE Extension Phase (if Applicable) 20-3
20.5 RCAF Fleets MSIP Reporting Requirements 20-4
20.6 Summary 20-4
20.7 References 20-4

Chapter 21 – Aircraft Mechanical Systems Integrity Management Activities in Finland 21-1
21.1 Introduction 21-1
21.2 In-Country Capabilities 21-1
21.3 MECSIP Approach 21-2
21.4 National R&D Activities 21-4
21.5 Conclusion 21-5
21.6 References 21-6

Chapter 22 – EWIS Monitoring Program in Canada 22-1
22.1 Background – Electrical Wiring Interconnect System (EWIS) Monitoring 22-1
22.1.1 Technical Airworthiness Manual Amendment 22-2
22.1.2 Compliance Guidance 22-3
22.1.3 Compliance Status 22-3
22.1.4 Training and Experience 22-3
22.1.5 Reporting 22-3
22.2 References 22-3

Chapter 23 – Life Extension of Tornado Aircraft Subsystems (Germany)[2] 23-1
Abstract 23-1
23.1 The Tornado Aircraft Programme 23-1
23.2 Organisations Involved in the Life Extension Programme 23-2
23.2.1 Panavia 23-2
23.2.2 NETMA 23-3
23.3 Workshare/Design Responsibilities 23-3

[2] Chapter 23, "Life Extension of Tornado Aircraft Subsystems (Germany)" is located in "Continuing Airworthiness of Aging Systems: Annex" (STO-TR-AVT-275-A).

23.4 Tornado Life Extension 23-6
23.4.1 Introduction 23-6
23.4.2 The Life Extension Certification Task 23-6
23.5 Applying the Four Phase Process for Certification 23-7
23.5.1 Phase A 23-7
23.5.1.1 Equipment 23-7
23.5.1.2 Supporting Structure 23-9
23.5.1.3 Panavia Standard Parts 23-9
23.5.2 Phase B 23-10
23.5.3 Phase C 23-11
23.5.4 Phase D 23-12
23.6 Examples of Work Performed During Phase C 23-12
23.6.1 Fuel System 23-12
23.6.1.1 System Schematic/Description and Work Breakdown 23-12
23.6.1.2 Interfaces 23-15
23.6.1.3 Failure Modes 23-15
23.6.1.4 Life Extension Measures 23-16
23.6.2 Secondary Power System (SPS) 23-25
23.6.2.1 System Schematic/Description and Work Breakdown 23-25
23.6.2.2 Interfaces 23-26
23.6.2.3 Failure Modes 23-26
23.6.2.4 Life Extension Measures 23-27
23.7 Summary/Outlook 23-32
23.8 References 23-33

Part 5: Summary on Best Practice and Lessons Learned 5-i

Chapter 24 – Best Practices Summary 24-1
24.1 Airworthiness Policy 24-1
24.2 Aircraft Structural Integrity Program (ASIP) 24-3
24.3 Propulsion Integrity 24-4
24.4 Mechanical Equipment and Subsystems Integrity 24-5
24.5 Summary 24-6
24.6 References 24-6

Part 6: Annex of Collection of Case Studies on Best Practice and Lessons Learned 6-i

Chapter 25 – Flow Control System Integration into the Substitute Models for Structural Components Loads Estimation Based on Flight Parameters and Statistical Inference Methods – MIG-29 Vertical Fin Use Case 25-1
25.1 Introduction 25-1
25.2 Determining Loads Applied to a Vertical Stabilizer of a Twin Tailed Aircraft 25-5
25.3 Summary 25-14
25.4 References 25-15

Chapter 26 – Su-22 FSFT Study Case and Mi-8 Hard Landing Test Study Case 26-1

26.1 Swept-Wing Jet Aircraft FSFT 26-1
26.1.1 Introduction 26-1
26.2 Service Life Extension Program 26-1
26.2.1 Summary of the Su-22 FSFT 26-3
26.3 Military Transport Helicopter Harsh Landing Test 26-3
26.3.1 Introduction to Transport the Helicopter Harsh Landing Case 26-3
26.3.2 Problem of Harsh Landings 26-4
26.3.3 Test Setup 26-4
26.3.4 Instrumentation 26-5
26.3.5 Release Mechanism 26-6
26.3.6 Drop Test Assumptions 26-6
26.3.7 Drop Test Execution 26-6
26.3.8 Test Summary 26-8
26.4 References 26-9

Chapter 27 – MiG-29 and F-16 Study Cases 27-1

27.1 Introduction 27-1
27.2 MiG-29 Study Case 27-1
27.3 F-16 Study Case 27-5
27.4 Conclusions 27-6
27.5 References 27-6

Chapter 28 – NDT Activities During Composite Bonded Repair of PL C-130E Wing Bottom Skin 28-1

28.1 Background 28-1
28.1.1 General 28-1
28.1.2 Bonded Repair 28-1
28.2 Workflow 28-2
28.2.1 Order of Work 28-2
28.2.2 Adaptation of the Procedure for NDT of Composite Bonded Repair 28-3
28.2.3 NDT Inspection 28-4
28.2.4 Comparison of NDT Results with Removed Patch 28-4
28.2.5 NDT Quality Control Procedure Development and Application 28-5
28.3 Summary 28-6
28.4 References 28-6

Chapter 29 – Corrosion Management Using Environmental Sensor Data[3] 29-1

29.1 Introduction 29-1
29.2 Approach to Use Corrosivity for Maintenance Scheduling 29-1

[3] Chapter 29, "Corrosion Management Using Environmental Sensor Data" is located in "Continuing Airworthiness of Aging Systems: Annex" (STO-TR-AVT-275-A).

29.3 Measurement of Corrosivity of the Environment 29-2
29.3.1 Measurement Approach 29-2
29.3.2 Sensor Suite 29-2
29.3.3 Measurement Setup 29-3
29.4 Measurement Locations 29-3
29.4.1 Airbase 29-3
29.4.2 Ship 29-3
29.4.3 Helicopter 29-4
29.5 Example of Re-Scheduling of Recommended Corrosion Inspection 29-4
29.6 Corrosivity Measurement Results 29-5
29.6.1 In-Service Measurement 29-5
29.6.2 Sensor Data and Corrosion Observations 29-7
29.6.3 Surface Contamination Effect 29-7
29.6.4 Conclusions from In-Service Measurements 29-8
29.7 Modelling of Corrosivity 29-8
29.8 Corrosion Modelling Results 29-9
29.8.1 Fitting of the Corrosion Model 29-9
29.8.2 Modelling Insights 29-10
29.9 Implications for Maintenance 29-11
29.9.1 Relative Humidity During Storage 29-11
29.9.2 Use of Dry Air Units 29-11
29.9.3 Sensor Data for Corrosion Maintenance Scheduling 29-11
29.10 Conclusions for Continued Airworthiness 29-11
29.11 References 29-12

Chapter 30 – Helicopter Blades Failures Modes 30-1
30.1 Helicopter Blades Failures Modes 30-1
30.2 Conclusions 30-7
30.3 References 30-7

Chapter 31 – Metallic Helicopter Blades Composite Repairs Study Case 31-1
31.1 Introduction 31-1
31.2 Construction and General Characteristics of Rotor Blade Loads in the Mi Family of Helicopters 31-1
31.3 Leading Edge Repair Technology 31-4
31.4 The Repair Technology of the Trailing Section 31-5
31.5 Technological Details of Repair 31-7
31.5.1 Drying Process 31-7
31.5.2 Preparation of Metal Surfaces Before Bonding 31-7
31.5.3 The Cure Cycle 31-8
31.6 Summary 31-9
31.7 References 31-9

List of Figures

Figure		Page
Figure 2-1	RCAF Airworthiness Risk Indices	2-4
Figure 2-2	Quantitative Hazard Probability	2-4
Figure 2-3	Snapshot of RARM Distribution for All RCAF Fleets	2-5
Figure 4-1	NE-3A Aircraft	4-6
Figure 5-1	Typical Sources for AMP Development	5-6
Figure 5-2	The Three Principal Sources of Non-Compliance with High and Moderate Safety Impacts Identified by the UK CAA During Audits	5-11
Figure 5-3	The Principal Sources of Non-Compliance Identified by PL CAA During Audits in Supervised Part-145 and CAMO Organisations	5-11
Figure 6-1	USAF Destroyed Aircraft Rates	6-3
Figure 7-1	Schematic for Projecting Crack Size Distribution as a Function of Flight Hours	7-1
Figure 7-2	POD Sensitivity Analysis for a Fatigue Critical Location	7-8
Figure 9-1	Defence Aviation Accidents 1980 − Present	9-2
Figure 10-1	Location of the Five IAT Strain Sensors in the F-16 of the RNLAF	10-2
Figure 10-2	Experimental Validation of the CSI Concept for the Lower Wing Skin at BL 120	10-3
Figure 10-3	One of the Test Specimens Used in the Assessment of Digital X-ray Application for Detecting Cracked F-16 Pre-Block 40 Wing Spars	10-5
Figure 10-4	Assessment of the Capability to Detect Cracked F-16 Pre-Block 40 Wing Spars Using One-Step Process Digital X-Ray Equipment at a Tilt Angle of 30°	10-5
Figure 10-5	Test Article and Test Setup Used in the Comparative Test Program	10-7
Figure 10-6	Examples of the Varying Installation Quality of the Two Fastener Systems	10-7
Figure 10-7	Workflow of the Enhanced F 16 Block 15 Wing Teardown Program	10-11
Figure 10-8	Schematic of Crack Opening Procedure	10-11
Figure 10-9	Root Area of Lower Wing Skin with Several NDI Indications	10-12
Figure 10-10	Crack Findings in RHS Wing at 4,200 FH	10-12

Figure 10-11	Hoisting of the Test Article Prior to Installation in the Test Rig	10-15
Figure 10-12	Wing Suspension in the Test Rig	10-15
Figure 10-13	Impression of the WDET Setup	10-16
Figure 10-14	Outline of the Process to Compute the Hydraulic Actuator Loads Spectrum	10-17
Figure 10-15	Validation of Flight Loads Computation Process	10-17
Figure 10-16	The Computed WDET Load Spectrum vs. the LM Generated Spectra for Two Different RNLAF Usage Spectra	10-18
Figure 10-17	Observed Fracture Surface Pattern for Marker Load Sequence #3	10-19
Figure 10-18	Composite Photograph that Shows the Wing Deflections During the Applied Up and Down Bending Limit Load Cases	10-20
Figure 10-19	Multi-Site Damage in Lower Wing Skin at BL 71.00 Rectangular Cutout	10-21
Figure 10-20	Crack Findings in LHS Wing at 18,200 FH	10-22
Figure 10-21	Fatigue Cracks Selected for Quantitative Fractography	10-24
Figure 10-22	Fractographic Analysis of the Lead Crack at the BL 71 Rectangular Cutout in the Lower Skin	10-25
Figure 10-23	Crack Growth Curves Derived from the Markers on the Fracture Surfaces	10-25
Figure 10-24	Use of the Lead Crack Fatigue Lifing Framework to Establish the Lower Limit on the Economic Service Life of the RNLAF F-16 Block 15 Wing Box	10-27
Figure 10-25	Required Stochastic and Deterministic Input Data for a Structural Risk Analysis	10-29
Figure 11-1	Scheme of Strain Gauge Location	11-2
Figure 11-2	Strain Gauges Installed on the Structure	11-3
Figure 11-3	FSFT Design and Actual Test Rig for the PLZ-13 Orlik Aircraft	11-5
Figure 11-4	Full-Scale Fatigue Test Progress Chart	11-6
Figure 11-5	Distribution of Damage Found Throughout the Structure and by Type of Damage	11-6
Figure 11-6	Example of Damage Found During the Test	11-7
Figure 11-7	Teardown Inspection of the PZL-130 TC-II Wing	11-7
Figure 12-1	Block Diagram of OLM System	12-3
Figure 12-2	Measurement Configuration of OLM System	12-4
Figure 12-3	Location of the Elements of OLM	12-5
Figure 12-4	Loads from Strain Gauges T1 and T4 During Typical Parts of the Flight	12-5
Figure 14-1	Propulsion Risk Process	14-5
Figure 15-1	Continued Airworthiness Process Flowchart	15-2

Figure 18-1	Probability of Failure in the Safe Life Approach	18-6
Figure 18-2	Schematic Representation of the Damage Tolerance Based Life Cycle Management Approach	18-7
Figure 18-3	Flow Diagram of the Damage Tolerance Assessment Algorithm	18-8
Figure 19-1	Steps Required for Completing the Five MECSIP Tasks	19-4
Figure 22-1	CC130 Damage	22-2
Figure 23-1	The Tornado Aircraft	23-2
Figure 23-2	Involved Organisations	23-4
Figure 23-3	Tornado Workshare – Manufacturing	23-5
Figure 23-4	Panavia Standard Parts Flow Chart	23-10
Figure 23-5	Fuel System Diagram Fuel Transfer System	23-13
Figure 23-6	Fuel System Diagram Engine Feed System	23-14
Figure 23-7	Fuel Cell Arrangement	23-16
Figure 23-8	Emergency Pump	23-17
Figure 23-9	Crossfeed Valve Assembly with Actuator	23-17
Figure 23-10	Double Ended Boost Pump	23-18
Figure 23-11	First Stage Pump	23-19
Figure 23-12	Fuel Cooled Oil Cooler	23-20
Figure 23-13	Air Cooled Fuel Cooler	23-21
Figure 23-14	Example of a Complex Pipe Arrangement	23-22
Figure 23-15	Pipe Inspection Results	23-23
Figure 23-16	Fuel System Coupling	23-24
Figure 23-17	Fuel System Coupling Inspection Results	23-24
Figure 23-18	Secondary Power System	23-25
Figure 23-19	Gearbox Arrangement	23-27
Figure 23-20	Auxiliary Power Unit	23-29
Figure 23-21	Cross Drive Shaft	23-30
Figure 23-22	SPS Control Unit	23-31
Figure 23-23	PTO Shaft	23-32
Figure 25-1	Examples of Load Modes of Failure	25-1
Figure 25-2	Two Modes of Beam Bending	25-2
Figure 25-3	Strain Gauges Readings for Two Modes of Bending as Defined in Figure 25-2	25-3
Figure 25-4	Strain Gauges Readings for Successive Bending in Mode 1 and Mode 2 for Strain Gauges A and B	25-4
Figure 25-5	Load Values for Successive Bending: Force in Y-Direction and Z-Direction	25-4
Figure 25-6	First and Second Canonical Parameters for Successive Bending in Mode 1 and Mode 2	25-4

Figure 25-7	A Scheme of MiG-29 Aircraft	25-5
Figure 25-8	Location of a Selected Strain Gauge Used for Loads Monitoring of MiG-29 Vertical Stabilizer	25-6
Figure 25-9	Example of Strain Gauge of OLM System	25-7
Figure 25-10	Examples of Normalized Strain Records from Strain Gauge and Canonical Flight Parameter for Steady and High Manoeuvre Flights	25-7
Figure 25-11	Example of CFD Computation for a Particular Flight Configuration	25-11
Figure 25-12	Example of the Aerodynamic Force Distribution on the Surface of the Stabilizer Based on CFD Computations	25-12
Figure 25-13	Vertical Stabilizer of the Aircraft with Indication of the Axis with Respect to which Bending Momentum is Computed	25-13
Figure 25-14	Examples of Normalized Records of Strain Gauge, Canonical Flight Parameter and Bending Momentum for Steady and High Manoeuvre Flights	25-14
Figure 26-1	Test Object Sukhoi Su-22 UM3K Fitter	26-1
Figure 26-2	The Test Rig of the Su-22 UM3K Full-Scale Fatigue Test	26-2
Figure 26-3	Mi-8 Hip Helicopter – Gantry Rail Test Set Up with Release Mechanism	26-4
Figure 26-4	Mi-8 Hip Helicopter – Instrumentation Location	26-5
Figure 26-5	Fast Camera Markers	26-7
Figure 26-6	Sequence of Events During Drop	26-7
Figure 26-7	Sample of Accelerations Overview for ~0.5 m Drop Test	26-8
Figure 26-8	Helicopter Before Release and at Maximum Strut Compression	26-8
Figure 27-1	MiG-29 Vertical Stabilizer Automated NDT Inspection	27-2
Figure 27-2	TOF C-Scan of a MiG-29 Vertical Stabilizer	27-3
Figure 27-3	Large Delamination Along Longeron of MiG-29 Vertical Fin	27-3
Figure 27-4	Foreign Object Inclusion (Embedded) in MiG-29 Vertical Fin	27-4
Figure 27-5	Distribution of Disbonds in the MiG-29 Vertical Stabilizer	27-4
Figure 27-6	F-16 Horizontal Fin Ultrasonic Inspection and Shearography Inspection	27-5
Figure 27-7	Amplitude C-Scan F-16 Horizontal Stabilizer	27-5
Figure 27-8	Amplitude and TOF C-Scan F-16 Horizontal Stabilizer with Damage Presence	27-6
Figure 28-1	Bonded Repair Corrosion Grind-Outs	28-1
Figure 28-2	Order of Work	28-2
Figure 28-3	Reference Specimen Prepared for Apply BFRP Patch	28-3
Figure 28-4	BFRP Patch Prepared for Apply	28-3
Figure 28-5	Void Trapped Between Patch and Wing Skin	28-3

Figure 28-6	Flaw Indication and Temperature Profile Plotted for Blue Line	28-4
Figure 28-7	Adhesive Layer After Patch Removing, with Evidence of Voids and Areas Without Bonding	28-4
Figure 28-8	Inspection Using MOI 308 TDF	28-5
Figure 28-9	Thermography Result	28-5
Figure 29-1	Luna Inc. LS2A Corrosivity Sensor	29-2
Figure 29-2	Indication of Sensor Location on the Helicopter	29-4
Figure 29-3	Cumulative Mass Loss and Corrosion Rate Measurement Results During Two Anti-Piracy Missions	29-6
Figure 29-4	Comparison of Cumulative Mass Loss and Corrosion Rate Measurement Results of Two Anti-Piracy Missions	29-6
Figure 29-5	Corrosion Rate at the Ship's Flight Deck and at the Naval Air Station	29-6
Figure 29-6	Solution Resistance vs. RH for Outdoor Exposed Sensors and Helicopter Exposed Sensors	29-7
Figure 29-7	Wetness Factor with Hysteresis Between RH = 40% and RH = 70%	29-9
Figure 29-8	Cumulative Corrosion as Measured with the Sensors and Calculated with the Model for Sensors Exposed in Helicopters and Indoors, Showing a Reasonable Goodness-of-Fit	29-10
Figure 29-9	Cumulative Corrosion as Measured with the Sensors and Calculated with the Model for Sensors Exposed Outdoors, Showing a Reasonable Goodness-of-Fit	29-10
Figure 30-1	Percentage Use of HSL	30-2
Figure 30-2	Percentage Share of Various Failure Modes	30-2
Figure 30-3	Spar Cross-Section	30-4
Figure 30-4	Crack in the Spar	30-4
Figure 30-5	Crack in the Spar	30-4
Figure 30-6	MOI Crack Visualization	30-5
Figure 30-7	X-Ray Results	30-6
Figure 30-8	Specimen with Disbonds	30-6
Figure 30-9	MIA Testing Results	30-6
Figure 30-10	MRB In-Service Inspection	30-7
Figure 31-1	Cross-Section of the Mi-2's Metal Rotor Blade	31-1
Figure 31-2	Scheme of Helicopter Rotor Blade Loads	31-2
Figure 31-3	Damage Types in Mi Metal Rotor Blades	31-3
Figure 31-4	Strength Testing of the Bonding Join on the Leading Edge	31-4
Figure 31-5	Repair of the Leading Edge	31-4
Figure 31-6	Repair Technology of Disbonding Between Skin Trailing Section and Spar	31-5

Figure 31-7	Repair Technology of Cracks in a Skin's Section and Puncture of a Skin's Sections	31-6
Figure 31-8	Repair Technology of Dented Trailing Section	31-6
Figure 31-9	The Section with Repairs	31-6
Figure 31-10	The Drying Equipment of the Structure	31-7
Figure 31-11	Water – Boiling Points at Vacuum Pressure	31-7
Figure 31-12	Surface Preparation for Bonding and Type of Failure During Wedge Test (ASTM D3762) of the Joint Subjected to 100% Humidity Exposure	31-8
Figure 31-13	Example of the Cure Cycle Curve	31-8
Figure 31-14	Schema of Device and Vacuum Bag During Cure Cycle of Patch	31-9

List of Tables

Table		Page
Table 4-1	List of Current MAWA Forum Airworthiness Documents and Requirements	4-2
Table 4-2	NATO Recognition Process Steps	4-5
Table 4-3	NATO Recognition Process Status Updated for September 2018	4-5
Table 5-1	Selected Cases of OO vs CAMO vs AMO Arrangements According to EMAR M Provisions Source: Author's Own Study	5-2
Table 5-2	Release to Service of NDT Tasks by EMAR 145 Organisations	5-4
Table 5-3	RCM vs S4000P vs MSG-3 Comparison	5-7
Table 5-4	Reliability Quantitative Parameters and Alarm Levels for Components, Engines and APU	5-8
Table 5-5	EMAR's Occurrence Reporting Requirements	5-10
Table 7-1	Input Data for Risk Analysis	7-2
Table 7-2	USAF Airworthiness Risk Assessment Matrix	7-7
Table 8-1	Summary of RCAF Aircraft Structural Lifing Policies, Original and Current	8-2
Table 10-1	Definition of the Marker Load Sequences	10-19
Table 10-2	Crack Findings in LHS wing at 18,200 FH	10-21
Table 15-1	LCF Engine Test Cycle	15-5
Table 18-1	Failure Modes and Life-Limiting Properties for Turbine Engine Components	18-1
Table 19-1	List of All MECSIP Systems	19-3
Table 23-1	Number of Aircraft Delivered	23-5
Table 23-2	Tornado Design Responsibilities	23-6
Table 23-3	Equipment Safety Classification	23-7
Table 23-4	Safety Relevance	23-8
Table 23-5	Phase A Flow Diagram	23-9
Table 23-6	Phase B Flow Diagram	23-11
Table 23-7	Phase C Flow Diagram	23-12
Table 25-1	Frequency of Occurrences of Peaks and Valleys of the Nozzle Term	25-8
Table 26-1	Suggested Landing Regimes	26-6

Table 27-1	Information about NDT Techniques Used and Their Capabilities	27-1
Table 29-1	Sensors and Measurement Techniques Used in the LS2A Sensor Suite	29-3
Table 30-1	Information about MRB Used in Polish Air Force	30-1

List of Acronyms

AELEV-MIL	Aero-elastic simulation tool for the lifing of military aircraft (Dutch acronym)
ASIP	Aircraft Structural Integrity Program
BL	Butt Line
CFD	Computational Fluid Dynamics
cgFEM	coarse grid Finite Element Model
CLASS	Computer aided Loads/Stress Sequencing
CSI	Crack Severity Index
CVM	Comparative Vacuum Monitoring
DADTA	Durability and Damage Tolerance Analysis
DOF	Direction Of Flight
DSG	Design Service Goal
DSTG	Defence Science and Technology Group
EC	Eddy Current
EIDS	Equivalent Initial Damage Size
EPAF	European Participating Air Forces
EPS	Equivalent Pre-Crack Size
EOL	End Of Life
FACE	Fatigue/Air Combat Evaluation system
FEA	Finite Element Analysis
FEM	Finite Element Model
fgFEM	fine grid Finite Element Model
FH	Flight Hours
FS	Fuselage Station
FSMP	Force Structural Maintenance Plan
fwd	forward
g	gravity
GE	General Electric Measurement and Control
IAT	Individual Aircraft Tracking
INBD	Inboard
LCO	Limit Cycle Oscillations
LEF	Leading Edge Flap
LEFRA	Leading Edge Flap Rotary Actuator
L/ESS	Loads/Environment Spectrum Survey
LHS	Left Hand Side
LM	Lockheed Martin Aeronautics Company
lwr	lower
-MIL	Lifing of Military Aircraft (Dutch acronym)
mm	millimetre
MPa	MegaPascal
MSR	Mechanical Strain Recorder
M(T)	Middle Tension (fatigue test specimen)

NASM	National Aerospace Standard/Military
NDI	Non-Destructive Inspection
NI	Neutral Interface
NLR	Royal Netherlands Aerospace Centre
N_z	Normal acceleration (vertical)
OEM	Original Equipment Manufacturer
QF	Quantitative Fractography
RNLAF	Royal Netherlands Air Force
RHS	Right Hand Side
SHM	Structural Health Monitoring
SIF	Stress Intensity Factor
SLM	Structural Life Management
SLR	Stress to Loads Ratio
SRA	Structural Risk Analysis
TAAI	Teardown Additional Areas of Interest
TBAI	Teardown Basic Areas of Interest
USAF	United States Air Force
VA	Variable Amplitude (loading)
WAB	Wing Attachment Beam
WAF	Wing Attachment Fitting
WDET	Wing Damage Enhancement Test

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Continuing Airworthiness of Aging Systems

(STO-TR-AVT-275)

Executive Summary

Due to high procurement costs associated with replacing aging aircraft fleets, NATO Nations are frequently required to operate their aircraft for longer than the original design life. Because of the extended life requirements and the fact that aircraft have likely flown more severely than designed, aging aircraft issues are a significant problem when it comes to maintaining the airworthiness of these aircraft. Given the unique situation each NATO nation experiences because of the different operational environments, maintenance procedures and flight envelopes, an opportunity exists for the various nations to share their best practices relating to ensuring the airworthiness of aging aircraft systems within this Task Group.

A workshop, AVT-222, was held in October 2015 at which time various NATO nations made presentations on how they were ensuring the safety of aging aircraft (airframe and systems). The results from the workshop highlighted the aging aircraft issues, which the nations are experiencing, that are seriously impacting aircraft airworthiness and availability. At the conclusion of the workshop, it was agreed that a focus on common maintenance airworthiness issues would help in strengthening the Maintenance Organizations' ability to meet airworthiness requirements. AVT-275 was created to fulfil this role.

The objective of this Task Group was to develop a technical report containing the best practices and lessons learned that exist in NATO nations for aircraft structural, propulsion, and mechanical systems. The documented best practices on continuing airworthiness of aging aircraft systems aim at capturing the unique aptitudes that have developed in each participating nation. With these documented practices, the different NATO nations will be able to adopt them as they see appropriate. This has the potential to decrease the cost of maintaining aging aircraft systems since the procedures/processes have already been developed by other nations.

The main topics of this report include:

a) General continuing airworthiness management policy/approach;

b) Aircraft structural systems;

c) Propulsion systems; and

d) General aircraft systems including Mechanical sub-systems, Avionics sub-systems, etc.

The primary motivation is that NATO Nations have similar methods (design criteria, analysis, testing, usage monitoring, aircraft damage surveillance, etc.) and results (acceptable mishap rates and tolerable experience associated with discovering unanticipated issues that must be corrected) for ensuring continuing airworthiness for the aircraft structure; but that there is a diverse approach with mixed results for safety-critical systems in various NATO military aircraft. Conversely, key differences in how some Nations sustain aircraft may lead to modifications in what should be done for other safety-critical systems, for example safe-life approach, and factors used for safety-by-inspection.

Aircraft structural systems have the most developed integrity program, with Propulsion systems well-defined and becoming matured. Mechanical systems are progressing, but many lessons from structural and propulsion integrity programs could be used to further mechanical systems integrity program efforts.

Employing aircraft structures-like methods may improve the overall aircraft continued airworthiness, especially at or beyond the original service life limit.

Navigabilité continue des systèmes vieillissants
(STO-TR-AVT-275)

Synthèse

Le coût d'acquisition élevé associé au remplacement des parcs d'aéronefs vieillissants oblige fréquemment les pays de l'OTAN à exploiter leurs aéronefs plus longtemps que la durée de vie théorique. À cause du prolongement de la durée d'exploitation et du fait que les appareils ont probablement connu des conditions de vol plus difficiles que prévu, les problèmes des aéronefs vieillissants sont un sujet important dès lors qu'il s'agit de maintenir la navigabilité. Étant donné la situation unique de chaque pays de l'OTAN, en raison des différences d'environnements opérationnels, de procédures de maintenance et de domaines de vol, les divers pays ont l'opportunité de partager au sein de ce groupe de travail leurs meilleures pratiques relatives au maintien de la navigabilité des systèmes d'aéronefs vieillissants.

Un séminaire, l'AVT-222, s'est tenu en octobre 2015, pendant lequel divers pays de l'OTAN ont fait des présentations sur leur façon d'assurer la sécurité des appareils vieillissants (cellules et systèmes). Les résultats du séminaire ont mis en lumière les problèmes que les pays rencontrent avec les aéronefs vieillissants et qui entament gravement la navigabilité et la disponibilité des appareils. Lors de la conclusion du séminaire, il a été convenu qu'il serait utile de faire le point sur les problèmes courants d'entretien de la navigabilité, pour renforcer la capacité des organisations de maintenance à respecter les exigences de navigabilité. L'AVT-275 a été créé dans ce but.

L'objectif de ce groupe de travail était de rédiger un rapport technique contenant les meilleures pratiques et les enseignements des pays de l'OTAN en matière de systèmes de propulsion et de systèmes structurels et mécaniques. Les meilleures pratiques documentées sur la navigabilité continue des systèmes d'aéronefs vieillissants visent à rendre compte des aptitudes uniques développées par chaque pays participant. Les différents pays de l'OTAN seront ainsi en mesure d'adopter ces pratiques s'ils les jugent adéquates. Cela est susceptible de réduire le coût de maintenance des systèmes d'aéronefs vieillissants, puisque les procédures/processus ont déjà été élaborés par d'autres pays.

Les principaux sujets de ce rapport sont les suivants :

a) Politique/démarche générale de gestion de la navigabilité continue ;

b) Systèmes structurels des aéronefs ;

c) Systèmes de propulsion ; et

d) Systèmes généraux des aéronefs, incluant les sous-systèmes mécaniques, d'avionique, etc.

La principale motivation est que les pays de l'OTAN ont des méthodes (critères de conception, analyse, essais, suivi de l'usage, surveillance des avaries, etc.) et des résultats (taux d'accident admissibles et expérience tolérable associée à la découverte de problèmes non anticipés qui doivent être corrigés) similaires pour assurer la navigabilité continue de la structure de l'aéronef, mais que l'approche des systèmes critiques sur le plan de la sécurité diffère, avec des résultats mitigés dans divers aéronefs militaires de l'OTAN. À l'inverse, des différences essentielles d'entretien des aéronefs dans certains pays pourraient modifier les interventions à mener sur d'autres systèmes critiques sur le plan de la sécurité, par exemple la démarche de vie sûre et les facteurs utilisés pour la tolérance de détérioration.

Les systèmes structurels des aéronefs disposent du programme d'intégrité le plus développé, avec des systèmes de propulsion bien définis et arrivant à maturité. Les systèmes mécaniques progressent, mais de nombreux enseignements des programmes d'intégrité structurelle et de la propulsion pourraient faciliter les travaux des programmes d'intégrité des systèmes mécaniques. L'utilisation de méthodes semblables à celles appliquées aux structures d'aéronefs pourrait améliorer la navigabilité continue globale des aéronefs, en particulier à la fin de la durée de vie théorique ou au-delà.

Part 1: CONTINUING AIRWORTHINESS POLICIES AND APPROACHES



Chapter 1 – CONTINUING AIRWORTHINESS POLICIES (UNITED STATES)

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1.1 UNITED STATES

The United States Air Force (USAF) has numerous written policies and instructions that establish requirements for aircraft development, production, and sustainment phases. The overall policy is titled Integrated Life Cycle Management and requires the acquisition chain of authority to apply standard systems engineering processes and practices to ensure the integrity, mission assurance, operational safety, suitability, and effectiveness of each system throughout the life cycle from concept development through disposal. More specifically, the policy requires the acquisition chain of authority to apply integrity programs to weapon systems and it cites the Standards and Handbooks that establish the detailed requirements [1].

1.1.1 Continuing Airworthiness

The USAF has issued written policy and instruction that establishes the requirements for formal airworthiness assessments to ensure that USAF operated aircraft are airworthy over their entire life cycle and maintain accepted levels of safety. An important aspect of the USAF policy is that it establishes the requirement for an independent technical airworthiness authority (outside the acquisition chain authorities) to make airworthiness determinations and issue flight certifications and authorizations [2]. The original USAF airworthiness certification requirements were primarily aimed at initial airworthiness certification only. A significant change was made in 2009 when the inclusion of service life limits in aircraft airworthiness certificates was mandated for all existing and future aircraft. This requirement led to the inclusion of additional airworthiness certification requirements, most notably in the aircraft structures section of the Airworthiness Certification Criteria Handbook [3].

The USAF airworthiness process requires a continual evaluation of fielded aircraft throughout their life cycle to ensure that all aircraft are in a condition for safe operation, i.e., that they have not exceeded the approved service life limit, that environmental (e.g., corrosion) or other factors have not degraded airworthiness, that aircraft are properly maintained in accordance with approved maintenance documentation, and the aircraft are operated in accordance with the approved flight manual within the approved mission usage. The USAF recognizes that the initial service life limit is not a fixed value and the airworthiness process includes procedures for determining service life extension potential and for executing a service life extension program when desired and practical [4].

1.1.2 Risk Management

Risk management is an integral part of USAF system safety and aircraft airworthiness. The USAF has established a formal airworthiness risk assessment and acceptance process for any non-compliance with applicable airworthiness certification criteria. The process includes identifying the potential safety hazard associated with the non-compliance and the corresponding probability of occurrence (probability level) and the consequence (severity category). Of these three ingredients for a risk assessment (hazard, probability, and consequence), estimating the probability of occurrence is typically the most challenging. After completion of the risk assessment and approval of the risk categorization by the technical airworthiness authority, the risk must be accepted by the appropriate risk acceptance authority prior to the issuance of a flight certification or authorization [5].

1.2 REFERENCES

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Chapter 2 – CONTINUING AIRWORTHINESS PROGRAM OF THE ROYAL CANADIAN AIR FORCE (RCAF)

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2.1 INTRODUCTION

This chapter presents a brief summary of the Royal Canadian Air Force (RCAF) continuing airworthiness (CAW) program including the major/unique features of the RCAF CAW policy/approach. It also provides the latest RCAF references related to the RCAF CAW program, as well as the lessons learned and future challenges/gaps.

Under the provisions of the Aeronautics Act, the Canadian Minister of National Defence (MND) is responsible for military aviation, including foreign aircraft within Canada. Under the Aeronautics Act, the MND delegates powers and responsibility to the Airworthiness Authority (AA), Technical Airworthiness Authority (TAA), Operational Airworthiness Authority (OAA), and Airworthiness Investigative Authority (AIA). Among them, the TAA is responsible for the regulation of the technical airworthiness aspects of design, manufacture, maintenance and material support of aeronautical products and the determination of the airworthiness acceptability of those products prior to operational service. The technical airworthiness program, which is outlined in the Technical Airworthiness Manual (TAM) [1], consists of three primary elements: Initial Airworthiness, Continuing Airworthiness, and Disposal. Initial Airworthiness includes the processes and activities necessary to ensure that aeronautical products are airworthy (including Type Certification and Equipment Certification), prior to their introduction into service.

2.2 CONTINUING AIRWORTHINESS (CAW)

Continuing airworthiness involves those activities necessary to ensure that aeronautical products continue to meet the appropriate airworthiness rules and standards throughout their operating life. Continuing airworthiness is an integral part of the day-to-day management and monitoring of an approved type design and the associated aeronautical products after a type certificate has been issued. Compliance with airworthiness standards during the in-service period ensures that the initial inherent safety of the approved type design and the actual aeronautical products are maintained throughout the product life cycle. The framework of the RCAF CAW includes:

1) Conduct and control of maintenance;
2) Design change certification;
3) In-service configuration management; and
4) In-service monitoring program.

2.3 IN-SERVICE MONITORING PROGRAM

A key element of the Department of National Defence's (DND) CAW requirement is for an In-service Monitoring Program (ISMP). As a minimum the ISMP covers the monitoring activities for airworthiness directives, service bulletins, flight safety occurrences, other operator experiences and aircraft usage and condition monitoring.

Under the aircraft usage and condition monitoring, the TAM stipulates that there shall be processes for monitoring the condition of the Aircraft Structure, Mechanical Systems, Propulsion Systems and Aircraft Electrical Wiring Interconnection Systems. While the requirement to monitor the condition of the Aircraft Structure has been included in the TAM from the beginning, it was only in November 2015, with the release of Change 7 of the TAM, were Annexes for monitoring of Mechanical Systems, Propulsion Systems and Aircraft Electrical Wiring Interconnection Systems populated.

2.4 AGING AIRCRAFT STRUCTURAL ASSESSMENT

DND initiated discussion with respect to an Aging Aircraft Maintenance Program in 2002. After assessment of the Aircraft Structural Integrity Programs in place for the Royal Canadian Air Forces (RCAF) aircraft fleets and review of other military air forces approaches an aging aircraft policy was drafted. This draft policy was circulated to the RCAF fleet operators and maintainers for their input and assessment of impact on the maintenance program.

The requirement for an Aging Aircraft Assessment (AAA) was initially introduced under the aircraft usage and condition monitoring requirement in June 2012 with release Change 6 of the TAM. At that time it was to apply to aircraft structures and systems. However, at Change 6 of the TAM, the Annexes describing the monitoring requirement for the Mechanical Systems, Propulsion Systems, and Aircraft Electrical Wiring Interconnection Systems had not been populated. As all of the AAAs activities at DND were related to the aircraft structure, Change 7 of the TAM only included the detail requirements specified for an Aging Aircraft Structural Assessment (AASA).

The AASA is to be carried out no later than 15 years after the production of the first aircraft delivered to the RCAF. As of Dec 2017, all of the RCAF fleets that have passed the 15 year mark have undergone an AASA. The approaches taken to perform the AASA has differed based on the fleet and the Aircraft Structural Integrity Program (ASIP) for the fleet. For the fleets that pronominally follow a civilian role, such as the CC144 (Bombardier Challenger CL601/604 variants) and CC150 (Airbus A310), AASA relied heavily on the work done by the Original Equipment Manufacturer (OEM) under the Federal Aviation Administration (FAA) mandated program for Aging Airplane Safety [2]. For the predominately military role fleets, a combination on physical audit and review of the structural maintenance records were performed as part of the AASA.

The level of effort to perform the AASAs was largely dependent on the strength of the ASIP for the fleet in question. Fleets that had a strong ASIP required little effort to perform the AASA as there was already very good documentation on the actual usage and physical condition of the airframe. Overall, the RCAF fleets are well maintained and no significant issues were raised during the AASAs. This is largely due to having healthy ASIPs for the RCAF fleets. This is not to say that some of the aircraft did not have corrosion issues, but these were already being monitored and addressed as part of the ASIP.

2.5 AGING AIRCRAFT SYSTEMS

DND currently has no plan to have a unique AAA activity for Mechanical Systems, Propulsion Systems and Aircraft Electrical Wiring Interconnection Systems. Instead, for these systems the requirement to address the effects of aging is built into their respective integrity monitoring requirements. The key source used for identifying aging concern is the maintenance records. Guidance material is currently under development for these systems.

2.6 RECORD OF AIRWORTHINESS RISK MANAGEMENT (RARM)

The RCAF TAA has established a Technical Airworthiness Risk Management, which is not only a qualitative decision-making tool but also a quantitative tool used to assist individuals in making informed risk management decisions. The key document in the process of managing airworthiness risk is identified as the Record of Airworthiness Risk Management (RARM) [1]. The use of a RARM is predominantly associated with the in-service phase of an aeronautical product as other methods are available to manage risk during the certification process. The RARM process was designed to cover the airworthiness for all aircraft systems, i.e., hydraulics, structural, mechanical, avionics, etc. Both qualitative and quantitative risk indexes are defined in an RARM document. In a quantitative manner, a hazard probability (or Probability Of Failure, POF) threshold per flight hour is used to define a risk index. In practice, the RCAF first intention is always to conduct a quantitative risk assessment; when there are not enough data, a qualitative risk assessment is performed using more engineering judgement.

The RCAF RARM process includes five steps for risk management, i.e., Hazard Identification, Risk Assessment, Risk Control, RARM Approval, and Risk Tracking [1], which are briefly defined as:

1) Hazard Identification. Identifies the potential mishaps to an aeronautical product that may arise from a particular root cause in conjunction with possible hazard conditions;
2) Risk Assessment. Identifies the level of risk by taking into consideration the severity and probability of occurrence of the potential hazard;
3) Risk Control. Identifies the options that are available to eliminate, reduce and/or mitigate the assessed risk and the rationale for the selection of the recommended options;
4) RARM Approval. Identifies the requirement for specific authorized individuals to approve a RARM dependent on the level of risk identified. Describes the approval responsibilities, which include verifying the technical airworthiness content and ensuring that risk management procedures were followed; and
5) Risk Tracking. Identifies measures to ensure the RARM is appropriately documented and that risk control measures are implemented and monitored for effectiveness.

In the RARM, a key airworthiness risk index, defined as in Figure 2-1, is measured by a product combining both Hazard Severity and Hazard Probability. The risk index definitions are aligned with other military and civil standards including FAA/JAR 25-1309, AC 25-1309, SAE ARP 4761, and MIL-STD-882. Detailed definitions for the Hazard Severity, i.e., Catastrophic (A), Hazardous (Severe Major) (B), Major (C), Minor (D), and Negligible (E), are documented in Ref. [1]. Detailed definitions for qualitative Hazard Probability (Probability of Occurrence), i.e., Frequent (Level 1), Probable (Level 2), Remote (Level 3), Extremely Remote (Level 4), and Extremely Improbable (Level 5), are also documented in Ref. [1]. The corresponding quantitative Hazard Probability Thresholds (HPT) per flight hour, such as 10-3, 10-5, 10-7, or 10-9, are presented in Figure 2-2. Note that the HPT defined in Figure 2-2 also depends on the type of RCAF aircraft platforms, such that an aircraft carrying passengers will require lower HPT than an unmanned air vehicle.

The RARM process has affected all RCAF fleets (DND-AD-2007-01), covering all the airworthiness and safety-related aircraft systems including hydraulics, structural, mechanical, avionics, etc. [3]. Today, the RARM has become the single most critical decision-making tool for the RCAF air fleet management [4]. When there are sufficient data available, a quantitative risk assessment can be performed to substantiate the assignment of a risk index number. When a qualitative risk assessment indicates a high or medium risk, a detailed quantitative risk assessment is often requested to calculate the hazard probability, i.e., the single flying hour probability of failure, to gain additional confidence in the decision making. In practice, the RCAF's first intention is always to conduct a quantitative risk assessment; when there are not enough data, a qualitative risk assessment is performed supported by engineering judgement [4].

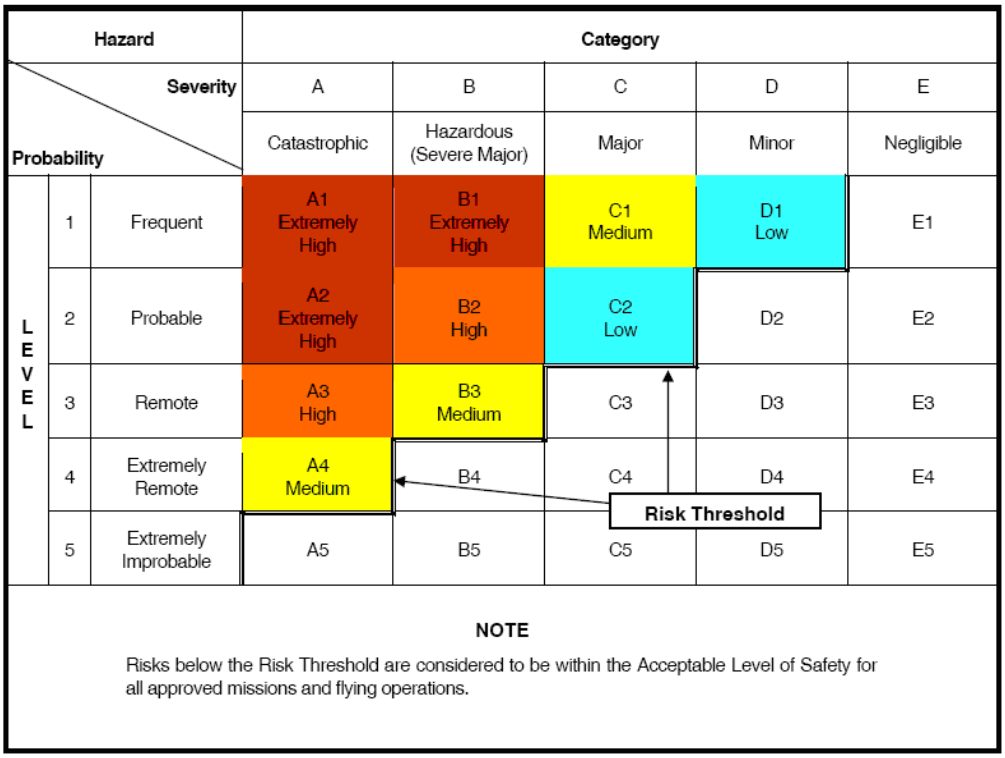


Figure 2-1: RCAF Airworthiness Risk Indices [1].

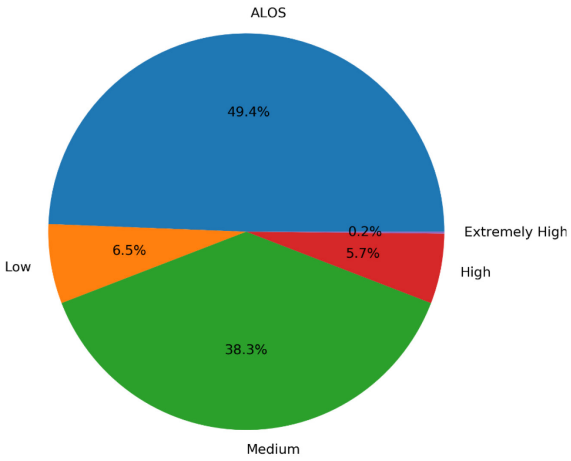
Hazard Probability Level	Hazard Probability Thresholds (Per Flight Hour)			
	DND Passenger Carrying Aircraft *(Derived from FAR 25/29 Civil Designs)*	Military Aircraft		
		Military Aircraft	Military Aircraft - *Ejection Seat Equipped*	Unmanned Aerial Vehicles (UAVs) * *Above 150Kg TOW*
Frequent	Greater than 1×10^{-3}	Greater than 1×10^{-3}	Greater than 1×10^{-2}	Greater than 1×10^{-2}
Reasonably Probable	Less than 1×10^{-3}	Less than 1×10^{-3}	Less than 1×10^{-3}	Less than 1×10^{-2}
Remote	Less than 1×10^{-5}	Less than 1×10^{-5}	Less than 1×10^{-4}	Less than 1×10^{-3}
Extremely Remote	Less than 1×10^{-7}	Less than 1×10^{-6}	Less than 1×10^{-5}	Less than 1×10^{-5}
Extremely Improbable	Less than 1×10^{-9}	Less than 1×10^{-8}	Less than 1×10^{-7}	Less than 1×10^{-6}

Figure 2-2: Quantitative Hazard Probability [1].

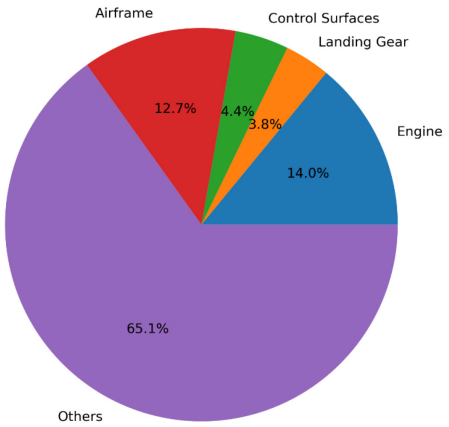
2.7 LESSONS LEARNED FROM THE RCAF CAW PRACTICE

DND experience with the AAA has shown that the assessment activity needs to be tailored for each fleet based on how the fleet is operated and maintained. There is a heavy reliance on the OEM for fleets that are operated in a predominantly civilian role, while a more active involvement is required for military role fleets. The level of effort to perform AAA is dependent on the strength of the integrity monitoring program, with a strong program requiring minimal effort to carry out the AAA. This highlights the importance of the integrity monitoring program. Overall, the RCAF fleets are well maintained with a strong awareness of the aircraft integrity.

Since the introduction of RARM into TAA process in 2001, it is shown that RARM is an effective tool for managing the RCAF fleets continuing airworthiness. A recent NRC work on RARM data mining has been investigating some statistics of the RARM database, including number of RARMs for all fleets and specific fleet; risk level/index (low, med, high) distributions; RARM cases distributions for different aircraft systems; RARM hazard cause/effect distribution; risk assessment technology solutions; qualitative vs. quantitative risk assessment. So far the study shows: there are about 1040 RARM cases for all fleets, including both closed and still open. Some RARMs have multiple versions and the risk index was revised/lowered in the final versions. As a snapshot in 2018, about half of them are ALOS (acceptable level of safety), 6.5% Low, 38.3% Medium, and about 5.9% High and Extremely High (Figure 2-3(a) and Figure 2-3(b)) shows the RARM case distribution for different aircraft components/systems, it is noted that about 65% of RARMs are for “other” systems which mainly include avionics and software, etc.



(a) RARM Risk Index Distribution.



(b) RARM Cases Distribution for Different Systems.

Figure 2-3: Snapshot of RARM Distribution for All RCAF Fleets.

2.8 REFERENCES

[1] Department of National Defence of Canada, *Technical Airworthiness Manual (TAM)*, Document No. C-05-005-001/AG-001, 2015, Change 7, 23 November 2015.

[2] US Department of Transportation, Federal Aviation Administration, *14 CFR Parts 119, 121, 129, 135, and 183, Aging Airplane Safety; Final Rule*, 2 February 2005.

[3] Department of National Defence of Canada (August 2007), “Review of Open Records of Airworthiness Risk Management”, Airworthiness Directive DND-AD-2007-01.

[4] Liao, M., Kainth, T., Renaud, G., and Bombardier, Y., “Quantitative Risk Analysis to Support Continued Airworthiness Management for Aircraft Structures”, NATO-RTO-AVT-222, Brussels, Belgium, October 2014.

Chapter 3 – LESSONS FROM AGING AIRCRAFT SYSTEMS AUDITS

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3.1 INTRODUCTION

The United Kingdom Ministry of Defence (UK MOD) has been undertaking Aging Aircraft Structural Audits (AASA) since the early 1990s. These audits were initiated following the well-known Aloha Flight 243, Boeing 737 pressure cabin failure in 1988 [1]. However, several civil accidents in the mid-1990s, including TWA Flight 800 [2] and Swiss Air Flight 111 [3], made the aviation community aware of the need to consider aging effects of electrical and mechanical systems alongside structural implications. For the UK MOD the need to understand these aging systems issues was reinforced starkly by the loss of Nimrod XV230 over Afghanistan in 2006. Thereafter, the inclusion of aircraft systems aspects into the UK MOD's Aging Aircraft Audit (AAA) process was introduced.

The UK MOD / Industry Systems Airworthiness Advisory Group (SAAG) and Aging Aircraft Programme Working Group (AAPWG) were established, chaired by the UK MOD Military Aviation Authority (MAA) to sit alongside the existing structures and propulsion MOD / Industry groups. One of the early outputs from the SAAG was SAAG Paper 001 [4], which focused upon initial lessons identified from these early AAA including systems elements (AASysA), Condition Survey (CS) and other associated integrity programmes. This chapter is primarily a precis of SAAG Paper 001 focusing on the critical issues, with updated references identified where appropriate. Readers wishing to gain a fuller picture of these issues should read SAAG Paper 001, which is freely available on the UK MOD website [4].

Lessons from these initial AASysA and CS, including programmes conducted on the Nimrod, VC10, C130, Sentry, Tucano and Historic Aircraft were collated, with gratefully acknowledged inputs from across the UK MOD and industrial support base. Common recommendations were identified under the categories of: regulatory or policy issues, programme conduct issues and wider airworthiness issues, and the major issues are discussed in the following sections of this chapter. The key recommendations from this study were:

- To include a requirement to validate the effectiveness of integrity assurance methods by undertaking a detailed physical condition survey of a sample of aircraft from within each fleet;
- To reinforce the airworthiness requirements of the AAA, rather than the cost of ownership and availability issues;
- To include a requirement to address the effectiveness of emergency systems within the AAA; and
- To streamline the three independent audits (structures, systems and propulsion) into a single AAA.

All four of these key recommendations have since been incorporated into the UK MOD Regulatory Framework [5]. Moreover, the recommendations discussed below and in SAAG Paper 001 have been used as the foundation for the UK MOD Aging Aircraft Research and Development Programme since the publication of the paper.

3.2 AGING AIRCRAFT REGULATORY ISSUES

3.2.1 Definition of Aging

The lack of a widely-accepted definition of aging was found to be causing confusion, with too great a focus on calendar age rather than system degradation. As a result, examples were found where degradation issues had not been identified initially because the platform or system was not considered old enough to be aging. Consequently, the following definition of aging was introduced:

> *"Ageing is defined as the degradation of the system (equipment, people or information) leading to an increased safety risk".*

3.2.2 Definition of the Aims of an Aging Aircraft Programme

There was significant debate within the community as to what the aims of the AAA were. There was a concern that too great a focus was placed on regulatory compliance and combined with financial pressures there was a danger of producing a 'box-ticking' approach, with emphasis on whether measures were in place rather than whether they were effective. Therefore a key aim of an aging aircraft programme was defined as identification of the onset of aging within a fleet and to recommend and implement remedial actions [5].

3.2.3 Audit or Programme?

The description of these programmes as audits was largely historic. However, the audit label had, on occasion, resulted in the scope being constrained to traditional audit functions. Evidence suggested that a more proactive approach was necessary. AAA programmes had shown a great many common issues across aircraft types, such as poor husbandry, lack of physical clearances, widespread systems corrosion, poor maintenance data, loss of knowledge and apparent insufficient or inadequate training. While these issues were being addressed by a range of initiatives, it was considered that the underlying circumstances leading to these degraded conditions were likely to persist or to reoccur in the future, particularly given the ongoing financial constraints within which military aviation continues to operate. Therefore, an ongoing approach was established to feedback experience from AAA findings into the airworthiness regulatory framework largely influencing acceptable means of compliance and the guidance material available [6], thereby effectively creating an aging aircraft programme rather than an audit alone.

3.2.4 Streamlining the AAA Approach

Initially, separate audits were being undertaken for structures, systems and propulsion. This was considered inefficient with considerable overlap in process and procedures and the risk of missing interface issues between these disciplines. It was estimated that up to 40% of the costs of the audit could be saved by combining the disciplines into a single audit. Therefore, a combined AAA was developed with common and specific discipline sections. This has proven to be a far more efficient approach [5].

3.2.5 Guidance for the Conduct of Aging Aircraft Programmes

With advent of the MAA, the UK MOD moved from a policy approach to one of regulation, Acceptable Means of Compliance (AMC) and Guidance Material (GM), as used in the civil regulatory frameworks. Also with significant increases in the levels of contractor-support maintenance arrangements, it was considered essential to ensure that the experience gained in all arenas and by all organisations in the conduct of multi-discipline (structures, systems and propulsion) AAA was made available to the entire community. An approach was developed based upon that used successfully by the structures community (Military Aircraft Structural Airworthiness Advisory Group (MASAAG)). Detailed guidance was developed by Subject Matter Experts (SME), peer reviewed by Industry and MOD SME partners and published and

maintained by the MAA. These papers when then referenced from the appropriate sections of the regulatory framework. This ensured that papers had suitable credibility, were endorsed by the relevant authorities, were easily accessible and had longevity. SAAG Paper 001 was the first non-structures paper developed using this approach. Other GM followed soon thereafter, including Refs. [7], [8], [9], [10]. This has proven to be an extremely successful method of knowledge capture, retention and continuous improvement.

3.2.6 The Requirement for On-Aircraft Condition Surveys

There had been considerable debate within the community as to whether a physical Condition Survey (CS) of a sample of the fleet was required as part of the AAA. This was one of the issues alluded to in Section 3.2.3 where the title 'audit' had behavioural risks associated with it. The AAA regulation at the time did not specifically identify the requirement for a CS. UK MOD structures experience and US civil and military experience clearly illustrated that surveying aircraft or CS was an essential element of verification. The crucial aspect of this performance assessment was illustrated by Mr Stewart Miller, FAA Aging System Program Manager, in his comments in the aftermath of TWA 800 [11] that:

> *"We were watching the fleet, but we did not understand that maintenance programs were not as robust as we thought."*

Consequently, the regulatory framework was amended to specify that a CS of a sample of the fleet was required to assess the performance of the measures used to assure an airworthy aircraft and to identify signs of aging (i.e., degradation) [5]. In addition, the MOD formed a MOD / Industry Condition Survey Working Group (CSWG) (a SAAG sub-committee) within which SMEs developed guidance material on the conduct of CS [10], now referenced from the AAA regulations [5].

3.2.7 Safety Management Systems Foundations for Supporting an AAA

It was recognised that understanding where to focus efforts (or scoping) was one of the most important aspects of the planning phase of a systems audit or in establishing a Systems Integrity (SysI) Programme. It is impractical to undertake in-depth investigations of every component in every system throughout all the zones of the aircraft and hence a targeted approach will always be necessary. Although this is easily said, it was recognised that this was more challenging to undertake in practice. To a certain extent, the complexity of this scoping task was dependent on the foundations that were in place for the systems safety management of the aircraft type. Not surprisingly, evidence demonstrated that the more successful programmes were those that had been well scoped.

Ideally, at the initiation of an AAA existing information would be readily available to identify all the known system hazards and inter-system hazards across the aircraft, from a detailed functional safety, operational safety and physical safety perspective. This would then form the basis of the AAA approach. However, for legacy aircraft fleets in particular, the available systems safety information and its source were found to vary considerably. Enhancements to the regulations [5] were recommended to emphasise the importance of clearly defining the scope of the AAA and the rationale for exclusions.

3.2.8 Validation of Emergency Systems Performance

Even a cursory view of accident sequences with technical causes will clearly identify a chain of events leading to that accident, plus, often, several opportunities to break that chain and either prevent the accident occurring or lessen the consequences. The widening of the remit of AAA to include systems now brought emergency systems within the bailiwick of an audit.

Therefore, it was considered that the continued performance and adequacy of each emergency system should be ascertained against the system requirements. Overheat detection devices provide an excellent example to

illustrate this point. Evidence identified that although the overheat detectors on some platforms may have been subject to electrical continuity checks, the actual performance of the detector had not been verified during the life of the aircraft, particularly if these sensors had been identified as 'on condition' items with no refurbishment or hard-life requirements.

Following these recommendations, the regulatory article for AAA [5] was amended to ensure that emergency systems were subject to specific attention within an AAA. Moreover, the systems integrity management regulations [6] were also amended to ensure that sensor-related emergency systems had an appropriate calibration policy in place.

3.2.9 Validation of Design and Usage Assumptions

The aircraft system designer must make assumptions of how a system will be used in service, how it will interact with the environment, and how it will interact with other systems in the aircraft. The structures community has, in the past, felt the implications of not fully appreciating the sensitivity of structural lives to changes in usage and operating environment. Validation processes [12], including Operational Loads Measurement (OLM) [13] and Operational Data Recording [14], are now entrenched within regulation. Validation of design and usage assumptions can be equally critical for aircraft systems, as was illustrated by the Nimrod loss [15]. Therefore, following recommendations the systems regulation now makes reference to the need to validate system usage assumptions [6].

However, experience identified shortfalls in the information readily available to validate these systems design and usage assumptions. It is important to understand the key sensitivities within a target system or zone and to be able to measure appropriate parameters to validate assumptions. For example, when considering the traditional fire triangle of oxygen, heat or ignition source, and fuel, the usual focus within a zone for an ignition source might be a spark from an electrical system. However, auto-ignition of fuels can occur without the presence of a flame or spark. The exact conditions for auto-ignition are influenced by factors such as surface geometry, closed or open environment, local air velocities and fluid residence time [16]. Nevertheless, aviation fuels are vulnerable to auto-ignition at temperatures as low as 210 °C to 300 °C, depending on the air-fuel ratio, at atmospheric pressure. Again it was considered essential to assemble guidance in how to assess the zonal hazards and this led to the development of guidance [17], which is now referenced from the systems integrity regulations [6].

3.3 AGING AIRCRAFT PROGRAMME CONDUCT ISSUES

3.3.1 Pan-Organisation Support

It was clearly evident from the initial programmes that no one organisation has all the skills and knowledge needed to undertake a successful AAA programme in isolation. The regulation [5] highlights the importance of an independent audit but, following recommendations, this was amended to emphasise the importance of making provision for support from the Design Organisations (prime and component) and all those other organisations responsible for the operation and maintenance of the aircraft and its component parts.

3.3.2 Systems Sampling

The issue as to whether sampling should be a requirement of an AAA has been debated within several programmes and was discussed briefly earlier in this chapter. The lead large aircraft fleets involved in the development of aging aircraft programmes, including the Nimrod, VC10, C130K and Sentry, with later programmes on Puma and Gazelle, had the opportunity to use an aircraft being retired from Service as part of their investigations. There was no doubt that having an example, even if it is only one aircraft and hence possibly not a representative sample size, from the fleet provides a unique opportunity to identify and

understand in-depth issues. However, the activity of sampling does not necessarily require a full aircraft, nor does it necessarily have to result in the destruction of all or part of the aircraft. Additionally, the sample size, with an aim to undertake sufficient samples to be representative of the fleet, should be considered [18], [19]. Evidence illustrated that with careful planning it was possible for the necessary systems testing, analysis and inspection to be largely accommodated within the realms of existing maintenance programmes. The additional burden of sampling beyond the normal maintenance regime into un-inspected or undisturbed systems would generally be expected to be relatively small.

Sampling has been identified in MOD structures policy and regulation for many years. However, it is only in relatively recent years that the true value has been recognised in the wider aerospace community as structural sampling has providing crucial evidence to continue operating aging aircraft fleets. As the focus has shifted towards the integrity of systems and lives of aircraft continue to be extended, it is likely that sampling of systems will also prove to be an invaluable tool. It should be remembered that the use of sampling, within an age exploration programme [20] is a fundamental aspect of Reliability Centred Maintenance (RCM). However, systems sampling programmes are still relatively rare. Consequently, when events do occur that necessitate investigations of systems lifing policy, such as studies conducted into lifing of seals [21], flexible hoses [22] and control rods [23], definitive evidence of the specific performance of these components can be difficult to ascertain purely from component replacement or flight safety incident/occurrence report data; hence sampling programmes are often necessary to supplement the available data. Following this study, recommendations were accepted to emphasise the potential value and importance of sampling of system components within the relevant regulations [5], [6].

3.3.3 Identification of Target Systems and Zones with Limited A Priori Information

As already discussed, for some of the UK MOD's fleets the systems safety information available at the time was limited and hence a method of identifying where to focus efforts was developed. SAAG Paper 001 [4] describes the approach employed for the VC10 programme, which used an initial 3-day workshop, facilitated by a highly-experienced design airworthiness engineer and supported by the UK MOD, design engineers, maintenance engineers, maintenance instructors, in-service engineering investigators and experienced aircrew to develop an initial Fault-Tree Analysis (FTA) using a Hull-Loss Model, as a template to ensure that faults that could produce hazards and single-failure points were identified.

The success of this approach was highly dependent upon having knowledgeable representation from designers, maintainers and operators (aircrew). Each of these organisations brought an essential element of understanding and perspective; without any one of the parties the picture would have been incomplete and the understanding of the implications of a potential systems failure could have been flawed. Consideration of this approach was recommended in the absence of available information with which to identify target systems and zones for investigation. SAAG Paper 001 [4] includes far more detail on the approach taken as a case study which, in the interests of brevity, cannot be reproduced in this chapter. However, this work led to a wider investigation on the methods of undertaking safety assessments for in-service aircraft. SAE ARP4761 [24] provided valuable guidance for the processes and methods used to conduct safety assessments. However, greater guidance for in-service platforms, where redesign is not always a feasible option was required. This in turn led to the production of guidance on the conduct of Zonal Hazard Analysis (ZHA) [17], referenced from the regulations [6] and has since been applied to most UK MOD aircraft fleets.

3.3.4 System Performance Assessment

One of the areas where there may well be a significant difference between systems and structural audits is in understanding the performance of the system and the significance of survey or sampling observations. Failure criteria in structural components are generally fairly well understood. For example, the residual strength of a structure in the presence of a crack would be identified and assessed against failure criteria, such as the structure being able to support 120% limit load or meet stiffness or deflection limits. Therefore, a

reasonably reliable estimate of the effect on the overall structural integrity of the aircraft can be identified from a disassembled component. For a system, however, the link between damage found in a component and the capability of the system to perform its required function or the effect on safety of the aircraft can be less clear. Equally, the performance of the system may well have degraded without readily identifiable physical evidence.

Therefore, where condition surveys or sampling programmes are being carried out, detailed functional checks of the performance of target systems before undertaking survey or sampling were found to provide an extremely useful yard stick. Such checks can identify degraded performance and assist in the understanding of the significance of any observations found during survey or sampling. Such an approach can be invaluable in prioritising recovery actions, following the identification of observations. Once a system is disturbed this information is potentially lost.

For many systems (such as flying control systems), there will already be detailed functional checks in the Air Publications (Aps). However, many of the checks will be pass/fail in nature. It is useful to identify greater resolution than just pass/fail in order to determine whether the system performance is degrading and whether any observations found are related to a degradation of performance. For systems without extant functional checks, reference to any certification testing or release to service test schedules can provide a valuable comparison of performance. In addition, maintenance staff with significant experience on the aircraft type should be consulted to identify target systems where there are difficulties meeting the required tolerances. Maintenance data may also show where systems are failing functional checks.

3.3.5 System Interconnection Issues

A significant proportion of the observations found during the aircraft condition surveys undertaken, within and outside of AAA, were found to be related to interconnecting elements of the systems (e.g., pipes, cables, linkages, control rods, wiring) rather than Line Replaceable Units (LRU) or equipment. As a consequence the regulatory material [5] and additional GM was generated and referenced [10] to ensure specific attention was paid to system interconnectivity.

3.3.6 Risk-Based Reporting

UK military aviation is managed using a risk-based approach. In order for the observations identified in an AAA to be afforded appropriate priority among the myriad of other issues being dealt with, it was identified that they needed to be assessed in terms of risk. The regulation has now been amended to reflect this approach [5].

3.4 WIDER AIRWORTHINESS ISSUES

3.4.1 Electrical Wiring and Interconnection Systems (EWIS) Integrity

The issues and risks associated with aging wiring were well-known within the aviation community. The assurance of wiring integrity was largely based upon visual inspection. However, aging systems programmes once again highlighted significant issues with wiring husbandry, despite detailed UK MOD wiring husbandry regulation [25]. Moreover, large sections of wiring were often inaccessible visually. Furthermore, it was unclear as to whether visual inspection was always sufficient to identify areas where wiring integrity had been compromised. Forensic capability for wiring integrity was also limited. Hence, a greater focus on understanding the key wiring integrity issues relevant to UK MOD aircraft was needed and a community-wide approach was recommended.

Consequently, the UK MOD / Industry embarked upon a comprehensive five-year EWIS Cradle-to-Grave (C2G) programme. The programme was aimed at informing the regulation and best practice required for

future EWIS installations and providing the tools necessary to determine and influence EWIS in-service condition. There are three sub-programmes: the Wiring Interconnect Systems Integrity Framework (WISIF), the Wiring Insulation Material Deterioration Assessment Programme (WIMDAP) and the EWIS Condition Surveys (EWISCS) [26]. The WISIF element of the programme has been completed with the development of an EWIS handbook which captures guidance material necessary to support the EWIS integrity across the MOD air fleets; this document will be referenced from the relevant regulatory articles. The aim of the WIMDAP programme was to gain a greater understanding of the insulation properties of the major electrical wire types used in service. The five-year testing programme of insulation properties of all the major wiring types in use is now nearing completion. The EWISCS task aim was to undertake EWIS surveys of at least two aircraft from all major platform types in service. This has now been completed and these surveys have continued to highlight that EWIS issues start with less than perfect initial build and that the condition of EWIS installations is further exacerbated by deterioration in service. The key issues identified were maintenance practices and policy, initial and ongoing training and aircraft acceptance standards.

3.4.2 Fault Reporting and Corrective Action Systems

Not surprisingly, the AAA programmes highlighted significant issues with quality and management of data. Essential airworthiness information, relating to certification of the aircraft, was, in some cases, no longer available. Furthermore, the quality of data (primarily fault reporting information) used to support airworthiness decisions was often considered suspect. In some cases those entering data were not necessarily aware that it could be used to support airworthiness decisions and simple education was sufficient to address many of these issues. It was clear, however, that although a requirement existed for a Fault Reporting and Corrective Action System (FRACAS) [27], there was little guidance on what a FRACAS should consist of. Therefore, a programme was launched to produce a UK Defence Standard for the development of a FRACAS. The aim was to be able to contract for a FRACAS which could be tailored to the scope and value of a project. This could then be applied throughout the life cycle and the standard would explain what data needed to be collected and why. A draft standard has been developed in parallel with development of FRACAS systems for two in-service aircraft platforms; it is scheduled for publication in early 2019.

3.4.3 Configuration Control Systems

Shortfalls in configuration control were universally highlighted. Most evident was the lack of configuration control for repair data and corrosion arisings across the fleets. The regulatory requirements were largely considered to be adequate but, in most cases, lack of tools was identified as the core reason for the shortfall. Consequently, a programme to develop repair and corrosion recording and tracking tools was initiated and initial stand-alone systems have been developed and populated for several aircraft platforms, including Puma and Sentry. The next stage in the development of this capability is to integrate these systems into the UK MOD information technology architecture. A number of trial programmes are currently underway.

3.4.4 Corrosion of Systems Components

Widespread corrosion, across a plethora of mechanical and electrical systems (such as hydraulic pipe end-fittings and electrical connectors), was identified within the AAA and associated CS. In many cases it was difficult, if not impossible, to identify the extent of corrosion damage from visual inspection in situ. In many cases, little evidence of remedial action or recording of corrosion was apparent and in some cases ineffective remedial measures were identified. As a result an in-depth corrosion study was initiated across all the MOD air platforms and detailed remedial actions were recommended [28]. These recommendations are being addressed by the MOD / Industry AAPWG.

3.4.5 Polymer Degradation

The issues associated with elastomeric fuel seals, in the context of sampling, were discussed earlier within this chapter. Initial systems AAA and CS programmes identified widespread issues with the degradation of a whole range of polymers, including seals, sealants, electrical wiring insulation, paints and coatings. Many of these polymers were operating well beyond their intended service life and often in hostile environments, such as in undercarriage bays. The majority of these polymers were effectively retained in service 'on condition', irrespective of whether the original manufacturer identified a recommended service life. Moreover, in some applications, such as structural fuel tank sealants, whole-scale replacement would be prohibitively costly and could only be justified on risk grounds, based upon a sound understanding of the degradation of the polymer.

Understanding aging polymers is an issue far wider than just aerospace and these issues are being tackled in a range of safety-related applications. However, the problem is often further complicated by insufficient understanding of the effects of changes in the chemical constituents within the polymer over time and limited understanding of the operating environment. That said, the complexity of the problem does not lessen the implications and hence there was a need to gain a greater understanding of the degradation of polymers when used in safety-related applications, with an aim of developing life assessment methods, where necessary.

Therefore, a programme was launched to develop a lifing framework for safety-related polymer components (such as fuel seals). The concept was to identify what information was needed to support integrity decisions for such materials and then to address any shortfalls in the data available. Much of the work has focused upon the key materials used in polymer fuels seals and in gaining an understanding of the effects of static and cyclic temperature variations on the compressive stress relaxation properties of the material (i.e., by how much does its sealing force reduce). This work has now been completed and it is planned to publish it as guidance material in the near future.

3.5 CONCLUSIONS

The inclusion of systems aspects within the AAA has provided a significant step forward in assuring the airworthiness of the UK's aging military aircraft fleets. Many lessons have been identified during these programmes and the continual-improvement approach to enhance regulation and identify best practice has been successful. However, there is still much work to be done and continually measuring the effectiveness of airworthiness assurance methods and implementing improvement is clearly an essential component of any airworthiness approach.

3.6 ACKNOWLEDGEMENTS

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Finally, the invaluable contribution to this programme over many years from the late Mr Martin Hepworth, who sadly passed away on 26 November 2017, is gratefully acknowledged.

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Chapter 4 – EUROPEAN UNION AND NATO MILITARY AIRCRAFT AIRWORTHINESS POLICY

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4.1 INTRODUCTION

The principles and arrangements set up by the Convention on International Civil Aviation signed in Chicago on 7 December 1944 (known as Chicago Convention) [1] and consequently the International Civil Aviation Organization (ICAO) standards and recommended practices issued as annexes to The Chicago Convention, are dedicated for civil aviation only. As a result, there was no agreement between European Union (EU) Member States regarding military (state) aviation regulations, processes and procedures that would enable a common approach in the field of Airworthiness (AW). Member States operate independent aviation safety systems and are individually responsible for the regulation of their military (State) aircraft. As a result, all military airworthiness activities had been conducted and regulated on a national basis. Some harmonisation was achieved only at an individual project level and repeated for each new project. These multinational programs demonstrated that this situation generated many shortcomings and was a primary cause for delay and additional cost [1].

4.2 EUROPEAN DEFENCE AGENCY (EDA) MILITARY AIRWORTHINESS POLICY

The European Union Member States decided to develop a solution based on a European Defence Agency (EDA) cooperation basis. Member States agreed on the 10th November 2008, to the formation of a Military Airworthiness Authorities (MAWA) Forum under the auspices of the EDA, as announced in EDA Document No. 2008/39 "Roadmap on an EU-wide Forum for Military Airworthiness Authorities (MAWA)" [2]. Formal confirmation at a political level was made in a "Defence Ministers' Political Declaration Regarding the timely Development and Implementation of the European Military Airworthiness Requirements" (EDA Document No. 2009/36, approved by the Steering Board on 17 November 2009) [3].

The MAWA Forum was tasked to harmonise military airworthiness requirements across Europe. To achieve this goal, the participating Member States (MS) agreed to the implementation of the following Roadmap:

1) Common regulatory framework;
2) Common certification processes;
3) Common approach to organisational approvals;
4) Common certification/design codes;
5) Common approach to preservation of airworthiness;
6) Arrangements for recognition; and
7) Formation of a European Military Joint Airworthiness Authorities Organisation (EMJAAO).

In delivering the first 6 objectives, the EDA MAWA Forum has developed agreed-upon cooperation principles, and harmonised airworthiness requirements and procedures. EDA's participating MS are now strongly encouraged to implement these principles, requirements and procedures (Table 4-1) into their national regulations.

Table 4-1: List of Current MAWA Forum Airworthiness Documents and Requirements.

Short Title	Title of Document	Current Edition / Date
BFD	The European Harmonised Military Airworthiness Basic Framework Document (BFD)	Ed. 3.0/23.05.2018
EMAR 21	Certification of military aircraft and related products, parts and appliances, and design and production organisations	Ed. 1.3/01.02.2018
EMAR 66	Military aircraft maintenance licensing	Ed. 1.0/23.09.2014
EMAR 145	Requirements for maintenance organisations	Ed. 1.2/04.10.2016
EMAR 147	Aircraft maintenance training organisations	Ed. 1.1/23.09.2014
EMAR M	Continuing airworthiness requirements	Ed. 1.0/12.10.2015
EMACC	European military airworthiness certification criteria	Ed. 3.0/01.02.2018
EMAD 1	Definitions and acronyms document	Ed. 1.3/10.10.2017
EMAD R	Recognition process	Ed. 2.0/03.02.2016
EMAD MFTP	Military Flight Test Permit Procedure	Ed. 1.0/04.10.2016
AMC & GM	Acceptable Means of Compliance and Guidance Material applicable for:	
	EMAR 21	Ed. 1.3/01.02.2018
	EMAR 66	Ed. 1.0/23.09.2014
	EMAR 145	Ed. 1.2/04.10.2016
	EMAR 147	Ed. 1.1/23.09.2014
	EMAR M	Ed. 1.0/07.06.2017
	EMAR Form Document	Ed. 1.3/07.06.2017
EMAD20-8	Occurrence Reporting	Working in progress

There is still no agreement between participating MS for the 7th goal – formation of EMJAAO. This objective is not acceptable for some participating MS because of the concern that it could tread upon their independence in the national defence domain.

Because the basic European Military Airworthiness System documents were already developed, a new strategic objective was defined. On 5 December 2017 the EDA approved the Document for the Steering Board (Nr SB Doc 2017/28) “Military Airworthiness Objectives for the Next Harmonisation Phase” [4]. “The Military Airworthiness Objectives in support of the EU Global Strategy” were published in the Annex to this document. These objectives are grouped into three areas:

1) Development of a harmonised European Military Airworthiness System:
    a) Permanent arrangements for the continuing development of common airworthiness policies and maintenance of the European Military Airworthiness Requirements (EMARs) and related documents;

b) Arrangements for a uniform and consistent exchange of oversight information, re-use of oversight artefacts by National Military Airworthiness Authorities (NMAAs) and the sharing of oversight obligations with respect to European based defence industries, at the discretion of individual Member States;

c) The development of a blueprint for a regulatory and oversight system and its related functions that will serve as a benchmark for participating MS;

d) The establishment of common minimum knowledge, experience and training requirement baselines for technical personnel carrying out military airworthiness oversight functions; and

e) The development of harmonised oversight processes and procedures for technical staff involved in oversight.

2) Implementation of the harmonised European Military Airworthiness System:

a) The use of EMARs as baseline for the national regulation of military airworthiness;

b) The implementation of the harmonised processes and procedures to ensure that personnel and organisations performing an aviation activity meet the established requirements or equivalent level of safety before being allowed to exercise the privileges of a license, certificate, authorisation and/or approval;

c) The implementation of harmonised standards and best practices for the execution of a continuous surveillance programme consisting of inspections and audits to ensure that aviation licence, certificate, authorisation and/or approval holders continue to meet the established requirements and functions at the level of competency and safety required by the participating MS; and

d) The implementation of the harmonised processes and procedures regarding the resolution of identified deficiencies impacting on aviation safety (safety concerns).

3) Indication of potential next steps and cooperation direction:

a) Re-consider the formation of a European Military Joint Airworthiness Authorities Organisation (EMJAAO) that will NOT be a supranational Authority. More likely, it would be an organisation that would continue and improve the achievements by the MAWA working structure; and

b) Closely working with the partners of the EU, in particular the United Nations and NATO.

4.3 NATO AIRWORTHINESS POLICY

Even though the International Civil Aviation Organization (ICAO) regulations do not apply to State aircraft, they explicitly require Member States to have due regard for the safety of navigation of civil aircraft when issuing rules, regulations and standards. Most NATO Nations have established military airworthiness authorities and have introduced a military airworthiness framework that is similar to their civil program.

During the process of developing coordinated a NATO Total Aviation Approach, Member Nations decided to prepare the principal document regarding military airworthiness. The basic aim of this document was to establish a robust framework that ensures airworthiness of aeronautical products, parts and appliances based on the principles of economy of effort, cooperation and interoperability. On 10 July 2013, the North Atlantic Council endorsed the document C-M(2013)0035 MC 0601/1 “NATO Airworthiness Policy” [5]. This policy applies to NATO and its Member and Partner Nations.

As a general principle the NATO’s Airworthiness Policy (NAWP) states that:

> *“while airworthiness certification of state aircraft is a sovereign national responsibility, NATO should put in place standardized collective processes and procedures to ensure the airworthiness of military and civilian aviation assets used by NATO or on its behalf. NATO member nations have*

a responsibility to provide airworthy products to their aircrew, ground crew, passengers, and to third parties".

The above statement was summarized particularly in paragraphs 9 and 10 of the NAWP:

"9. All aeronautical products, parts and appliances provided on behalf of NATO shall be:

a) Certified as airworthy by a NATO recognized airworthiness authority;

b) Properly controlled in accordance with approved continued airworthiness provisions; and

c) Operated and maintained in accordance with approved continuing airworthiness provisions.

10. All work associated with the airworthiness process shall be performed by authorised individuals employing approved processes within organizations accredited/approved by a NATO recognized airworthiness authority."

There is one exception in the policy: for any aeronautical products, parts and appliances provided on behalf of NATO that do not have a NATO recognized authority. Paragraph 15 states that only for exceptional circumstances may Supreme Headquarters Allied Power Europe (SACEUR) waive the requirements by a reasoned decision and for limited duration, reserving the right to accept risks in order to meet urgent operational needs.

There are three established stakeholders who fulfil of NAWP principles: NATO Aviation Committee (AVC), NATO Airworthiness Executive (NAE) and Airworthiness Advisory Group (AWAG).

In order to execute the airworthiness policy additional key documents were prepared [6], [7], [8]:

- NATO Airworthiness Policy (NAWP) Implementation Plan (NAWP IP);
- AWAG Action Plan (AP); and
- NATO Recognition Process (NRP).

4.3.1 NATO Airworthiness Policy Implementation Roadmap

NAWP IP directs priorities for that implementation (schedule is yearly updated in Action Plans – AP).

1) NATO Common Assets:
   - Recognition of NATO Airborne Early Warning and Control Programme Management (NAPMA) and NATO Airborne Early Warning and Control (NAEW&C) Headquarters (HQ) responsible for Airworthiness of NATO NE-3A;
   - Recognition of the Hungarian Military Airworthiness Authority (AA) responsible for C-17 as Strategic Airlift Capabilities (SAC) fleet; and
   - Recognition of Italian Military AA (Directorate of Air Armaments and Airworthiness (DAAA)) responsible for the RQ-4 Global Hawk as the Alliance Ground Surveillance (AGS) fleet.
2) Recognition of 27 remaining NATO Nations AAs;
3) Recognition of Partner and non-Partner nations who intend to contribute aviation assets to NATO operations; and
4) Assessments of AAs of nations who provide aviation assets to NATO on a case-by-case basis (one-time lease, etc.).

The NATO Recognition Process assessment consists principally of nine steps, shown in Table 4-2. Stakeholders for these steps of NRP are NAE, AWAG and AVC [8].

Table 4-2: NATO Recognition Process Steps.

Nr	Input	Step	Output
1.	NATO Airworthiness Executive (NAE) / requesting activity	Identify National Airworthiness Authority (AA) to be identify	Identified AA
2.	List of available nominees for NATO membership	Assemble a NATO Assessment Team (NAT) and Select NAT Lead	Established NAT
3.	Available (online) information	Research the National AA being assessed	Initial impression / understanding of the National AA
4.	Nominated National AA	Determine Point of Contact (POC) for the NRP (NATO Recognition Process)	Identified POC
5.	Scope of and general conditions for the recognition	Develop NATO Recognition Plan (RP)	Signed Recognition Plan (RP)
6.	Provided NRS	Carry out NATO Recognition Survey (NRS)	Accomplished NRS
7.	Results of the NRS	Prepare NATO Assessment Report (NAR)	NAR
8.	NAR	Carry out NAR Concurrence	Concurred NAR
9.	Concurred NAR	Issue NATO Recognition Certificate (NRC)	Issued NRC

The status of the NATO recognition process is presented in Table 4-3 [9].

Table 4-3: NATO Recognition Process Status Updated for September 2018.

	Step of NRP	1	2	3	4	5	6	7	8	9	Remarks
Recognized AA	Dutch MAA (MAA-NDL)	√	√	√	√	√	√	√	√	√	Pilot recognition process in 2017
	Italian MAA (DAAA)	√	√	√	√	√	√	√	In progress		
	NAPMA + NAEW&C HQ	√	In progress		√						Potential delay due to NAPMO's procedural issue
	Hungarian MAA	√	In progress		√						
	French MAA(s) DSAE+DGA	√	√	√	√	√	√	√	In progress		
	Canadian MAA	√	√	√	√	√	In progress				
	Norwegian MAA	√	√	√	√	√	In progress				
	Spanish MAA (DGAM)	√	In progress		√						

4.4 CONCEPT OF AIRWORTHINESS REGULATION FOR THE NE-3A FLEET

4.4.1 Background of the Programme

During the 1960s, it became clear that military aircraft could no longer fly high enough to avoid surface-to-air missiles. To survive in an increasingly lethal air defence environment, aircraft were forced down to levels little higher than tree-top. By the 1970s, the requirement to detect high speed combat aircraft, with low level penetration capability, made it necessary to augment NATO's system of ground-based radars with new effective means [10].

The NATO military authorities determined that an Airborne Early Warning (AEW) capability would provide the key to meeting the challenge. The operational requirement for the NATO AEW system stressed the need to detect small cross-section, high speed intruder aircraft at long range. The need to detect maritime surface targets was also specified to account for the geographical regions in which the AEW aircraft would be required to operate. The inherent mobility and flexibility of the system, especially for control function, were also foreseen by NATO planners as providing air, maritime, and land force commanders with an enhanced Command and Control (C2) capability [10].

In December 1978, NATO approved acquisition of 18 aircraft based on the US Air Force (USAF) Airborne Warning and Control System (AWACS) to be operated as an Alliance-owned Airborne Early Warning system (Figure 4-1).



Figure 4-1: NE-3A Aircraft [10].

4.4.2 NATO Airborne Early Warning and Control (NAEW&C) Airworthiness System

The NE-3A was introduced to service in NATO in 1982. The aircraft were registered by Luxembourg with the understanding that the NATO aircraft configuration and Airworthiness certifications would mirror the USAF E-3, that NATO aircraft would be maintained in accordance with regulations adapted from USAF, and that the USAF Airworthiness process would provide the requisite certifications for the NATO programme. This airworthiness concept, where the NE-3A aircraft mirrored the certified USAF E-3 configuration, and the USAF certification was accepted by NATO as sufficient, with NATO providing individual aircraft airworthiness certifications (Military Airworthiness Certificates – MCAs), was used from program inception until the early 2000s [11].

In 2008, NATO pursued a unique mission systems modernization program, NATO Mid-Term (NMT), which had significant changes to the NE-3A baseline configuration [11]. In years 2007 – 2009 the NMT configuration was further upgraded to provide self defence capability: Large Aircraft Infrared Countermeasures (LAIRCM). This modification was assessed as "reportable" (per MIL-HDBK-516) [12]. With these changes in configuration, the USAF communicated that it was no longer able to support the NE-3A Airworthiness Authority, and that to maintain the appropriate level of airworthiness certification (to include NMT-appropriate Military Type Certificates and Military Certificates of Airworthiness) NATO needed to establish its own Airworthiness capability [11].

The Force Command Commander recognized the challenge of the unique NE-3A configuration and his responsibilities as the Airworthiness Authority. Consequently in 2008(9) Force Command and US Agent called for an Integrated Product Team (IPT) to review and establish Airworthiness assurance process based on USAF E-3 best practices [12].

Meanwhile in the years 2008 – 2011, Software (SW) and Hardware (HW) modifications continued with approval by separate, independent Configuration Control Boards. The modifications included: HW modifications to improve mission computing performance (configuration control lead by NATO AEW&C Programme Management Agency – NAPMA), capabilities developed for the USAF fleet and implemented by Force Command (configuration control lead by Force Command) and mission system SW updates developed at the Main Operating Base (configuration control lead by NE-3A Component) [12]. There was no formal mechanism to cross check impact of changes on the fleet.

In December 2011, the NAPMO (NATO AEW&C Programme Management Organisation) Board of Directors (BOD) approved Airworthiness Policy based on IPT study recommendation i.e., split airworthiness responsibility between Force Command and NAPMA General Manager (NAPMA GM) established Chief Engineer's Office to support and execute Operational Safety Suitability and Effectiveness (OSS&E) and AW checklist process [12].

In 2012 the BOD took the first step of approving an Airworthiness concept via a Memorandum of Understanding for Airworthiness and Configuration Management (AW MOU), that made the NAPMA GM the Technical Airworthiness Authority (TAA) and the Force Commander the Operational Airworthiness Authority (OAA) [13]. This document requires Airworthiness Review Board (ARB), defines Configuration Management Responsibilities including Single Configuration Control Board (SCCB) and defines Technical and Operational Airworthiness responsibilities.

An Airworthiness Review Board (ARB) was established to assist the NAPMO Nations on airworthiness matters related to the NE-3A fleet [14]. The Terms of Reference for the ARB [15], including membership, was developed jointly by the OAA and TAA for NAPMO BOD approval. The ARB responsibilities include [13]:

- Conducting an annual review of the airworthiness programmes and procedures established by the OAA and TAA and reporting to the NAPMO BOD on its observations and concerns; and
- Providing independent advice to the NAPMO BOD regarding the information provided semi-annually by the OAA and TAA.

The OAA is responsible for:

- Developing and implementing the NE-3A operational airworthiness programme and procedures;
- Approving waivers and exemptions to applicable NE-3A operational airworthiness criteria as defined in implementing documents;
- Certifying the operational airworthiness of the NE-3A capability;

- Maintaining and operating the NE-3A fleet and related assets in accordance with the certified baseline (continuing airworthiness);
- Supporting the TAA in the implementation of technical airworthiness procedures and criteria; and
- Keeping the NAPMA GM or his delegated representative informed on all common airworthiness issues by exchanging information concerning the NE-3A fleet in their respective area of responsibility; and informing the NAPMO BOD on a semi-annual basis of the operational airworthiness of the NE-3A aircraft fleet [13].

The TAA is responsible for:

- Developing and implementing the NE-3A technical airworthiness programme and procedures, including the relevant Modification Management and Operational, Safety, Suitability and Effectiveness (OSS&E) processes;
- Approving technical airworthiness certification and recertification documentation;
- Approving waivers and exemptions to applicable criteria within MIL-HDBK-516, Airworthiness Certification Criteria;
- Certifying technical airworthiness;
- Controlling the certified baseline for technical airworthiness in accordance with relevant Modification Management and OSS&E processes;
- Supporting the OAA in the implementation of operational airworthiness procedures and criteria; and
- Keeping the Force Commander or his delegated representative informed on all common airworthiness issues by exchanging information concerning the NE-3A fleet in their respective area of responsibility; and informing the NAPMO BOD on a semi-annual basis of the Technical Airworthiness of the NE-3A aircraft fleet [13].

The Single Configuration Control Board (SCCB) was established to manage the NE-3A certified configuration baseline. The SCCB is co-chaired by the OAA and the TAA and consist of representatives from Force Command, the NE-3A Component, NAPMA and other NE-3A stakeholder organisations approved for membership by the Participants. All proposed changes to the certified configuration baseline of the NE-3A system, including temporary modifications, must be reviewed by the SCCB.

The certified configuration baseline of the NE-3A system is understood to mean:

- For software items, the configuration that is documented in a Version Description Document for each software configuration item; and
- For hardware items, including those with embedded firmware, the configuration that is documented by the AWACS Modification and Integration Program (AMIP), and defined in the NE-3A Certification Configuration Baseline Document. Any configuration changes thereafter will be certified separately and included in the configuration baselines for subsequent airworthiness certification criteria and associated documentation [14], [16].

The AW Memorandum is associated with an Implementing Agreement (IA) [16] that defines the agreed hardware, software and documentation elements describing the currently fielded NE-3A system configuration, together with the available airworthiness assurance evidence, applicable on initial establishment of the TAA; and outlines the key responsibilities of the OAA and the TAA.

The TAA maintains the configuration baseline, as approved through the SCCB. The TAA has authority to approve changes to the certified configuration baseline, including temporary modifications of the NE-3A system and for related configuration controlled fielded assets.

The TAA is responsible for regulating the design, manufacture, maintenance and material support for the NE-3A fleet. The Technical Airworthiness of the NE-3A system is assured and documented through the use of the OSS&E AW process. The NAPMA Chief Engineer oversees the OSS&E AW process for all proposed changes to the aircraft [16]. The TAA ensures that the conditions under which the aircraft design was certified, including its specifications, manufacturing and configuration data, remain valid. In the event of any deviation from the applicable certification basis he defines any necessary corrective measures. The TAA also sets requirements to ensure the airworthiness of the NE-3A during its service life [16].

The TAA supports the OAA by providing engineering assistance for aircraft incidents and accidents and reviews repair instructions and/or flight limitations together with the Original Equipment Manufacturer (OEM). The support also includes the provision of access to NAPMA contractor support, OEM and support agencies where applicable [16].

The OAA has authority to approve changes for operations and support as defined in the implementing documents that do not affect the certified configuration baseline for the fielded NE-3A system and for related configuration controlled fielded assets.

When there is a compelling operational need to employ an NE-3A aircraft for which it is infeasible or impractical to comply with the certified configuration baseline, the OAA may issue a Special Flight Release (SFR) after consultation with the TAA to ensure technical risks are understood.

The OAA supports the OSS&E Process by assigning a Change Project Officer, as required, to coordinate the OSS&E AW Process for experimental changes as well as changes for operations and support; and by providing focal point expertise when requested by the TAA. The OAA is responsible for regulating the operations, operational personnel and operational facilities of the NE-3A fleet.

The OAA supports the TAA by providing expertise and data to support the establishment of the baseline configuration of the NE-3A. He/She also reviews current waivers with the TAA and provides access to Operation and Sustainment contracted support and support agencies where applicable. The OAA also assists in the development of new working relationships with support agencies.

The OAA fulfils the responsibilities of the Operating Nation for Accident Investigation, and initiates investigations into accidents and occurrences involving NE-3A aircraft.

The joint responsibilities of the TAA and OAA include coordination between the Authorities, Safety Management (on the principles outlined in ICAO Doc 9859 and MIL-STD-882), Configuration Management (co-chairing the SCCB), Change Management [16].

4.5 SUMMARY

The basic Airworthiness (AW) principles are common for each and every stakeholder of military aviation. However, the detailed approaches, and the ways of implementing them in the particular systems differ between Nations and users. The European Defence Agency has initiated an activity aiming for development of a common (commonly understood by all EU Nations) system of AW requirements, and further on regulations, for European military aviation. The EDA Military Airworthiness Authority Forum (EDA MAWA Forum) was established to achieve this goal, and a set of European Military Airworthiness Requirements was developed under the Forum umbrella. The importance of having common approach to the AW issues in military domain is very well understood by all national military AW authorities (or their equivalents) and a process of harmonisation, bilateral and multilateral recognition is continuously in progress.

NATO missions and operations are supported by aircraft which are owned, leased, rented or chartered by NATO Member, Partners or other contributing Nations. Airworthiness certification is a sovereign responsibility

of aircraft originating country; however, it is assumed that all aircraft contributing to NATO or NATO led missions and operations are airworthy, as certified by an appropriate national Authority. NATO affiliated assets, such as NATO E-3A (NE-3A), C-17 fleets and Alliance Ground Surveillance (AGS) system, have also to comply with this requirement. There is no single "appropriate Authority" for these kinds of assets. The C-17s (Strategic Airlift Capability – SAC) are registered in Hungarian (HUN) register of military aircraft and are under authority of HUN Military Airworthiness Authority. The AGS systems are registered in the Italian (ITA) Military Aircraft Registry and are under authority of Directorate of Air Armaments and Airworthiness (ITA MAA). The NE-3A aircraft are registered in Luxemburg register, however, there is no single Military Airworthiness Authority for this fleet. The NE-3A airworthiness issues are addressed in intentionally developed (and signed) memorandum of understanding. To address such "complicated" (from AW perspective) environment, NATO has developed the NATO Airworthiness Policy (NAWP) and NAWP Implementation Plan, where a recognition process between stockholders: NATO – National MAA(s) is a crucial element.

Looking at the subject under discussion from a Polish perspective, it is necessary to mention that according to Polish military regulations, the Chief Engineer of Military Aviation (GIWL) is a Polish NMAA. The GIWL, based on authorisation granted from the Ministry of National Defence, establishes rules and regulations of military airworthiness, which are common for aviation of all Polish military services: Air Force, Army and Navy. The Polish military airworthiness system is built on decades of operational experience of military aviation in peacetime and wartime conditions. The AW system is comprehensive and dedicated to safety in the military environment. Presently there is no full compliance of the Polish AW system with requirements provided in EMARs. Some differences are caused by Polish military aircraft operation and maintenance philosophy derived from the past experiences and harmonisation with a different philosophy of aircraft design (post-Soviet), which formed the majority of the fleet. However, along with the aircraft replacement process, where several "western designed" aircraft (F-16, C-130, C-295, M-346, G550, B737) have already been implemented into the fleet, the AW regulations are also changing. Poland has signed the agreement in principle of The European Harmonised Military Airworthiness Basic Framework Document (BFD) [17]; therefore, in order to fulfil the obligation for harmonisation of European military airworthiness regulations, bilateral and multilateral recognition, the GIWL and special Attorney of Ministry of National Defence for Military Aviation Authority are responsible for updates of Polish AW regulations to be compliant with EMARs.

4.6 REFERENCES

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Chapter 5 – EUROPEAN MILITARY AIRWORTHINESS MAINTENANCE REQUIREMENTS

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5.1 INTRODUCTION

A complete set of harmonized European Military Airworthiness Requirements (EMARs) has been developed under the European Defence Agency Military Airworthiness Authority Forum (EDA MAWA Forum) umbrella. In parallel, the Australian Department of Defence, introduced the Aviation Safety Regulations (DASRs) in 2016. The DASRs align with the EMARs and both sets of airworthiness requirements contain specific provisions for maintenance of military products (aircraft, engines and propellers) and components including software.

Responsibility for the oversight and realization of any Aircraft Structural Integrity Program (ASIP) [1], Avionics Integrity Program (AVIP) [2], Mechanical Equipment and Subsystems Integrity Program (MECSIP) [3], Engine Structural Integrity Program (ENSIP) [4], Propulsion Structural Integrity Program (PSIP) [5], Weapon System Integrity Program (WSIP) [6] or their equivalents is spread among the Military Airworthiness Authority (MAA), Military Design Organisation or Military Type Certificate Holder (MTCH), Aircraft Maintenance Organisation (AMO) and Continuing Airworthiness Management Organisation (CAMO).

According to EMAR M [7] and DASR M [8] provisions, maintenance of each military aircraft shall be organised in accordance with the Aircraft Maintenance Programme (AMP). Thus any ASIP, AVIP, MECSIP, ENSIP, PSIP and WSIP or analogues must be a part of well-developed AMP.

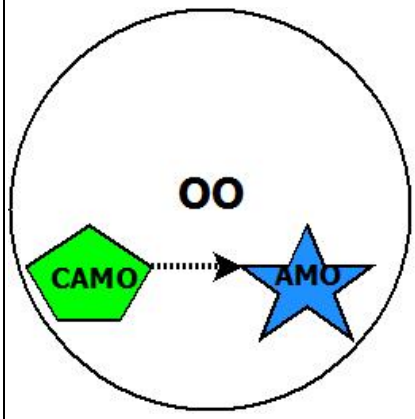
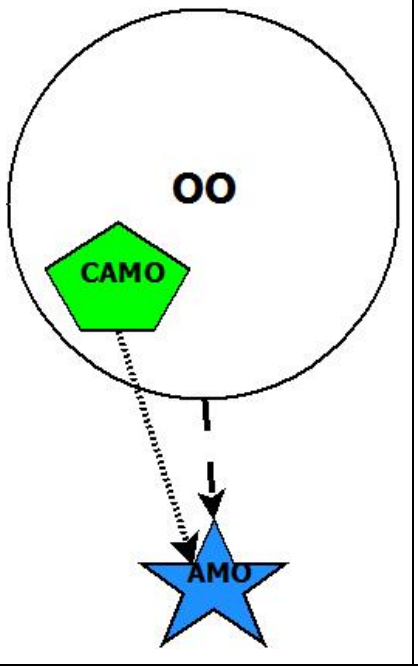
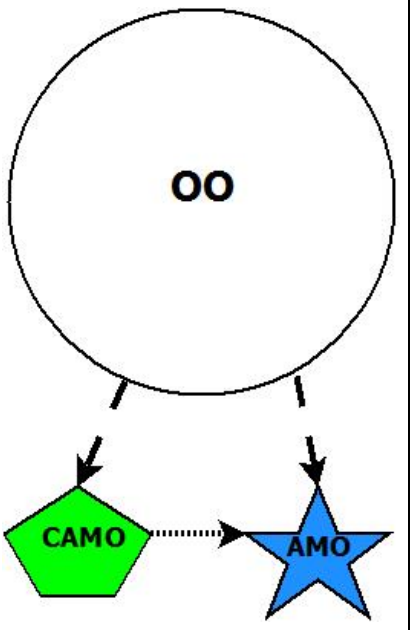
5.2 CONTINUING AIRWORTHINESS RESPONSIBILITIES RELATED WITH MAINTENANCE

The continuing airworthiness responsibilities are defined in EMAR M.A.201 [7] according to which the Operating Organisation (OO) or CAMO is responsible for all activities aimed at determining the airworthiness status of the military aircraft it operates and to suitably plan and coordinate maintenance. In turn, only the contracted/tasked EMAR 145 AMO is responsible for adequately performing and certifying the maintenance ordered/tasked by the Operating Organisation / CAMO. Simply put, neither OO nor CAMO can issue Certificates of Release to Service (CRS) for both aircraft or component following their maintenance; the CRS always has to be issued always by certifying staff of the EMAR 145 AMO.

It is worth mentioning that in contrast to their civilian equivalents (i.e., Part-M), EMAR M allows OO to contract/task so-called external CAMO for the management of the continuing airworthiness of the military aircraft.

These provisions may lead to several more or less complex maintenance arrangements but due to limitation of this chapter length, only three of them are described below, in brief, and are presented schematically in Table 5-1.

Table 5-1: Selected Cases of OO vs CAMO vs AMO Arrangements According to EMAR M Provisions Source: Author's Own Study.

Case 1	Case 2	Case 3
		

Symbol	Process
– – →	Contracting/Tasking
·····→	Coordination of maintenance activities

5.2.1 Case 1

The OO is responsible for the continuing airworthiness of the military aircraft it operates and:

- Is approved in accordance with EMAR M Subpart G; and
- Is approved in accordance with EMAR 145.

Contract/Tasking Arrangement(s) between OO, internal CAMO and internal AMO are not required. Internal CAMO is responsible for proper coordination of all maintenance activities with internal EMAR 145 AMO. Internal AMO is responsible for accomplishing all maintenance activities requested by Internal CAMO.

5.2.2 Case 2

The OO is responsible for the continuing airworthiness of the aircraft it operates and:

- Is approved in accordance with EMAR M Subpart G; and
- Contracts/tasks directly external EMAR 145 AMO.

Contract/Tasking Arrangement(s) between OO and internal CAMO is not required. However, Contract/Tasking Arrangement between OO and external EMAR 145 AMO is required. Internal CAMO is responsible for proper coordination of all maintenance activities with external EMAR 145 AMO. External AMO is responsible for accomplishment of all maintenance activities contracted/tasked by Internal CAMO.

5.2.3 Case 3

The OO is responsible for the continuing airworthiness of the aircraft it operates and:

- Contracts/tasks external CAMO directly; and
- Contracts/tasks external EMAR 145 AMO directly.

Contract/Tasking Arrangement between OO and external CAMO and between OO and external EMAR 145 AMO are required. External CAMO is responsible for proper coordination of all maintenance activities with external EMAR 145 AMO. External AMO is responsible for accomplishing all maintenance activities contracted/tasked by OO.

Reference [9] provides information about splitting up responsibility for the execution of ASIP elements among the approved design, maintenance and continuing airworthiness management organisations from the Defence Aviation Safety Regulations (DASR) perspective. Keeping the above in mind and in light of EMAR's provisions, responsibilities for the execution of any Integrity Process (IP)[1] elements should be distributed among the approved organisation as follows:

- Military Type Certificate Holder (MTCH) or EMAR 21/J Military Design Organisation (MDO) responsibility;
  - Establish certification basis;
  - Establish integrity program;
  - Ensure access to required type design data;
  - Conduct structural assessments and tests (including occurrence reporting);
  - Establish Loads/Environment Spectra Survey (L/ESS) and Individual Aircraft Tracking (IAT) systems or Operational Loads Monitoring (OLM) program, where applicable;
  - Maintain design/initial/continued airworthiness aspects of the integrity programme; and
  - Provide occurrence reporting.
- EMAR M/G (CAMO) responsibility; and
  - Implement any integrity programme through Aircraft Maintenance Programme (AMP);
  - Establish routine usage and condition monitoring;
  - Coordinate OLM programme;
  - Coordinate Aging Aircraft Assessments (AAA) or Analytical Condition Inspections (ACI); and
  - Provide occurrence reporting.
- EMAR 145 (AMO) responsibility:
  - Execute structural management policy in accordance with AMP;
  - Support L/ESS, IAT or OLM programmes;
  - Support collection of structural (usage and condition monitoring) data, including occurrence reporting;
  - Support AAA or Aircraft Inspections (ACI);
  - Support Corrosion Prevention and Control Programme (CPCP); and
  - Provide occurrence reporting.

[1] ASIP, AVIP, MECSIP, ENSIP, PSIP, WSIP.

In addition, the MAA also has some responsibilities in relation to any Integrity Program, which result from Aircraft Continuing Airworthiness Monitoring (ACAM) provisions of the EMAR M (EMAR M.B.303 refers) [7]. ACAM puts obligations on the MAA to create and execute an airworthiness survey programme for monitoring the airworthiness status of the aircraft fleet on its military register, based on 14 Key Risk Elements (KREs). The KREs that are directly related to an Integrity Programme are:

- A.1 – Type design and changes to type design e.g., information on materials and processes and on methods of manufacture and assembly of the product;
- A.2 – Airworthiness limitations e.g., Critical Design Configuration Control Limitations (CDCCL) for the fuel tank safety;
- A.3 – Airworthiness Directives;
- B.6 – Defect management;
- B.7 – Symmetry check;
- C.1 – Aircraft Maintenance Programme;
- C.2 – Component control;
- C.3 – Repairs; and
- C.4 – Records.

The EMAR 145 AMO may issue an authorisation to its employees to provide certification of maintenance for specialised services e.g., NDT, composite repairs or Arms, Munitions and Pyrotechnic Systems services on the basis of appropriate competence, training and experience in accordance with a procedure(s) contained in the Maintenance Organisation Exposition. Table 5-2 presents a release to service of NDT tasks scheme.

Table 5-2: Release to Service of NDT Tasks by EMAR 145 Organisations. Source: Author's own study based on Ref. [10].

EMAR 145 AMO Class	Certifying Staff (CS) with EMAR 66 Military Aircraft Maintenance Licence (MAML) Required	NDT Personnel Qualification and Certification System	Release Procedure for an NDT Task
Class A (Aircraft).	Yes	EN 4179 or national equivalent.	The NDT CS performs the NDT task and signs the work order. The aircraft is released by appropriately qualified B1, B2 or C MAML categories CS.
Class B (Engines).	No	EN 4179 or national equivalent.	The NDT CS performs the NDT task and signs the work order. The engine is released by appropriately qualified CSS on an EMAR Form 1 or its equivalent.
Class C (Components).	No	EN 4179 or national equivalent.	The NDT CS performs the NDT task and signs the work order. The engine is released by appropriately qualified CSS on an EMAR Form 1 or its equivalent.

EMAR 145 AMO Class	Certifying Staff (CS) with EMAR 66 Military Aircraft Maintenance Licence (MAML) Required	NDT Personnel Qualification and Certification System	Release Procedure for an NDT Task
Class D Specialised Services. Rating D1 Non-Destructive Testing.	No	EN 4179 or national equivalent.	The NDT CS performs the NDT task and certifies it on an EMAR Form 1 or its equivalent.
Non-approved organisation working under contracting/ tasking EMAR 145 AMO quality system.	No	EN 4179 or national equivalent.	The release to service document defined by the contracting/tasking EMAR 145 AMO.

Due to the nature of ASIP, AVIP, MECSIP, ENSIP, PSIP or WSIP related maintenance activities, they should be classified as specialised services and in order to provide such maintenance services, in accordance with the current EMAR 145 provisions, an organisation should be either:

- EMAR 145 Class A approval rating – an EMAR 145 (AMO holding an A approval rating on a particular aircraft type must have in its approved scope of work ASIP, AVIP, MECSIP and/or WSIP maintenance tasks for this aircraft type. This organisation needs to have EMAR 66 certifying staff with MAMLs and ASIP, AVIP, MECSIP and/or WSIP personnel qualified in accordance with standards approved by MAA. In this case the ASIP, AVIP, MECSIP and/or WSIP inspector performs his/her task and signs the work order. The aircraft is released by appropriately qualified B1, B2 or C certifying staff under the AMO's A rating; or
- EMAR 145 Class B approval rating – an EMAR B AMO holding a B approval rating on a particular engine type must have in its approved scope of work ENSIP and/or PSIP maintenance tasks for this engine type. This organisation needs to have ENSIP and/or PSIP personnel qualified in accordance with standards approved by MAA. In this case the ENSIP and/or PSIP certifying staff performs and releases the ENSIP and/or PSIP task on an EMAR Form 1 or on a release to service document defined by the AMO in the Maintenance Organisation Exposition; or
- Non-approved organisation working under quality system of contracting/tasking of EMAR 145 AMO Class A or B, when appropriate. The contracted/tasked non-approved organisation needs to have ASIP, AVIP, MECSIP, ENSIP, PSIP or WSIP staff qualified in accordance with standards acceptable to MAA In this case the staff of contracted non-approved organisation performs and releases the ASIP, AVIP, MECSIP, ENSIP, PSIP or WSIP task on a release to service document defined by the contracting/tasking EMAR 145 AMO.

5.3 AIRCRAFT MAINTENANCE PROGRAMME (AMP)

In the European civil airworthiness environment, the organisation responsible for the Aircraft Maintenance Programme (AMP) development is CAMO. This is not the case in the EMAR environment, where this restriction does not exist. According to EMAR M [7] provisions, an AMP should normally be based upon

the Maintenance Review Board (MRB) report or equivalent report where applicable, the Maintenance Planning Document (MPD), the relevant chapters of the maintenance manual or any other maintenance data containing information on scheduling. Furthermore, an OO's AMP should also take into account any maintenance data containing information on scheduling for components. Typical sources for AMP development are shown on Figure 5-1.

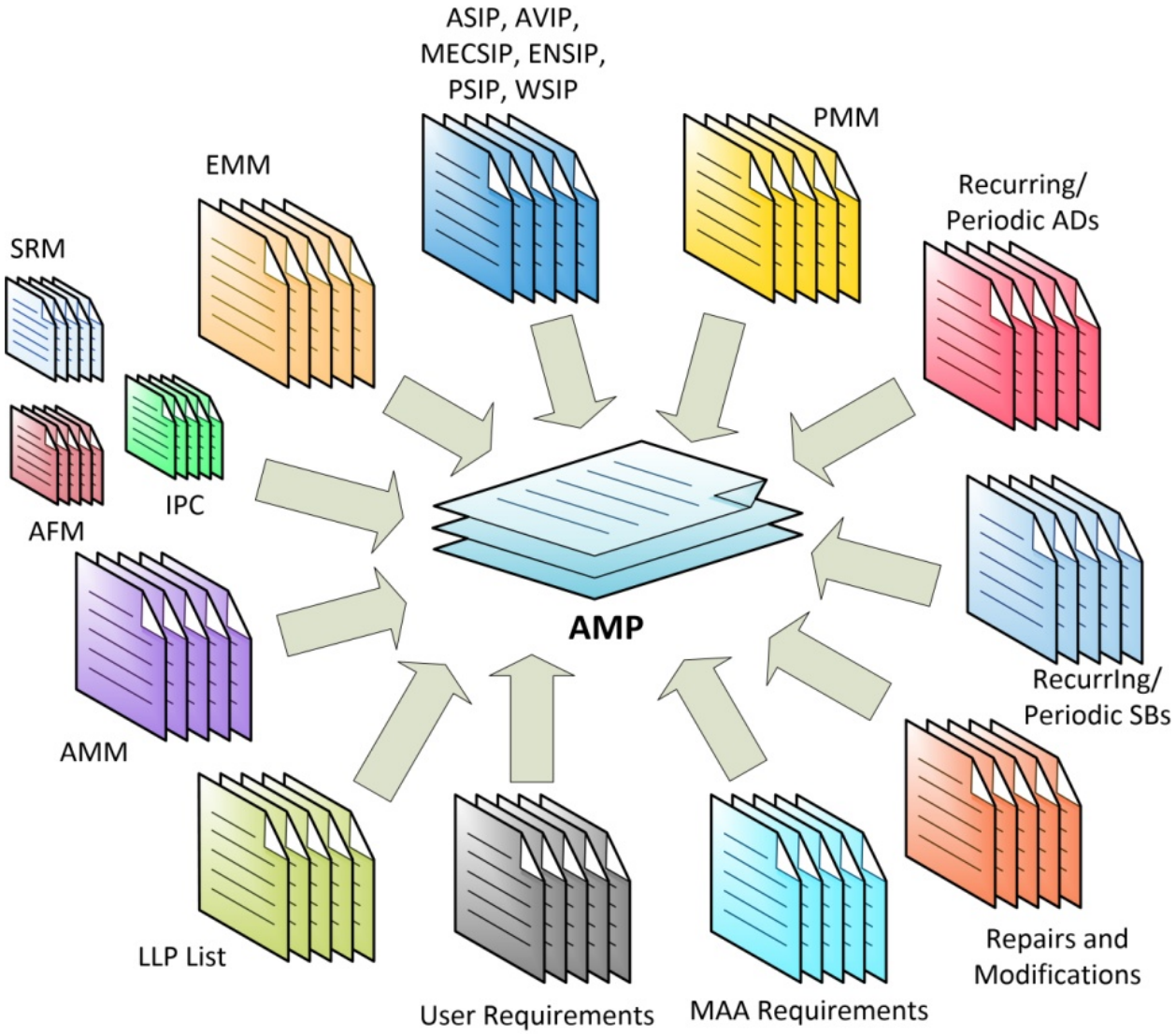


Figure 5-1: Typical Sources for AMP Development.

Note: PMM – Propeller Maintenance Manual, AD – Airworthiness Directive, SB – Service Bulletin, LLP – Life Limited Parts, AMM – Aircraft Maintenance Manual, AFM – Aircraft Flight Manual, IPC – Illustrated Parts Catalogue, SRM – Structural Repairs Manual, EMM – Engine Maintenance Manual.

EMAR M makes it possible to use others than MRB processes for AMP development. Practically it may lead to use two alternative approaches: Reliability-Centered Maintenance (RCM) [11] or Continuous Improvement Preventive Maintenance, S4000P [12]. Detailed discussions about these approaches are outside the scope of this chapter and therefore only a cursory comparison is shown in Table 5-3.

Table 5-3: RCM vs S4000P vs MSG-3 Comparison. Source: Ref. [13].

Systems and Powerplant Analysis					Zonal Analysis			Structure Analysis		
RCM										
Safety	?	Mission	?	Economy	Standard zonal analysis	?	?	SSI analysis	?	Other structure analysis
S4000P										
Safety	Law/ Ecology	Mission	Operation	Economy	Standard zonal analysis	Enhanced zonal analysis incl. L/HIRF analysis		SSI analysis	Maintenance rel. structure analysis	Other structure analysis
MSG-3										
Safety	?	?	Operation	Economy	Standard zonal analysis	Enhanced zonal analysis	L/HIRF analysis	SSI analysis	?	Other structure analysis

Note: SSI – Structurally Significant Items.

EMAR M (M.A.302(f) refers) [7] requires that any AMP should contain a Reliability Programme (RP) unless otherwise specified by MAA. It is a substantial difference in comparison with Part-M provisions (Part-M: M.A.302(f) refers), which requires a RP to be included in the AMP only for complex motor-powered aircraft (CMPA) [14], when the AMP is based on Maintenance Steering Group (MSG) logic or on Condition Monitoring.

RP's ultimate aim is to ensure that the all AMP tasks are effective and their frequency is appropriate. The RP has two basic functions:

- RP is understood as an element of statistical processing of reliability data, providing summary information on the reliability of the entire aircraft fleet and its components, thus reflecting the effectiveness of the AMP being implemented, providing appropriate ways to monitor the effectiveness of the AMP; and
- RP provides timely and important technical information that allows reliability to be maintained at the required and acceptable level through changes to the AMP or ways of its implementation. The result may be the extension or limitation of maintenance activities, as well as the re-extension or addition of maintenance activities.

The RP enables continuous control and analysis of maintenance activities, thereby revealing unfavourable trends in the maintenance process and effecting the effective corrective actions. These actions should take into account the economic aspects, in particular, the cost of achieving required reliability level.

The reliability of the aircraft, aircraft systems, components, engines and Auxiliary Power Units (APU) are monitored through comparison with established reliability quantitative parameter alarm levels. This system prevents the development of unfavourable tendencies as a result of corrective actions in due time.

The resulting reliability quantitative parameters and the corresponding alarm levels cannot be compared with reliability parameters and alarm values provided by manufacturers or other aviation organisations without prior checking of the compatibility of the applied analytical methods.

In an RP alarm, values definitions can be different for a product (aircraft, engines, propeller) vs. components, as illustrated in the Table 5-4.

Table 5-4: Reliability Quantitative Parameters and Alarm Levels for Components, Engines and APU. Source: Author's own work.

Reliability Quantitative Parameter/Alarm Types (States)	Components Other than Engine or APU	Engine or APU
Examples of reliability quantitative parameters (RQP) considered in RP.	Removal Rate, Failure Rate, Mean Time Between Removals (MTBR), Mean Time Between Failure (MTBF), Mean Time Between Unplanned Removals (MTBUR).	For engine: In-Flight Shut-Down, Unplanned Removals Rate, Shop Visits Rate. For APU: Removal Rate, Number of successfully performed APU start-ups per 100 attempts of APU start-ups during flight, MTBR, MTBF, MTBUR.
Normal State (NOS).	Occurs when the monthly and -month RQP is below the Upper Control Limit (UCL) of the alarm value or above the Lower Control Limit (LCL) of the alarm value depending on the type of RQP being considered.	Normal state occurs when 3 monthly and 12 monthly RQPs simultaneously do not exceed the alarm value.
Preliminary Alarm State (PAS).	Occurs when the monthly RQP is above the UCL or below the LCL depending on the type of RQP being considered and the 3-month RQP is below the UCL or above the LCL depending on the type of RQP to be considered. This condition warns of the possibility of an emergency situation in the coming month.	This condition occurs when the 3-month RQP exceeds the alarm level and the 12-month RQP does not exceed this level. This condition warns of the possibility of an emergency situation in the next quarter.
Critical Condition State (CCS).	Occurs when the monthly and 3-month RQP is above the UCL or below the LCL, depending on the type of RQP to be considered.	This condition occurs when 3-month and 12-month RQPs simultaneously exceed the alarm level.

Reliability Quantitative Parameter/Alarm Types (States)	Components Other than Engine or APU	Engine or APU
Pre-Alarm Condition State (P-ACS).	Occurs when the monthly RQP is below the UCL or above the LCL depending on the type of RQP to be considered and the 3-month RQP is above the UCL or below the LCL depending on the type of RQP being considered. This state indicates a slow and gradual improvement of the situation.	N/A

The Alarm Levels (AL) could be defined in various ways from the simple to very complex e.g., such as:

$$AL = \text{Mean of RQP} \pm 2 * \text{Standard Deviation of RQP} \quad (5\text{-}1)$$

$$AL_{UPL} = \text{Mean of RQP} + 2 * \text{Standard Deviation of RQP} \quad (5\text{-}2)$$

$$AL_{LCL} = \text{Mean of RQP} - 2 * \text{Standard Deviation of RQP} \quad (5\text{-}3)$$

5.4 OCCURRENCE REPORTING

According to the EMAR's set provisions, organisations involved in both continued/design and continuing airworthiness activities, except EMAR 147 MTO, must establish an occurrence reporting system. Within EMAR requirements context an occurrence means: "Any failure, malfunction, defect or other occurrence which has resulted in or may result in an unsafe condition".

Thus any of the above mentioned organisations is required to:

- Record occurrences;
- Submit reports within 72 hours of the event in accordance with the reporting lines scheme schematically shown in the Table 5-5; and
- Have the necessary procedures, defined in their organisational expositions, to follow-up and close occurrence reporting analyses at the discretion of their MAA.

The objective of the occurrence reporting is the prevention of accidents and incidents by means of reporting, collecting, storing, protection and dissemination of the occurrence related information only, and not to assign blame or responsibility on the reporting persons.

The details about occurrence reporting will be included in EMAD 20-20, which is currently under development. It is expected that in case of aircraft technical occurrences related with the structure, the following occurrences should be reported:

- Damage to a Principal Structural Element (PSE);
- Damage to or defect of a structural element exceeding allowed tolerances whose failure could: reduce the structural stiffness, result in the liberation of items of mass or jeopardise proper operation of systems; and
- Loss of any part of the aircraft structure in flight.

Table 5-5: EMAR's Occurrence Reporting Requirements. Source: Author's own study.

Who/To Whom	NMAA	EMAR 145 AMO	OO/CAMO	External CAMO	MTCH	EMAR 21/F	EMAR 21/G (MPO)	EMAR 21/J (MDO)
NMAA		-	-	-	-	-	-	-
EMAR 145 AMO	+		+	+	+	+	+	+
OO/CMO	+	+		+	+	+	+	+
External CAMO	+	-	+		+	+	+	+
MTCH	+	-	-	-		-	-	-
EMAR 21/F	+	-	-	-	+		-	-
EMAR 21/G (MPO)	+	-	-	-	+	-		-
EMAR 21/J (MDO)	+	-	-	-	-	-	-	

Note: MPO – Military Production Organisation; MDO – Military Design Organisation

5.5 IDENTIFICATION OF SOURCES OF POTENTIAL PROBLEMS RELATED TO THE MAINTENANCE PROCESS AFTER THE IMPLEMENTATION OF EMAR

Currently, there are no publications identifying sources of potential problems related to the maintenance process in relation to EMAR requirements implemented in EU countries. However, some conclusions can be drawn from the published results of audits carried out by civil aviation authorities in Europe.

The UK Civil Aviation Authority (UK CAA) oversees approximately 1,400 production, maintenance, continuing airworthiness and maintenance training organisations. Each year, it performs over 4,000 audits of these organisations and detects in their course several thousand findings, of which about 14% concern the organisation, including about 1/3 of non-compliances related to the ineffective quality/compliance system [15]. Of the three major sources of non-compliance with a high and moderate impact on safety identified by the UK CAA, unfortunately, the quality system is put on the outsider's position [15] – see Figure 5-2.

The Polish Civil Aviation Authority (PL CAA) oversees about 60 Part-145 maintenance organisations and about 90 continuing airworthiness management organisations. Annually, it conducts several hundred audits in these organisations, during which it detects on average 6 – 10 non-compliances per audit [16]. The main sources of non-compliance identified by PL CAA during certification audits and audits as part of ongoing oversight are presented in Figure 5-3, from which it can be seen that the main sources of non-compliance should be sought in the organisation exposition, personnel, quality system and aircraft maintenance programme.

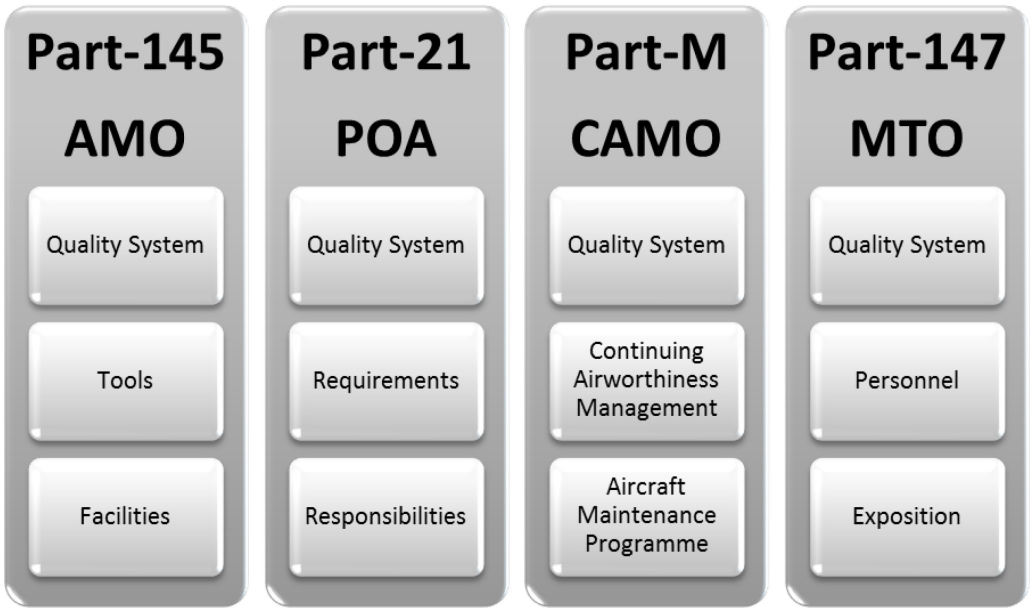


Figure 5-2: The Three Principal Sources of Non-Compliance with High and Moderate Safety Impacts Identified by the UK CAA During Audits. Source: Author's own study based on Ref. [15].

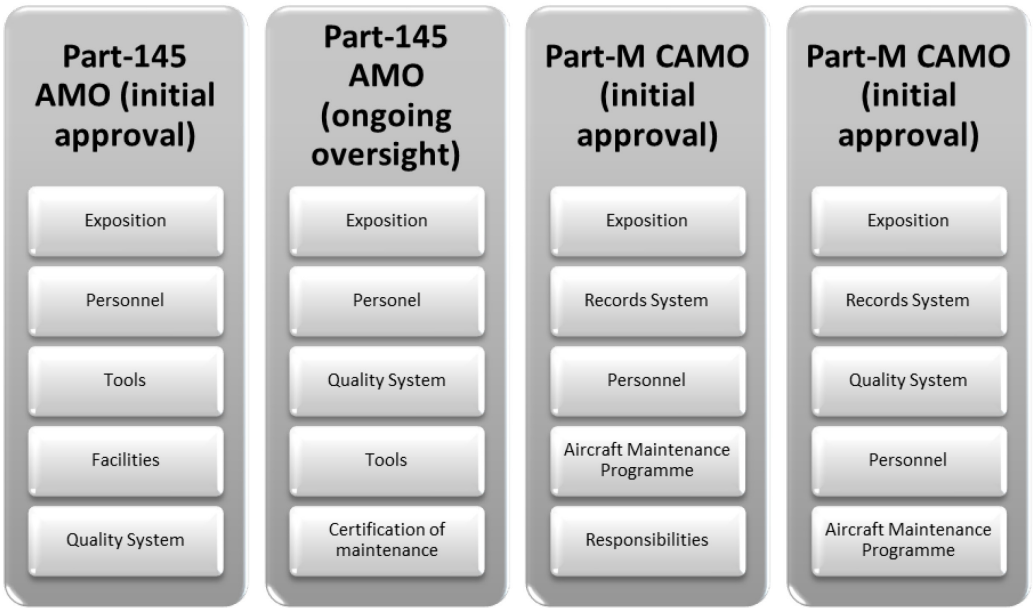


Figure 5-3: The Principal Sources of Non-Compliance Identified by PL CAA During Audits in Supervised Part-145 and CAMO Organisations. Source: Author's own study based on Ref. [16].

5.6 CONCLUSIONS

As indicated in the summary of Chapter 4.5, the current airworthiness system of military aircraft in Poland is not fully compliant with EMAR, although it provides equivalent level of safety.

The gradual replacement of military aircraft fleet in Poland, including in particular the acquisition of new Military Commercial Derivative Aircraft (MCDA) i.e., G550 and B737-800 has necessitated a gradual

change in Polish military airworthiness regulations towards fulfilling NATO commitments and taking full advantage from a harmonized approach to airworthiness in a complementary sense to EASA and non-European military airworthiness authorities.

The challenge does not necessarily lie in the general understanding of EMAR requirements, but in the detailed implementation of distinct requirements in Polish military airworthiness regulations, in particular EMAR 145 and EMAR M planned for the near future.

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Part 2: AIRCRAFT STRUCTURAL SYSTEMS



Chapter 6 – AIRWORTHINESS OF STRUCTURES (UNITED STATES)

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6.1 INTRODUCTION

The United States Air Force (USAF) established the Aircraft Structural Integrity Program (ASIP) in November 1958 in response to in-flight structural failures resulting in five destroyed B-47 aircraft from March through April 1958 [1]. Four of the B-47 losses were attributed to fatigue, which led to a probabilistic approach for establishing the aircraft service life capability. This was called the "safe-life" approach, and it relied upon the results of a laboratory test of a full-scale airframe subjected to loading that simulated the operational service environment of the aircraft. The USAF established the safe life of the aircraft by dividing the number of successfully test simulated flight hours by a scatter factor. The intent of the factor was to account for aircraft-to-aircraft variation in materials and manufacturing quality. The USAF believed the process to be sufficient to preclude in-service structural failures attributable to fatigue. The safe life approach was the basis for all new designs during the 1960s and was also used to establish the safe life of earlier designs that were subjected to a fatigue test. Losses of an F-111 in December 1969 and an F-5 in April 1970 [1], each far short of their qualified safe life, demonstrated that the safe life approach had shortcomings. The safe life approach allowed the use of low ductility materials operating at high stresses, which resulted in designs that were intolerant to manufacturing and service-induced defects. The aircraft failures arising from the deficiencies of the safe life approach demanded a fundamental change be made in the design, qualification, and inspection of aircraft. The damage tolerance approach emerged as the candidate chosen for this change.

Developers of the damage tolerance approach recognized that an aircraft's structure is subject to a wide range of initial quality from manufacturing processes as well as from service-induced damage during operations and maintenance. They also recognized that the aircraft structure had to be inspectable. To ensure the aircraft operates safely in the presence of anomalies, the USAF requires the structure to tolerate the defects for some inspection-free period of service usage. The damage tolerance approach provides the USAF a safety limit for each critical area in the aircraft. The safety limit is the time, in flight hours, required for a crack to grow from either an assumed initial flaw size, or the inspectable flaw size, to a critical size. Inspections are scheduled to occur at a time equal to one-half the determined safety limit. The USAF used the damage tolerance approach to upgrade the structural integrity of several operational aircraft in the early 1970s including the F-111, C-5A, and F-4. The success of these efforts convinced the USAF that damage tolerance should be the structural safety basis for all future designs. In December 1975, the USAF formally integrated the damage tolerance approach into the ASIP. During the 1970s and 1980s, the USAF performed a damage tolerance assessment on every major aircraft weapon system to develop inspection or modification programs necessary to maintain operational safety. The results of the damage tolerance assessments were incorporated into USAF Technical Orders which established maintenance requirements to maintain structural integrity and to control risk to an acceptable level.

6.1.1 Initial Airworthiness

The process to achieve initial airworthiness certification for the aircraft structure is established in ASIP MIL-STD-1530 [2]. The process requires establishing the design information, performing design analyses and development testing, performing full-scale ground and flight testing, and resolving findings that indicate one or more requirements are not satisfied. The culmination of these activities is the development of the force management approach which includes the items listed below:

1) The flight limits (Mach, altitude, rates, accelerations, etc.) that were used to establish the initial airworthiness certification are documented in the flight manual Technical Order (TOs) or similar product;
2) The maintenance requirements to maintain airworthiness are established and documented in TOs, depot work specifications, and other products as needed;
3) A force management method is developed and implemented prior to initiation of operations to: determine actual usage for the fleet and each aircraft, adjust planned inspection intervals for each individual aircraft as needed, update analysis as required, perform surveillance inspections, and revise the maintenance requirements as needed; and
4) Finally, a Service Life Limit (SLL) is established and documented in the flight certificate/authorization.

6.1.2 Continued Airworthiness for Operations Up To ~50% SLL

1) Execute maintenance and force management requirements as initially established. This includes collecting and evaluating operations and maintenance data related to structural integrity such as: damage, repairs, modifications, and component replacements;
2) Collect and evaluate Loads/Environment Spectra Survey (L/ESS) data, determine if flight limits are being exceeded, and develop baseline operational loads spectra;
3) Perform Durability and Damage Tolerance Analysis (DADTA) update using baseline spectra and revise the SLL if required;
4) Collect and evaluate Individual Aircraft Tracking (IAT) data, adjust maintenance intervals for each aircraft based on actual usage, and track each aircraft to its SLL;
5) Perform corrosion assessments;
6) Perform Analytical Condition Inspection (ACI) program;
7) For safe life managed components (e.g., landing gear structure), perform depot overhauls to preclude the need to track each component up to their SLL and then replace it or execute safe life as intended for selected components; and
8) Revise the aircraft maintenance requirements based on results of above.

6.1.3 Continued Airworthiness for Operations Approaching SLL

1) Continue to execute all tasks described above;
2) Perform teardown inspection and evaluation of high time aircraft if practical and deemed necessary;
3) Perform structural risk analysis and compare results to established maintenance intervals; and
4) Update Non-Destructive Inspection (NDI) equipment, procedures, training, etc. as required to enable maintenance intervals to control risk to the acceptable level.

6.1.4 Continued Airworthiness for Operations Beyond SLL

1) Perform full-scale airframe durability test, verify no onset of Widespread Fatigue Damage (WFD) up to the desired SLL increase;

2) Implement modifications based on service, analysis and test results to increase the SLL as required; and

3) Document the revised SLL in each aircraft's flight authorization when modifications (if required) are implemented.

6.1.5 USAF Aircraft Structural Safety Experience

As a measure of success for the USAF implementation of the damage tolerance approach, the USAF destroyed aircraft rate due to structural reasons is approximately three destroyed aircraft per ten million flight hours accumulated in the fleet. This is approximately ten times lower than the overall USAF destroyed aircraft rate due to all causes, except combat related. Accordingly, the USAF believes the damage tolerance approach incorporated into the ASIP in the 1970s continues to be the cornerstone for protecting the safety of the USAF fleet. To illustrate this point, Figure 6-1 compares USAF destroyed aircraft rates for all causes except combat related and the subset associated with structural failures. The "All Causes except Combat" plot is based on annual rates of USAF aircraft losses since the USAF was established in 1947. The "Structural Failure" plot shows the cumulative rate of aircraft losses due to structural failure since the damage tolerance philosophy was implemented into the USAF in 1975.

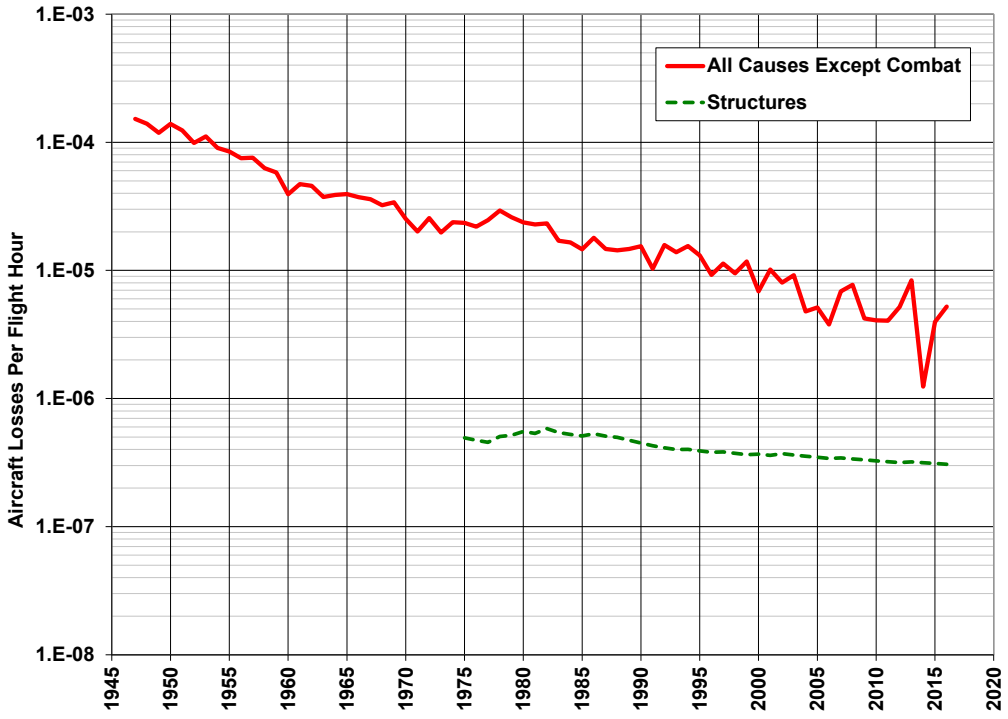


Figure 6-1: USAF Destroyed Aircraft Rates.

6.2 REFERENCES

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Chapter 7 – APPROACH TO STRUCTURAL RISK ANALYSIS (USAF)

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7.1 RISK ANALYSIS BACKGROUND

The quantitative substance of a probabilistic risk analysis is contained within the Probability Of Failure (POF) calculation. The POF for aircraft structures is calculated for known Fatigue Critical Locations (FCLs) using a probabilistic approach to fracture mechanics analyses so that variabilities in loads, material, and initial flaw sizes can be accounted for. Inspection and repair variabilities are also modelled to determine the effectiveness of different methods.

In a fracture mechanics approach to probabilistic risk analysis, failure is defined as the probability that the maximum stress encountered in a flight will produce a stress intensity factor at an FCL that exceeds the fracture toughness of the material. Figure 7-1 is a simplified schematic of how a distribution of initial flaw sizes is projected to grow along a deterministic crack growth curve as a function of time. At time T_1, some proportion of this distribution is greater than the critical crack size, i.e., the crack size at which the fracture toughness is exceeded (which may or may not be deterministic as shown here). This proportion translates into probability of failure at T_1.

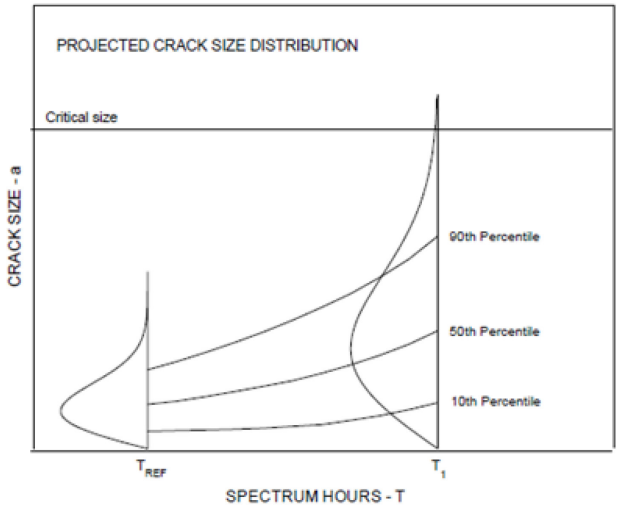


Figure 7-1: Schematic for Projecting Crack Size Distribution as a Function of Flight Hours [1].

7.2 OVERVIEW OF INPUT DATA FOR RISK ANALYSIS

Dr. John (Jack) Lincoln is credited with maturing the USAF Aircraft Structural Integrity Program (ASIP) and defined many risk assessment practices that are still in use today. The PRobability Of Fracture (PROF) program [1] put Lincoln's risk analysis method into software form and was the first for quantifying risks associated with inspection, replacement, and retirement decisions for aging USAF aircraft. This method accounted for a growing population of cracks in aircraft structure while factoring in the uncertainties

associated with material properties, usage, inspection, and repair. Program inputs included material and geometry information, aircraft usage, Non-Destructive Evaluation (NDE) information, and repair capabilities. It should be noted that many current USAF structural risk analyses are based on the original Lincoln and PROF methods, but are not limited to them.

Table 7-1 lists typical inputs that are used in a risk analysis as well as possible sources of the data. The following sections will explain each input in detail.

Table 7-1: Input Data for Risk Analysis.

Item	Description	Type	Form	Source
1	Normalized Stress Intensity Factor, K/σ vs Crack Length	Deterministic Curve	Data File	DTA Analysis
2	Fracture Toughness	Normal Distribution	Distribution Parameter Values	Material Data
3	Number of Analysis Locations per Airframe and Number of Airframes in Fleet	Constants	Values	DTA Locations and FSMP Data
4	Initial Crack Size Distribution	Cumulative Distribution Function	Data Files	Experience, Teardown Data, Estimates
5	Crack Growth Life Curve	Deterministic Curve	Data File	DTA Analysis
6	Maximum Stress per Flight	Gumbel Distribution	Distribution Parameter Values	Flight Test Data DTA Analysis
7	Inspection Intervals	Constants	Values	User Defined
8	Probability of Detection (POD) for NDE System	Cumulative Lognormal POD Function	Function Parameter Values	Experience with NDE System
9	Crack Size Distribution at Repaired Crack Sites	Cumulative Distribution Function	Data File	Repaired as Good as New, Equal to Initial Crack Size Distribution, or Other Assumption

7.2.1 Normalized Stress Intensity Factor

The geometry of the crack growth location is accounted for by the normalized stress intensity factor, K/σ. The stress intensity factor K(a) for a linear elastic fracture mechanics analysis is expressed as:

$$K(a) = \sigma\beta\sqrt{\pi a} \tag{7-1}$$

where:

σ = the reference stress;

β = a geometry correction factor that depends on the size and shape of the crack; and

a = the relevant crack size dimension, usually crack depth or surface crack length.

Geometry correction factors (β) are obtained from the crack growth model and a normalized stress intensity factor, α(a) or "alpha", is defined as:

$$\alpha(a) = \frac{K(a)}{\sigma} = \beta\sqrt{\pi a} \tag{7-2}$$

Risk analysis software generally requires the input of the stress intensity factor in this normalized form using a data table of crack length and corresponding alpha. Since this form is independent of stress, the same alpha curve theoretically represents any aircraft usage.

7.2.2 Fracture Toughness

The variability in fracture toughness is typically modelled by a normal distribution. Fracture toughness data should be compiled from tests of the material that comprises the FCL. A typical Coefficient Of Variation (COV) for aircraft aluminums is 10%; however, this value should only be used as a guide. Fracture toughness data found in literature or databases is a reasonable substitute when test data from the FCL is not available.

7.2.3 Initial Crack Size Distributions

A distribution of initial crack sizes is necessary for the risk analysis calculation, as well as the distribution of flaw sizes that would be present following an inspection and a repair. This distribution usually takes the form of lognormal or Weibull since negative values are not possible. Studies have found that the POF can be very sensitive to this variable, particularly when the critical crack size is small (less than one inch) [2]. Therefore, care must be taken to properly characterize it.

A common method for determining an initial crack size distribution is with the Equivalent Initial Flaw Size (EIFS) method as outlined in the 1989 USAF Durability Design Handbook [3]. According to the Handbook, the EIFS is a *hypothetical* crack that is meant to capture the equivalent effect of *actual* material imperfections such as random scratches, microscopic flaws, or other damage types. An EIFS distribution is determined by taking a population of crack sizes with known usage and using the crack growth curve to determine their sizes at time 0.

EIFS data should come from teardown data of the FCL of interest, when possible. See Ref. [2] for methods of determining the EIFS distribution from teardown data. EIFS data from other sources should only be used as a last resort and should, at minimum, be of the same material and geometry (such as an edge detail or hole detail). The material form and manufacturing process can also have a significant effect on the EIFS distribution.

7.2.4 Crack Growth Life Curve

The crack growth analysis used for the DTA of the location is usually the same used for the risk analysis. Initial crack lengths of 0.05 inches or 0.005 inches are common for DTA analyses. However, initial crack lengths assumed in risk analyses are typically much smaller. The deterministic crack growth analysis should be run from the smallest point in the initial flaw size distribution and use the largest possible fracture toughness to ensure that the curve covers all possible input values.

It is also possible to use a probabilistic crack growth analysis that varies crack growth rate and geometry parameters. Due to the increased complexity of the analysis, Monte Carlo and other sampling methods are recommended.

7.2.5 Maximum Stress Per Flight

The distribution of maximum stress per flight models the peak stress expected in a flight and can be gleaned from spectrum or exceedance curve data. The typical model of the peak stress per flight exceedance curve is in the form of a Gumbel (extreme value) distribution with parameters A and B. The Gumbel exceedance Cumulative Distribution Function (CDF) has the form:

$$H(\sigma) = exp\{-exp[-(\sigma - B)/A]\} \tag{7-3}$$

where H(σ) is the probability of exceeding a certain stress in a flight, and the constants A and B are determined using a least squares curve fit to the stress exceedance data.

The PROF manual describes a procedure for fitting a Gumbel distribution to exceedance data [1]. First, the exceedance curve must first be converted to the distribution function, $F_{all}(\sigma)$:

$$F_{all}(\sigma_i) = 1 - \lambda(\sigma_i) / \lambda(\sigma_{thr}) \tag{7-4}$$

where $\lambda(\sigma_i)$ is the number of peak stresses per unit time exceeding σ_i and $\lambda(\sigma_{thr})$ is the number of exceedances per unit time of the stress threshold. Let n represent the average number of stress peaks per flight greater than threshold:

$$n = (\text{\# of peaks in spectrum}) / (\text{\# of flights in spectrum})$$

Then, the cumulative distribution of the maximum stress per flight is estimated by:

$$F_{max}(\sigma_i) = [1 - \lambda(\sigma_i) / \lambda(\sigma_{thr})]^n \tag{7-5}$$

Next, Equation (7-3) can be transformed to:

$$ln\{-ln[H(\sigma_i)]\} = -\sigma_i / A + B / A \tag{7-6}$$

A least squares fit of the $(\sigma_i , ln\{-ln[H(\sigma_i)]\})$ data pairs will yield estimates of $-1/A$ and B/A. To ensure that the fit is acceptable at the high stress levels of most influence in the hazard computation, only the highest stress ranges in the data should be used in determining the least squares fits. It might be noted that B is the stress that is exceeded in 63 percent of the flights and A is proportional to the steepness of the exceedance probability vs. stress curve. The larger the value of A, the flatter the exceedance probability curve (resulting in a larger probability of large maximum stress peaks in a flight).

A practical approach to estimating A and B is to vary these parameters until an acceptable fit is obtained for the probability of exceeding the high stress levels which drive POF calculations. Engineering judgement is required when selecting the appropriate fit. It is easily possible to have a large estimate of A that can result in a probability of encountering a practically impossible stress. If these artificially high stress estimates are found to drive up the POF, a Weibull exceedance curve may be more suitable.

7.2.6 Initial and Recurring Inspection Intervals

Initial and recurring inspection intervals are determined by the DTA analysis. Alternatively, the risk analysis may be used to set the inspection intervals. This is known as risk-based maintenance. For example, the maintainer may wish to perform an inspection when the FCL of interest is reaches a POF of a certain value. Care must be taken to ensure that all variables are properly characterized and that appropriate conservatism is included.

7.2.7 Probability of Detection Curves

Inspection capability is typically modelled using a lognormal CDF of the Probability Of Detection (POD). The parameters that define the POD curve are the median detectable crack size, a_{50}, and the POD slope parameter. A third variable, known as the minimum detectable crack size, is an optional input for cases when a crack may not be detectable until it reaches a certain length, such as when the crack surface is covered by the head of a fastener.

Structures Bulletin EN-SB-08-012, Rev. D, defines the recommended Non-Destructive Inspection (NDI) capability flaw sizes for USAF aircraft structures when no other supporting data is available [4]. Customarily, the capability of an inspection system is quantified by a_{90}, the crack length at which the POD is 0.90. A full POD curve can be developed using the a_{50} and a_{90} values from EN-SB-08-012, Rev. D.

7.2.8 Probability of Inspection

In addition to a POD curve, the Probability Of Inspection (POI), i.e., the probability that the location was inspected correctly or at all, should also be taken into account. This POI term accounts for the possibility that an inspection at a location may not be performed as required and acts as a multiplier (scale factor) on the POD function. For example, using a POI value of 0.90 would imply that ten percent of the inspections were not performed satisfactorily.

7.2.9 Repair Strategies

The risk analysis should take into account any repairs that occur due to NDI crack detections. The most common way of incorporating these repairs in risk analysis is by using a “repair flaw size distribution” for the affected population. In the simple case of a replacement of a part with an identical new part, the initial flaw size distribution can be used as the repair flaw size distribution. Repairs that are more complicated require careful consideration of possible changes to geometry, residual stress fields, and repair-induced damage.

7.3 PROBABILITY OF FAILURE CALCULATION

A cumulative probability of failure calculation determines the probability that the FCL will experience a failure due to fracture throughout its lifetime. A more useful metric is a hazard rate, or the probability that failure will occur over a certain time period, given that failure has not already occurred. For this metric, Lincoln proposed the term “single flight probability of failure,” or SFPOF, for use in risk assessment of military aircraft [5], [6]. SFPOF, in hazard rate terms, is “the probability that a structural element will fail in flight t, given that it has survived flight t-1.” This definition accounts for the possibility that prior failures may have occurred, as opposed to a cumulative POF. This section will outline a method for calculating POF and the corresponding SFPOF and is taken from Ref. [7].

An analytical approach for computing cumulative or single flight probability of failure is based on the concept of conditional expectation [8]. In this method, probability of failure is expressed analytically in terms of one random variable, known as the control variable, while all others are held constant. Then, the overall probability is computed by integrating over the other random variables. In probabilistic terms, this is taking the expectation of the conditional probability over the other random variables. This approach enables formulation of failure probability as a tractable, low-dimensional integral, while still taking proper account of maximum stress per flight.

First, consider the cumulative probability of failure up to flight t. This represents the distribution of time-to-failure as a function of flights. The control variable will be maximum stress per flight, so the probability of failure conditional on initial crack size and fracture toughness is defined here first. The cumulative probability of failure during the first t flights is equal to one minus the probability of surviving

the first t flights. Given the initial crack size a_0 and fracture toughness K_c, the probability of surviving flight t is simply the probability that the maximum stress for that flight will be less than K_c/α:

$$P(\text{survive flight } t \mid a_0, K_c) = H\left(\frac{K_c}{\alpha(a_0, t)}\right) \tag{7-7}$$

where H is the cumulative maximum stress distribution, and $\alpha(a_0, t)$ is the normalized stress intensity factor for the crack at time t obtained from a damage tolerance analysis and deterministic crack growth curve. For a given a_0 and K_c, the only random variable in the problem is maximum stress per flight. Since the stress for each flight is independent, failure on each flight is independent (given a_0 and K_c). As a result, the probability of surviving the first t flights, conditional on a_0 and K_c, can be expressed as:

$$P(\text{survive first } t \text{ flights} \mid a_0, K_c) = \prod_{i=1}^{t} H\left(\frac{K_c}{\alpha(a_0, i)}\right) \tag{7-8}$$

Now the cumulative probability of failure can be defined:

$$\text{POF}(t \mid a_0, K_c) = 1 - \prod_{i=1}^{t} H\left(\frac{K_c}{\alpha(a_0, i)}\right) \tag{7-9}$$

Equation (7-1) to (7-9) gives the cumulative failure probability conditional on particular values of initial crack size and fracture toughness. In order to introduce these as random variables, take the expectation of Equation (7-9), which is a double integration:

$$\text{POF}(t) = \int_0^\infty \int_0^\infty \left[1 - \prod_{i=1}^{t} H\left(\frac{K_c}{\alpha(a_0, i)}\right)\right] f(a_0) g(K_c) \, da_0 \, dK_c \tag{7-10}$$

where $f(a_0)$ and $g(K_c)$ are the PDFs of the initial crack size and fracture toughness, respectively.

Next, consider the single flight failure probability. The quantity of interest is the probability of failure during flight t, given that the aircraft survives the first t-1 flights. This requires a conditional probability, written in conceptual terms as:

$$P(\text{failure at } t \mid \text{survival to } t\text{-}1) = \frac{\text{survival to } t\text{-}1 \text{ AND failure at } t}{\text{survival to } t\text{-}1}$$

In terms of the cumulative failure probability POF(t), this is equivalent to:

$$\text{SFPOF}(t) = \frac{\text{POF}(t) - \text{POF}(t-1)}{1 - \text{POF}(t-1)} \tag{7-11}$$

This could be computed efficiently in terms of Equation (7-10) by performing the numerical integration on two integrands simultaneously: with and without flight t in the product. This would allow one to obtain both POF(t) and POF(t-1) without having to re-compute $\prod_{i=1}^{t-1} H\left(\frac{K_c}{\alpha(a_0, i)}\right)$ at each integration point.

SFPOF here is formulated as a post-processing operation on the POF. Therefore, calculating the POF for the entire period of interest also allows calculation of the SFPOF. Note that versions of PROF released prior to 2015 use a different SFPOF formulation that does not account for prior failures and may produce overly conservative results.

7.4 RISK ANALYSIS OUTPUT INTERPRETATION

The updated MIL-STD-882E [9] characterizes the risk of potential mishaps by using a severity category and probability level for each hazard. Severities are assigned a category code between 1 and 4, with 1 being catastrophic consequences and 4 being negligible consequences. Probability levels are assigned a letter code from A to F corresponding to the frequency of the hazard. These two codes are then combined into a Risk Assessment Code (RAC) to fully characterize the risk and the corresponding acceptance authority (see Table 7-2).

Table 7-2: USAF Airworthiness Risk Assessment Matrix.

USAF Airworthiness Risk Assessment Matrix			Severity Category			
Probability Level	Probability per FH or Sortie	Freq per 100K FH or 100K Sorties	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)	$10^{-3} \leq$ Prob	100 ≤ Freq	1	3	7	13
Probable (B)	$10^{-4} \leq$ Prob < 10^{-3}	10 ≤ Freq < 100	2	5	9	16
Occasional (C)	$10^{-5} \leq$ Prob < 10^{-4}	1 ≤ Freq < 10	4	6	11	18
Remote (D)	$10^{-6} \leq$ Prob < 10^{-5}	0.1 ≤ Freq < 1	8	10	14	19
Improbable (E)	0 < Prob < 10^{-6}	0 < Freq < 0.1	12	15	17	20
Eliminated (F)	Prob = 0	Freq = 0	Eliminated			

High	CAE Risk Acceptance RAC = 1 - 5	Medium	PM Risk Acceptance RAC = 10 - 17
Serious	PEO Risk Acceptance RAC = 6 - 9	Low	Risk Acceptance as Directed RAC = 18 - 20

Note: FH – Flight Hours.

The USAF ASIP guidelines and standards reflect an emphasis on risk analyses of aircraft structural integrity. However, the more generalized MIL-STD-882E document does not explicitly relate its probability levels to the singular FCL SFPOF values computed using risk analysis software. To provide guidance in the consistent use of MIL-STD-882E for airworthiness issues, the Air Force Life Cycle Management Center (AFLCMC) recently issued Airworthiness Bulletin 150 [10]. This bulletin lists ranges of probability of aircraft loss per flight hour and the corresponding risk acceptance authority. The risk assessment matrix is reproduced in Table 7-2.

7.4.1 Sensitivity Analysis

A sensitivity analysis can be conducted for the SFPOF calculation by changing a single input variable, leaving other inputs unchanged, and comparing the results. This type of analysis is important for when there is a large amount of uncertainty about an input, such as the initial flaw size distribution or the POD model. Figure 7-2 is an example of a sensitivity analysis considering three different POD models. The analysis shows that POD A and B are sufficient at keeping the SFPOF below the 1.0E-6 threshold, while POD C is not.

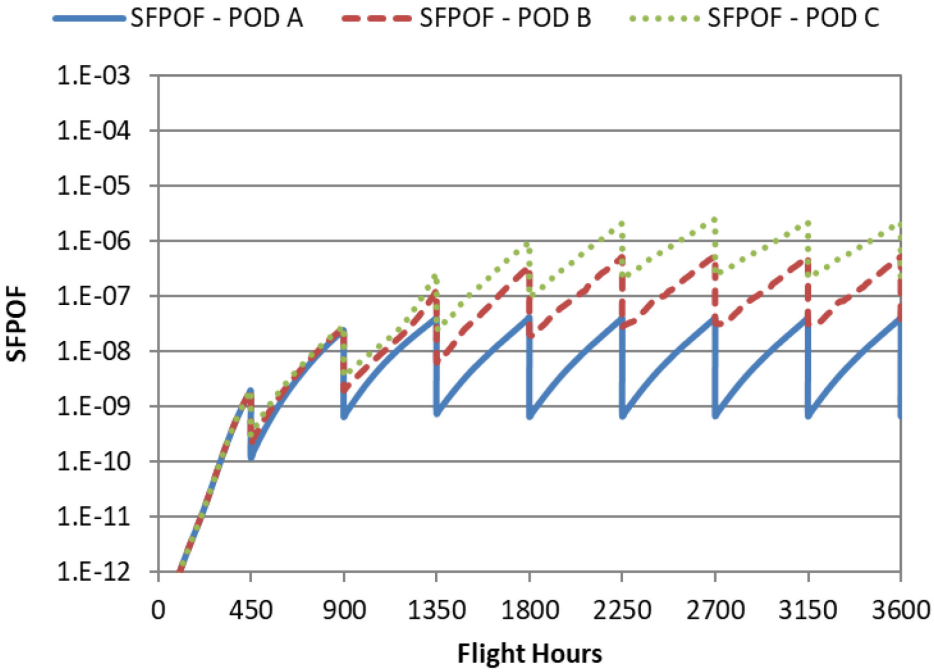


Figure 7-2: POD Sensitivity Analysis for a Fatigue Critical Location.

7.5 SUMMARY

Probabilistic risk analysis for aircraft structures is a powerful tool that can take into account geometric, material, and usage variabilities. In addition, risk analyses can be useful for comparing different inspection intervals and methods. The effects of different repair options may also be explored to determine a reasonable trade-off between repair types and their direct effect on probability of failure. Although the risk analysis methods are rigorous, the analyst must keep in mind the quality and veracity of the input data. Over-conservatism can lead to costly additional and unnecessary inspections, while under-conservatism could lead to catastrophic failure. The analyst should also keep in mind what variables are not included in the risk analysis; unknowns are often the downfall of an otherwise acceptable analysis.

7.6 REFERENCES

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Chapter 8 – CONTINUING AIRWORTHINESS OF STRUCTURES (CANADA)

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8.1 INTRODUCTION

This chapter presents a brief history of the Royal Canadian Air Force (RCAF) continuing airworthiness (CAW) process on aircraft structures. It also provides the latest RCAF references related to the CAW on aircraft structures, as well as the lessons learned and future challenges.

Under the provisions of the Aeronautics Act, the Canadian Minister of National Defence (MND) is responsible for military aviation, including foreign aircraft within Canada. Within the Department of National Defence (DND), the Technical Airworthiness Authority (TAA) is responsible for the regulation of the technical airworthiness aspects of design, manufacture, maintenance and material support of aeronautical products and the determination of the airworthiness acceptability of those products prior to operational service. The technical airworthiness program, which is outlined in the Technical Airworthiness Manual (TAM) [1], consists of three primary elements:

- Initial Airworthiness,
- Continuing Airworthiness, and
- Disposal.

A key element of the DND's CAW requirement is for an In-Service Monitoring Program (ISMP). As a minimum, the ISMP covers the monitoring activities for airworthiness directives, service bulletins, flight safety occurrences, other operator experiences and aircraft usage and condition monitoring. The Aircraft Structural Integrity Program (ASIP) falls under the ISMP.

8.2 HISTORICAL PERSPECTIVE

The RCAF was an early adopter of the United States' Department of Defense Standard Practice Aircraft Structural Integrity Program (ASIP) (MIL-STD-1530) [2]. An ASIP Master Plan was mandated for all RCAF fleets. The ASIP Tasks IV and V of the MIL-STD-1530 covered the CAW requirements for the aircraft structure.

Starting with the procurement of the CH146 helicopter (Bell 412) in 1994, the DND no longer required the inclusion of the aircraft design engineering data with the acquisition of the aircraft. As such, the information required under Tasks I, II and III of the MIL-STD-1530 was either very limited or not available to the RCAF.

Around the same time the DND started to formalize their technical airworthiness program and the assembly of the Technical Airworthiness Manual. As it was understood that the DND would have very limited influence on and access to the design information (i.e., design analysis and full-scale testing), it was decided to NOT mandate the MIL-STD-1530 in its entirety. Rather, it was decided to focus on those tasks for which the DND had control and would affect the CAW of the aircraft. This was brought under the In-service Monitoring Program chapter of Part 3 – Continuing Airworthiness of the TAM. Several annexes were included to cover the various systems of the aircraft. One of these annexes is the Aircraft Structural Integrity Monitoring Requirements.

8.3 AIRCRAFT STRUCTURAL INTEGRITY MONITORING REQUIREMENTS

The aircraft structural integrity monitoring requirements, outlined in an annex of the ISMP chapter, contains five key elements:

1) Baseline Usage;
2) Structural Usage Monitoring;
3) Structural Condition Monitoring;
4) Aging Aircraft Structural Assessment; and
5) Aircraft Structural Integrity Management Plan (ASIMP).

The ASIMP, along with providing an overview of the aircraft design and certification activities, outlines the tasks performed under the first four key elements.

The RCAF has very diverse aircraft fleets with varying operational roles. As such, the level of details required under the monitoring requirement varies from fleet to fleet. Aircraft for which the structural integrity is manoeuvre dependent requires a monitoring system that will take into account every manoeuvre flown. Whereas, aircraft that fly well-defined profile missions, such as troop transport aircraft, may only require tracking of flight hours and ground-air-ground cycles. Similarly, fleets that follow a civilian maintenance program will rely more on the Original Equipment Manufacturer (OEM) for structural condition monitoring and aging aircraft structural assessment as the OEM will be able to pool their experience from other fleet operators.

The RCAF aircraft fleets have been certified using different airworthiness standards. A summary of the RCAF aircraft structural lifing policies, including original OEM and current RCAF methods, is presented in Table 8-1 (updated from a Table from Ref. [3]). Table 8-1 indicates that two major lifing methods, i.e., Safe Life and Damage-Tolerant, are used across the RCAF fleets, either in a separate or combined manner.

Table 8-1: Summary of RCAF Aircraft Structural Lifing Policies, Original and Current.

No.	Aircraft (Fleet Age in 2019)	Service Usage (Fleet Size)	Manufacturer (When Acquired)	Original Lifing Policy	Current Lifing Policy
1	CC115 Buffalo (52 years)	SAR (6)	de Havilland (1967)	Safe Life	Safe Life, Damage Tolerance
2	CC130 H Hercules (23 to 59 years)	Transport, Tanker, SAR (12)	Lockheed Martin (1960 to 1996)	Safe Life	Damage Tolerance
3	CC130J Hercules (7 to 9 years)	Transport, Tanker, SAR (17)	Lockheed Martin (2010 to 2012)	Damage Tolerance	Damage Tolerance
4	CC138 Twin Otter (49 years)	Transport, SAR (4)	de Havilland (1970)	Residual Strength, Fail Safe	Safe Life, Damage Tolerance
5	CC144 Challenger (17 and 32 years)	VIP Transport (4)	Bombardier (1985 and 2002)	Damage Tolerance	Damage Tolerance

No.	Aircraft (Fleet Age in 2019)	Service Usage (Fleet Size)	Manufacturer (When Acquired)	Original Lifing Policy	Current Lifing Policy
6	CC150 Polaris (A310) (27 years)	Transport, Cargo, Tanker (5)	Airbus (1992 to 1993)	Damage Tolerance	Damage Tolerance
7	CF188 Hornet (31 to 37 years)	Fighter (76) (modernized)	McDonnell Douglas/Boeing (1982 to 1988)	Safe Life (US Navy MIL-STD-1530)	Safe Life, Damage Tolerance (safety-by-inspection)
8	CP140 Aurora (32 years)	Patrol (18)	Lockheed Martin (1980)	Residual Strength, Fail Safe	Safe Life, Damage Tolerance
9	CC177 Globemaster III (4 and 12 years)	Transport (4)	McDonnell Douglas/Boeing (2007 and 2015)	Damage Tolerance	Damage Tolerance
10	CT114 Tutor (Snowbirds) (57 years)	Training, Aerobatic (24)	Canadair (1962)	Safe Life	Safe Life, Damage Tolerance
11	CT142 Dash 8 (29 to 32 years)	Navigation Training (4)	de Havilland (1987 to 1990)	Damage Tolerance (FAR 25)	Damage Tolerance
12	CT155 Hawk (leased) (19 years)	Fighter Trainer (16)	BAE Systems (2000)	Safe Life	Safe Life
13	CT156 Harvard II (leased) (19 years)	Pilot Training (25)	Raytheon (2000)	Damage Tolerance (FAR 25)	Damage Tolerance
14	CH139 Jet Ranger (38 years)	Training (13)	Bell Helicopter Textron (1981)	Safe Life	Safe Life (under civilian contract)
15	CH146 Griffon (22 to 24 years)	Utility, Transport, Combat Support (85)	Bell (1995 to 1997)	Safe Life (FAR 29)	Safe Life
16	CH149 Cormorant (16 to 18 years)	SAR (14)	AgustaWestland (2001 to 2003)	Safe Life, Flaw Tolerant (JAR 29)	Safe Life, Flaw Tolerant
17	CH148 Cyclone (0 to 4 year)	SAR, Patrol (12 of 28 delivered)	Sikorski (2015 to present)	Safe Life, Damage Tolerance	Safe Life, Damage Tolerance
18	CH147F Chinook (5 to 6 years)	Tactical Transport (15)	Boeing (2013 to 2014)	Safe Life, Damage Tolerance	Safe Life, Damage Tolerance

Note: SAR – Search and Rescue; VIP – Very Important Person.

8.4 ASIP GAP ANALYSIS

In 2003 a gap analysis done against the Aircraft Structural Integrity Monitoring Requirements for all RCAF fleets revealed that while some of the RCAF fleets were mainly compliant, there were a few that had some serious deficiencies. Corrective Action Plans (CAP) were compiled by the Weapon System Managements (WSM) of the respective fleets. The progress on the CAP was reported annually to the Airworthiness Review Board. It took several years for the RCAF fleets to become largely compliant to the Aircraft Structural Integrity Monitoring Requirements.

At the time of the gap analysis, the Aging Aircraft Structural Assessment requirement was not part of the TAM. The requirement for an Aging Aircraft Assessment (AAA) was introduced under the aircraft usage and condition monitoring requirement in June 2012 with release Change 6 of the TAM. At that time it was to apply to aircraft structures and systems. However, at Change 6 of the TAM, the Annexes describing the monitoring requirement for the Mechanical Systems, Propulsion Systems, and Aircraft Electrical Wiring Interconnection Systems had not been populated. As all of the AAAs activities at DND were related to the aircraft structure, Change 7 of the TAM only included the detail requirements specified for an Aging Aircraft Structural Assessment (AASA).

8.5 STRUCTURAL USAGE MONITORING

The TAM clearly stipulates that a Structural Usage Monitoring (SUM) program shall be implemented for every aircraft type on the DND register that includes, but is not limited to, the following components. The key components:

1) A fatigue monitoring program on each individual aircraft capturing enough data to permit continual structural life consumption evaluation of lifed items;
2) A review process to compare collected fatigue data against the baseline usage on which the design and maintenance is predicated, to capture increases in usage severity or detrimental trends;
3) A process to re-evaluate component lives and/or critical locations when significant changes in usage severity is detected; and
4) Changes in fatigue life or critical locations resulting from divergences in usage severity shall be reflected in the maintenance program.

For fleets that have well-defined repetitive mission profile, such as a passenger/troop transport aircraft, the requirement can be simplified to the collection of flight hour, pressure cycles and ground-air-ground cycles resulting in a very simple SUM program. However, for aircraft that have heavily manoeuvre based missions, a more robust and detail SUM program is required. In this case a manoeuvre recognition algorithm based SUM system is required that can account for the fatigue life consumption for safety-of-flight critical components. To make thing more interesting a hybrid system may be required for aircraft that have distinct dual roll such as the RCAF CC150, which has two configurations. One configuration is solely as a passenger aircraft and second configuration as an air-to-air refueller. In the air-to-air configuration, all refuelling exercises must be tracked and the associated fatigue life damage accounted for.

All of the RCAF legacy fleets have a TAM compliant SUM program, while the newly acquired fleets are in the process of meeting the TAM SUM requirements.

8.6 STRUCTURAL CONDITION MONITORING

Similar to the SUM, the TAM stipulates the following requirement for the Structural Condition Monitoring (SCM) program:

1) There shall be a program implemented to monitor structural repairs and inspection records. The program shall apply at least to primary structure (and dynamic components for helicopters);
2) The structural condition monitoring program shall include long-term impact assessment of structural repairs at or near critical locations and other repairs;
3) The structural condition monitoring program shall include review of inspection records to determine trends in the frequency of fatigue damage in specific locations;
4) The structural condition monitoring program shall include review of service difficulty reports (or equivalent) to detect any difficulty that could impact the long-term aircraft structural integrity; and
5) A process shall be implemented to re-evaluate the maintenance program (including corrosion prevention and control procedures) as a result of detrimental trends identified through structural condition monitoring.

For the RCAF fleets meeting the above requirement is not difficult when tracking fleet-wide modifications or non-standard repairs, as these are often very well documented due to the nature of the design change. What is difficult to track are those repairs that are covered by Standard Repair Manual (SRM). Often the record set for these repairs have very limited information. Routinely, the only comment available in the maintenance record is that the damage was repaired in accordance to the repair 'XX' of the SRM. Little, if any, information is available on size of damage, making analysis of repair interaction and damage trends difficult. As a result many of the RCAF fleets are not fully compliant to the TAM SCM requirements.

8.7 AGING AIRCRAFT STRUCTURAL ASSESSMENT

DND initiated discussion with respect to an Aging Aircraft Maintenance Program in 2002. After assessment of the Aircraft Structural Integrity Programs in place for the Royal Canadian Air Forces (RCAF) aircraft fleets and review of other military air forces approaches an aging aircraft policy was drafted. This draft policy was circulated to the RCAF fleet operators and maintainers for their input and assessment of impact on the maintenance program.

The requirement for an Aging Aircraft Assessment (AAA) was initially introduced under the aircraft usage and condition monitoring requirement in June 2012 with release Change 6 of the TAM. At that time it was to apply to aircraft structures and systems. However, at Change 6 of the TAM the Annexes describing the monitoring requirement for the Mechanical Systems, Propulsion Systems, and Aircraft Electrical Wiring Interconnection Systems had not been populated. As all of the AAAs activities at DND were related to the aircraft structure, Change 7 of the TAM only included the detail requirements specified for an Aging Aircraft Structural Assessment (AASA).

The AASA are to be carried out no later than 15 years after the production of the first aircraft delivered to the RCAF. As of Dec 2017, all of the RCAF fleets that have passed the 15 year mark have undergone an AASA. Similar to the SUM and SCM requirements, the approaches taken to perform the AASA has differed based on the fleet and the Aircraft Structural Integrity Program (ASIP) for that fleet. For the fleets that pronominally follow a civilian role, such as the CC144 (Bombardier Challenger CL601/604 variants) and CC150 (Airbus A310), AASA relied heavily on the work done by the OEM under the Federal Aviation Administration (FAA) mandated program for Aging Airplane Safety [4]. For the predominately military role fleets a combination on physical audit and review of the structural maintenance records were performed as part of the AASA.

The level of effort to perform the AASAs was largely dependent on the strength of the ASIP for the fleet in question. Fleets that had a strong ASIP required little effort to perform the AASA as there was already very good documentation on the actual usage and physical condition of the airframe. Overall, the RCAF fleets are

well maintained and no significant issues were raised during the AASAs. This is largely due to having a healthy ASIPs for the RCAF fleets. This is not to say that some of the aircraft did not have corrosion issues, but these were already being monitored and addressed as part of the ASIP.

8.8 FUTURE CHALLENGES

The Aircraft Structural Integrity Monitoring Requirements are clearly defined in the TAM. However, assessing the health of the execution of the requirements will be more challenging in the future. This is due to the lack of aircraft engineering design data acquired with the new fleet acquisitions. Without access to the aircraft engineering data, it will be difficult for the RCAF to perform independent analysis. The RCAF will be heavily dependent on the OEM for all in-service support and the execution of the ASIP. To mitigate this concern the MND has built into the acquisition and in services support contracts the ability of the TAA staff to access the engineering data behind the engineering support activities executed by the OEM or in-service support contractor. This will help to ensure that SUM, SCM and AASA are based on sound aerospace engineering practices.

8.9 REFERENCES

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Chapter 9 – AUSTRALIAN STRUCTURAL INTEGRITY APPROACH

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9.1 INTRODUCTION

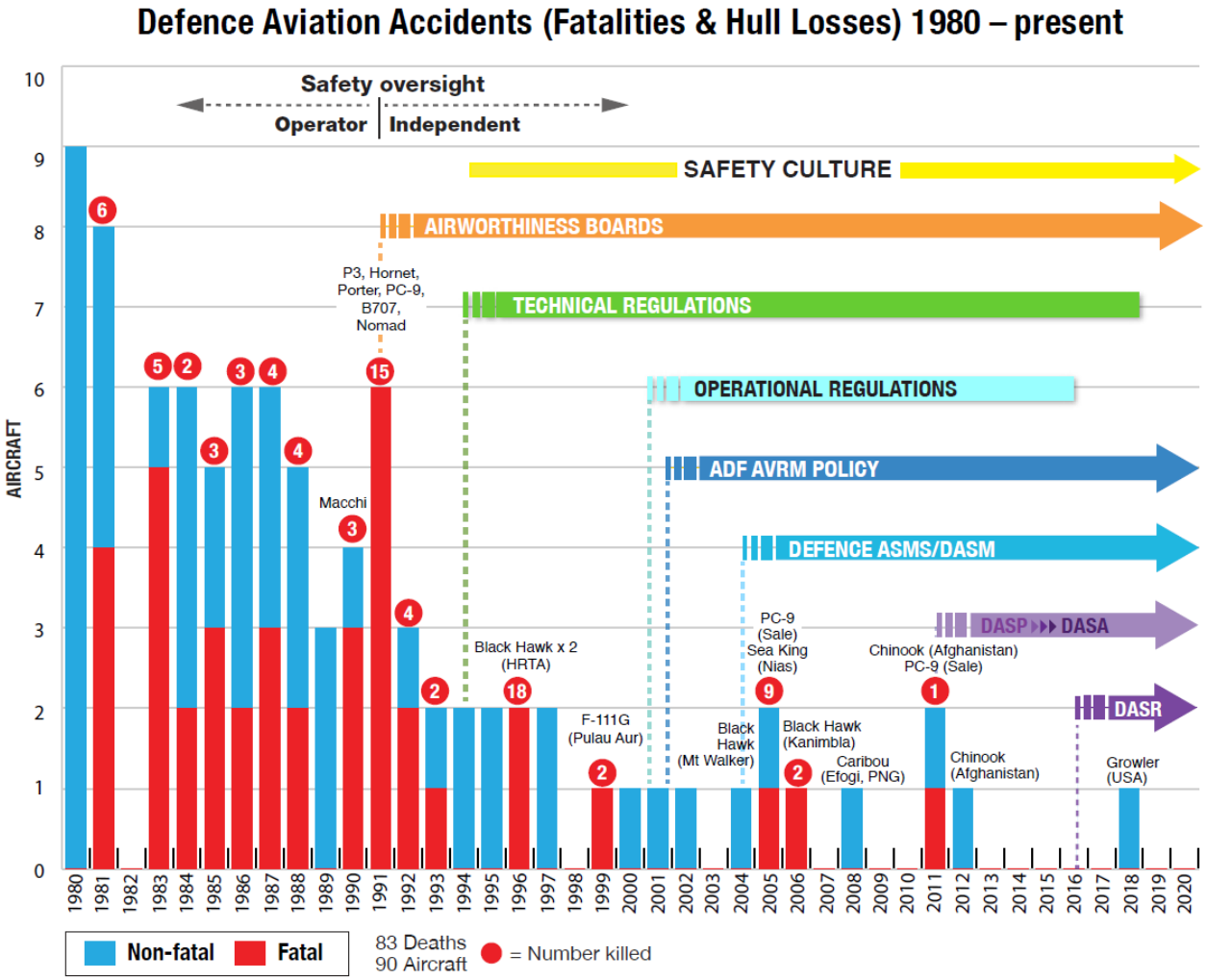
A Joint Directive signed by Secretary, Department of Defence and Chief of the Defence Force established the Defence Aviation Safety Framework as of 30 Sep 2016. The framework required the implementation of a credible and defensible aviation safety framework that recognises and supports compliance with statutory safety obligations. Where appropriate the framework was aligned with International Civil Aviation Organisation (ICAO) principles and European Military Airworthiness Requirements (EMAR). As at 01 Jan 19, the ADF fully transitioned to the Defence Aviation Safety Regulation (DASR) [1].

Under the previous Technical Regulations, the Australian Defence Force (ADF) managed Aircraft Structural Integrity (ASI) via a MIL-STD-1530 Aircraft Structural Integrity Program (ASIP), documented within an Authority approved Aircraft Structural Integrity Management Plan (ASIMP). Under the DASR, the ASIP construct was preserved for existing weapon systems and established as Acceptable Means of Compliance (AMC) for new acquisitions (as per DEFLOGMAN Part 2, Volume 10, Chapter 18 and Airworthiness Design Requirements Manual (ADRM) Section 3 Chapter 12 [2]). Responsibility for the execution of ASIP elements is divested amongst the Part 21 *Initial Airworthiness*, Part M *Continuing Airworthiness* and Part 145 *Maintenance* regulations, supplemented by ADRM Section 3 Chapter 12 *Aircraft Structural Integrity*.

As per MIL-STD-1530D [3], the ASIP is composed of the following primary tasks:

- **Task I (Design Information).** Task I consists of establishing those criteria and other requirements which must be applied during design to ensure the overall program goals will be met;
- **Task II (Design Analyses and Development Testing).** Task II consists of the characterisation of the environment in which the aircraft must operate, the testing of materials, components, and assemblies, and the analyses of the aircraft design;
- **Task III (Full-Scale Testing).** Task III consists of laboratory and flight tests of the aircraft structure to assist in determining the structural adequacy of the analysis and design;
- **Task IV (Certification and Force Management Development).** Task IV consists of the analyses that lead to certification of the aircraft structure as well as the development of the processes and procedures that will be used to manage force operations when the aircraft enters the inventory; and
- **Task V (Force Management Execution).** Task V consists of the execution of the processes and procedures developed under Task IV to ensure structural integrity throughout the life of each individual aircraft. This task may involve revisiting elements of earlier tasks, particularly if the service life requirement is extended, if the operational usage is different than the design spectrum, or if the aircraft is modified.

Figure 9-1 demonstrates the effectiveness of the ASIP approach, implemented in ADF airworthiness regulations since 1994.



ACRONYMS

ASMS	Aviation Safety Management System	DASM	Defence Aviation Safety Manual
AVRM	Aviation Risk Management	DASP	Defence Aviation Safety Program
DASA	Defence Aviation Safety Authority	DASR	Defence Aviation Safety Regulation

Figure 9-1: Defence Aviation Accidents 1980 – Present [4].

9.2 INITIAL AIRWORTHINESS

Initial Airworthiness (DASR Part 21) has obligations to support initial type certification, modifications/repairs, ongoing validation of the type design and rectification of latent defects in design. DASR Initial Airworthiness aspects, supplemented by the ADRM, broadly encompass ASIP Tasks I through IV. Under DASR Part 21 the Design Organisation is responsible for the following ASIP elements:

- Establish certification basis with verification accounting for the ADF's Configuration, Role and Environment (CRE);
- Establish structural integrity program;
- Ensure access to required type design data;
- Conduct structural assessments (including occurrence reporting on critical structure);

- Establish operational loads measurement program; and
- Maintain design / initial airworthiness aspects of the ASIP.

As per the ADRM it is essential for Initial Airworthiness of new aircraft types that flight and ground loads tests, as well as static and durability tests compliment certification by analysis. During Initial Airworthiness activities, an Aircraft Structural Integrity Documentation Package (ASIDP) is required to summarise the final analysis and other relevant structures information that will provide the basis for ADF type certification, and describe important characteristics, limitations and capabilities information for in-service management agencies.

Aircraft procured by the ADF are designed and certified to a wide range of standards such as UK and US military standards and civil Federal Aviation Regulations (FARs) and Joint Aviation Requirements (JARs). The ADF therefore accepts a range of structural design standards for type certification and continuing airworthiness. Seldom, however, is structural verification and certification undertaken with ADF Configuration, Role and Environment (CRE) in mind. The ADF must therefore, at the time of acquisition, identify the structural design standard applied during aircraft development; assess the adequacy of that standard and the adequacy of structural verification and certification for ADF CRE.

An Aircraft Structural Integrity Management Plan (ASIMP) is established during Initial Airworthiness activities to document the ASIP and sources of the in-service data pack required for ASI management activities. The ASIMP is a proactive plan that addresses the ASIP activities required to be undertaken over the short, medium and long-term of an aircraft type's service life with particular emphasis on the next three to five years. Throughout the sustainment phase, the ASIMP will reflect the activities necessary to assure that structural integrity is maintained at the level established at introduction to service.

9.3 CONTINUING AIRWORTHINESS

Continuing Airworthiness (DASR Parts M and 145) is focused on ensuring individual aircraft remain airworthy through compliance with instructions for continuing airworthiness (including usage/condition monitoring obligations), and working closely with the Type Certificate Holder in the event of a defect/occurrence. The Continuing Airworthiness Management Organisation (CAMO) is responsible for the following ASIP elements:

- Implement structural integrity program through Aircraft Maintenance Program (AMP);
- Establish routine structural (usage and condition) monitoring;
- Support operational loads measurement program;
- Support aging aircraft structural assessments; and
- Maintain continuing airworthiness elements of the ASIP.

The aircraft Maintenance Organisation is responsible for the following ASIP elements:

- Execute structural management policy in accordance with Aircraft Maintenance Program;
- Support operational loads measurement program;
- Support collection of structural (usage and condition monitoring) data, including occurrence reporting for critical structure; and
- Support aging aircraft structural assessments (aircraft inspections).

9.3.1 Continuing Airworthiness for Initial Operations

Aircraft are designed to approved airworthiness standards, which prescribe the requirements that assure an acceptably low risk of structural failure. These standards recognise that aircraft structure degrades throughout its service life as a result of fatigue damage, environmentally induced degradation or accidental damage. To identify, record and assess the continuing airworthiness implications of this degradation as well as to reduce the ADF's cost of ownership and preserve aircraft availability, an ASI Assessment Cycle is implemented for each aircraft type. The ASI Assessment Cycle comprises closed loop systems for the acquisition, evaluation and reporting of fleet operational usage and condition data for the assessment of ASI, encompassing the following:

- **Usage Monitoring (UM) and Individual Aircraft Tracking (IAT).** A UM or IAT system monitors the fatigue accrual of primary structure and dynamic components through the recording, storage and assessment of aircraft usage parameters and/or strain data. In-service variations in individual aircraft usage, role changes, weight growth and stores vary the rate with which aircraft degrade due to fatigue. Often these rates exceed that forecast during initial design posing a risk that inspection intervals, Safe Life Limits (SLLs) or Component Retirement Times (CRTs) will be overflown. To avoid this risk, and that of overly conservative management (modification and inspection intervals that are too onerous), each aircraft's usage is monitored throughout its service life;
- **Operational Loads Monitoring (OLM).** Typically fitted to 10 – 20% of fleet, OLM provides direct measurement of the actual flight loads and environment experienced by the aircraft in service. Periodic validation of operational usage, environmental assumptions and design tools, using actual in-service data, serves to validate the UM and IAT systems and maintain minimum levels of conservatism in ASI management. A highly informed CRE assessment enables the ASIP manager to prolong the service life and optimize the through life cost and availability of ADF aircraft. Without an OLM system, in-service usage deviations or role changes from initial design assumptions with a likely impact for ASI, may trigger a conservative, or inefficient, lifing policy due to the degree of uncertainty in the repeated loads environment. A typical OLM system is most easily installed during production and is comprised of strain gauges and other basic sensor types coupled with ground-based data analysis and recording software; and
- **Structural Condition Monitoring (SCM).** An SCM system monitors the structural degradation of primary structure and dynamic components through the recording, storage and assessment of aircraft condition data.

Outputs from the ASI Assessment Cycle are used to ensure that inspection intervals, SLLs and CRTs from initial type certification remain valid. This information is used to verify the structural Life of Type (LOT) and remaining economic life of aircraft fleets relative to Planned Withdrawal Date (PWD). The systems which underpin the ASI Assessment Cycle are documented in the ASIMP for each aircraft type.

9.3.2 Continuing Airworthiness for Operations Approaching the SLL

An aging aircraft audit is conducted at approximately half the service life, as documented by the ASIMP. In instances of known certification deficiencies additional testing or teardown inspections may be conducted. Such a decision is guided by the activities of the ASI Assessment Cycle, which is critical to ensuring continuing airworthiness for aging platforms.

9.3.3 Continuing Airworthiness for Operations Beyond Original SLL

Planned operation beyond the original SLL essentially involves a new certification effort to verify and approve revised life limits under a Major Change to Type Design. Australia favours enhanced teardowns of

retired aircraft and component where possible in lieu of traditional teardowns and where a Full-Scale Durability Test (FSDT) is judged unnecessary to achieve the required life extension.

9.4 ENHANCED TEARDOWNS

Enhanced teardowns of ex-service aircraft structures are a method of rapid, destructive, structural experimentation devised to unlock the key data, parameters and evidence required for fleet structural integrity management. DST Group is a pioneer of this concept through its FINAL centre barrel testing program [5], [6], for F/A-18A/B fleets with demonstrated tremendous cost of ownership and availability dividends [7]. More recently, a PC-9/A wing underwent enhanced teardown at resonance to examine the fatigue effects of production misdrills in the fleet [8]. Whilst there have been notable examples of mid-life FSFT of retired airframes, sometimes identified as Damage Enhancement Tests (DET) [9], [10], FINAL and the PC-9/A wing are the best examples of enhanced teardowns undertaken in Australia thus far.

An enhanced teardown differs from traditional full-scale certification testing in at least two key aspects:

- The test article must be a retired fleet asset with the structural degradation arising from service usage 'locked in' for identification through further testing and forensics; and
- Limitations in loads fidelity are accepted from the onset if testing remains fit for purpose and can be simplified and/or accelerated as a result.

The primary benefit of the enhanced teardown approach over conventional teardowns or age exploration inspections of high time airframes [3] the improved probability of detection of production and in-service defects. Correctly sized for fatigue, a structure designed to either 'Crack Initiation' or 'Slow Growth' requirements should not exhibit detectable evidence of fatigue crack growth within one service lifetime. That is, fatigue cracking in well-designed and certified structure will remain below conventional Non-Destructive Testing (NDT) detection thresholds and should not be identified in-service. These thresholds are typically of the order of 1 – 6 mm (0.04 – 0.25 inches) length for surface breaking anomalies when using conventional eddy current inspection methods in aluminium alloys [11], [12]. The advantage of the enhanced teardown concept is that, through structural experimentation post airframe retirement, flaw sizes can be grown to and beyond detectable limits, including to failure of the structure. Optimum evidence for forensic analysis, Quantitative Fractography (QF) and subsequent use in Aircraft Structural Integrity (ASI) management is therefore developed from an enhanced teardown. Further it is good practice to investigate the robustness of an aircraft ASIP through mid-life teardown inspections. As Australia has shown the enhanced teardown delivers the most benefit in a relatively economical fashion.

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Chapter 11 – IMPLEMENTATION OF THE AIRCRAFT STRUCTURAL INTEGRITY PROGRAM PRINCIPLES FOR PZL-130 "ORLIK" TC-II TRAINER AIRCRAFT

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11.1 INTRODUCTION

The Air Force Institute of Technology (AFIT) has been involved in the SEWST (Introduction of Damage Tolerance Based Operation, SEWST) research program for the PZL-130 "Orlik" TC-II Polish trainer aircraft. The aim of the program was to establish a new fatigue life limit for the modernized structure (refurbished fuselage and brand-new set of wings) as well as to introduce a new maintenance system incorporating the Aircraft Structural Integrity Program (ASIP) principles. The SEWST program was led by EADS PZL-Okęcie, the manufacturer of the aircraft, however AFIT was responsible for most of the research activities.

The SEWST program was carried out throughout five years (2010 – 2014). The program was contracted by the Polish MOD (Ministry of Defence) and led by EADS PZL-Okęcie, the manufacturer of the aircraft. The AFIT was the main subcontractor and was therefore responsible for most research activities. The total cost of the program was 7 million USD, whereas the estimated savings after introduction of the program are around 70 million USD.

The main goals of the program were:

- Reduction of operating costs;
- Increase of availability of the PZL-130 TC-II aircraft;
- Cancellation of major overhauls every 1000 Flight Hours (FH); and
- Introduction of periodic inspections depending on actual usage of individual aircraft.

The SEWST program consisted of several activities among which the most important were:

- Operational Load Monitoring;
- Load Spectrum Development;
- Full-Scale Fatigue Test (FSFT) (including Non-Destructive Inspection (NDI) program);
- Teardown Inspection (TI); and
- Individual Aircraft Tracking (IAT) Program.

The main task of the structural part of the program was to carry out the FSFT. In order to achieve this goal a set of subtasks had to be performed. Beginning with the definition of the flight profile of the PZL-130 aircraft operated in the Polish Air Force [1], followed by the Operational Load Monitoring Program (OLM), the load spectrum for the FSFT was defined [2]. During the OLM as well as the FSFT, two aircraft were instrumented with sets of over 100 strain gauges. The aircraft used in the FSFT was a TC-I version withdrawn from service, overhauled to TC-II version by reinforcing the fuselage and installing a brand-new pair of modernized wings. The TC-II version wings have a larger span as well as wing area. The overhaul carried out on the FSFT test specimen is identical to the modernization which all the TC-II aircraft undergo.

11.2 OPERATION LOAD MONITORING

In order to define the characteristic operational loads for Polish PLZ-130 Orlik aircraft, both historical Flight Data Recorder (FDR) data were analyzed, and a tailored OLM program was carried out. The selected aircraft was instrumented with a set of foil strain gauges.(Figure 11-1 and Figure 11-2); in addition, a subset of flight parameters was recorded using the KAM-500 FDR from ACRA.

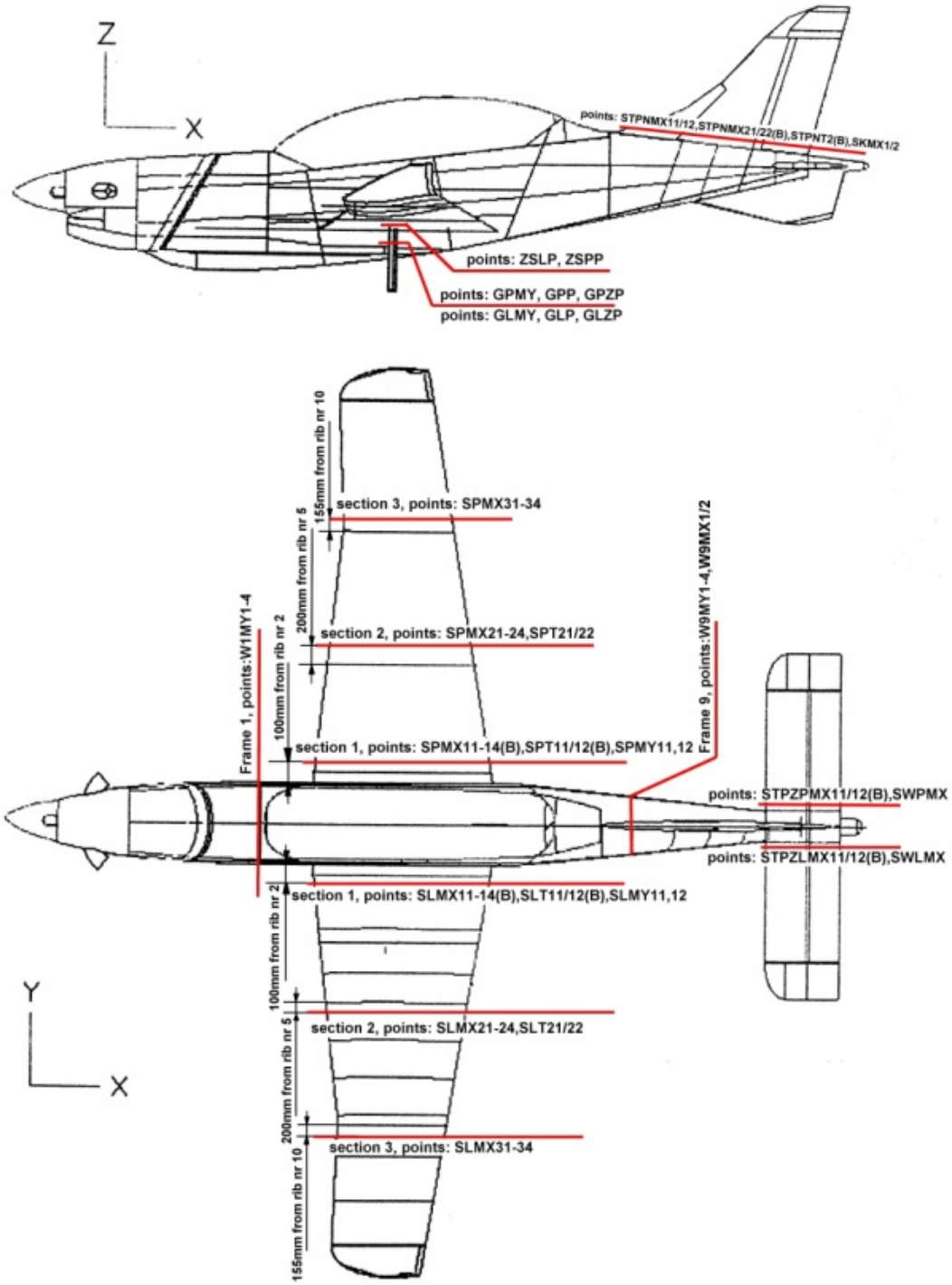


Figure 11-1: Scheme of Strain Gauge Location.

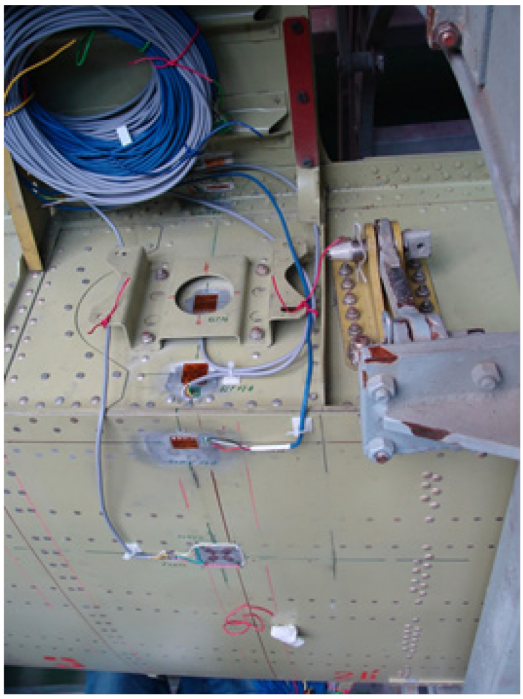


Figure 11-2: Strain Gauges Installed on the Structure.

The wing bending moment was measured in three sections of each wing. For each section, four strain gauges were installed (two on the upper and lower flange of the front spar and two on the upper and lower flange of the rear spar). Fuselage bending moment was measured in two sections (front near Frame no 1 and in the rear near Frame no 9), in each section the bending moment was measured by means of strain gauges installed on the stringers. Moreover, in the rear fuselage sections, two rosettes were installed on the sheeting in order to measure tail section torque. The empennage loads were measured with strain gauges installed in both horizontal and vertical stabilizers root sections. Finally, landing loads (vertical load and bending) were measured by sensors installed both on main landing gear as well as the support structure.

During the test flight program, 19 carefully planned flights were carried out, which consisted of selected flight exercises and additional maneuvers (like spins) in order to gather necessary and representative load. The load monitoring system was calibrated before flights by applying known loads to the structure and measuring the corresponding strain signals.

In addition to the above flight test program, several additional flights carried out by military pilots after the aircraft was handed over to the Air Force Base, allowing the comparison of test flight severity with actual service flights.

11.3 LOAD SPECTRUM DEVELOPMENT

According to SEWST program assumptions, the load block for the test was developed on the basis of flight loads measured during experimental flights, which were designed in such manner to represent the pilot training program for the PZL-130 airplane [1], [2]. This assured, that the obtained loads are consistent with the mean flight profile for the PZL-130 "Orlik" TC-II in Polish Armed Forces (PAF).

The assumed load blocks were to represent four main flight components: taxiing, flight, landing and buffeting. Flight and buffeting loads were developed directly using strain data gathered during flights. Since landings performed during the experimental flight program were very smooth, which is usually not the case, a decision

was made to develop landing loads separately according to known literature [3]. Similarly, taxiing loads showed very low amplitudes, and due to limitations in number of load lines within a load block (discussed in following paragraph), could not be introduced directly. Instead, three types of artificial taxiing loads were developed: full stop, left and right turn. These were randomly placed within the load block. The load levels were chosen based upon the actual loads measured during experimental flights.

The time schedule of the FSFT and technical capabilities of the loading system imposed some limitations for the load block. Preliminary estimations showed that a ratio of about 120 load lines per hour of flight, (the planned 200 Simulated Flight Hours (SFH) were to have 24 000 load lines in one block), had to be achieved in order to finish the test within the contracted time schedule. Since the sampling frequency of the measured data was approximately 100 Hz, (400 Hz for buffeting loads), the amount of collected data was too high. In order to achieve estimated ratio, the gathered data had to be filtered.

The level of filtration was chosen using iterative methods. Basing on the preliminary assumptions, resulting from defined flight profiles in the Polish Armed Forces, representing 194 flights within the load block, flights were filtered and put together to be close to the number of lines estimated. Since further reduction was planned, and there was possibility to increase the loading frequency for buffeting loads when only empennage actuators operate, this initial number of load lines was within acceptable range. As such, the preliminary load block consisted of approximately 30 000 load lines.

The load block contained 194 flights each composed of: initial taxiing, flight with or without buffeting, landing and final taxiing. Components were filtered and prepared separately. Hence it was necessary to verify load sequences after load block assembly in order to eliminate load lines, for which load levels for all 20 actuators either differed by less than 5%, or three sequential loads for all actuators were either ascending or descending.

Since the test specimen was not fully constrained within the test rig, it was necessary to assure that for all load lines the resultant forces will be in static balance. Additionally, loads exerted on the structure were checked along with the *g* factor to check if the resultant mass of the aircraft remained within a reasonable range (empty airplane and fuel).

After performing all of the above steps, the final load block consisted of approximately 26 000 load lines: that is acceptable due to the possibility of accelerating the test during buffeting loads.

11.4 FULL-SCALE FATIGUE TEST (INCLUDING NDI PROGRAM)

The FSFT was carried out in Výzkumný a Zkušební Letecký Ústav (VZLU) in Czech Republic. The aircraft was loaded by means of 20 hydraulic actuators [1], [2], [4], [5] which were exerting forces on the main structural elements:

- 4 actuators for each wing (3 for bending along wing span one for wing torque);
- 1 actuator for each side of the horizontal tail plane;
- 1 for vertical tail plane;
- 3 actuators for each of the main landing gears;
- 1 for each of the two pilot seats; and
- 1 final for the engine dummy mount (Figure 11-3).

The FSFT started in autumn 2011 and was contracted for 36000 Simulated Flight Hours (SFH). The load spectrum used in the test represented 200 SFH, including landing and taxiing loads. The loading frequency, achieved after initial tuning of the system, was around 0.5 Hz, which for the load spectrum consisting of 24 000 load lines allowed accomplishment of 1000 SFH every 15 working days, excluding shutdowns for NDT inspections and holidays.

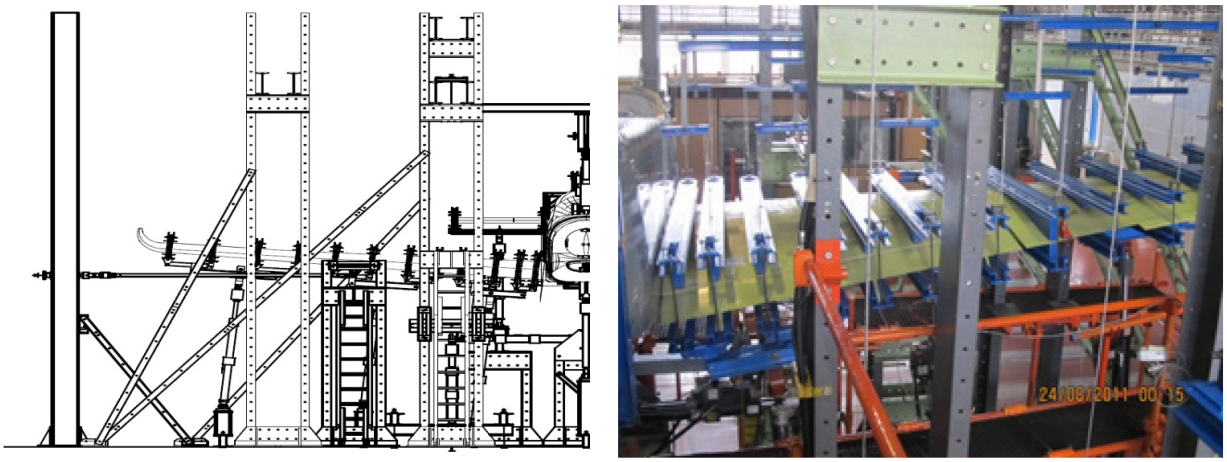


Figure 11-3: FSFT Design and Actual Test Rig for the PLZ-13 Orlik Aircraft.

During the entire test, the structure was monitored using various NDT methods ranging from simple visual inspection to eddy current or ultrasonic testing. According to tripartite consultations between EADS, AFIT and VZLU, the non-destructive tests were divided into three levels.

Level 1 was based on simple NDI techniques and was carried out every 1000 ± 50 SFH. This inspection was executed by VZLU in accordance with NDI instructions delivered by ITWL. The estimated time for inspection was 2 man hours. No modifications to the test specimen or test rig were necessary for this level.

Level 2 inspection required using advanced NDI equipment thus additional access to the structure was needed. This inspection was conducted every 5000 ± 1500 SFH for between 0 and 30000 SFH and the time interval was shortened to 3000 SFH ± 1500 SFH for 30000 to 36000 SFH. VZLU also conducted this level of inspection in accordance with NDI instructions delivered by the ITWL although first inspections were conducted in the presence of ITWL qualified personnel. Estimated time for this inspection was 2 working days.

Level 3, detailed NDI inspection, included dismounting of wings and fuselage. Four major inspections were planned throughout the test every 10 000 ± 2500 SFH. ITWL was responsible for this level of inspection in accordance with NDI instructions delivered by ITWL. Estimated time for inspection was 5 working days.

A reporting routine, valid for all levels of inspection, was developed. It included detailed documentation of found damage including photographic documentation and detailed definition of location, as well as methods used to find and verify it. It allowed precise identifying of damage and its location, as well as enabled tracking of it throughout the test to verify its severity and impact on structure integrity. Reports were developed by VZLU and delivered to ITWL for interpretation and storage.

Figure 11-4 shows the test progress. Blue diamonds on the graph represent NDI inspections whereas the thick red line defines the contracted test limit. Despite initial tuning problems, the test course was rather stable, which allowed it to be finalized close to the estimated deadline. The test ended at 35056 SFH due to critical lower wing spar damage, for which repair was both difficult to carry out and economically unjustified due to its being so close to the FSFT limit.

Damage found during inspections was located in different structural parts of the aircraft. Most of the damage was found in the wing area both in the right (137 findings, 35% of total findings) and left (124 findings, 32% of total findings) wing parts. A total of 16 damages which account for 27% of the total findings were detected in the fuselage area. Total of 21 damages were found in the horizontal stabilizer area and only

4 damages in the landing gears. The damage also differed by the type, e.g., cracked rivets (32%), ERW (Electro Resistance Welded joints failure, 27%) removed material or structure (22%), removed material or rivet head (10%), and cracked screw (8%).

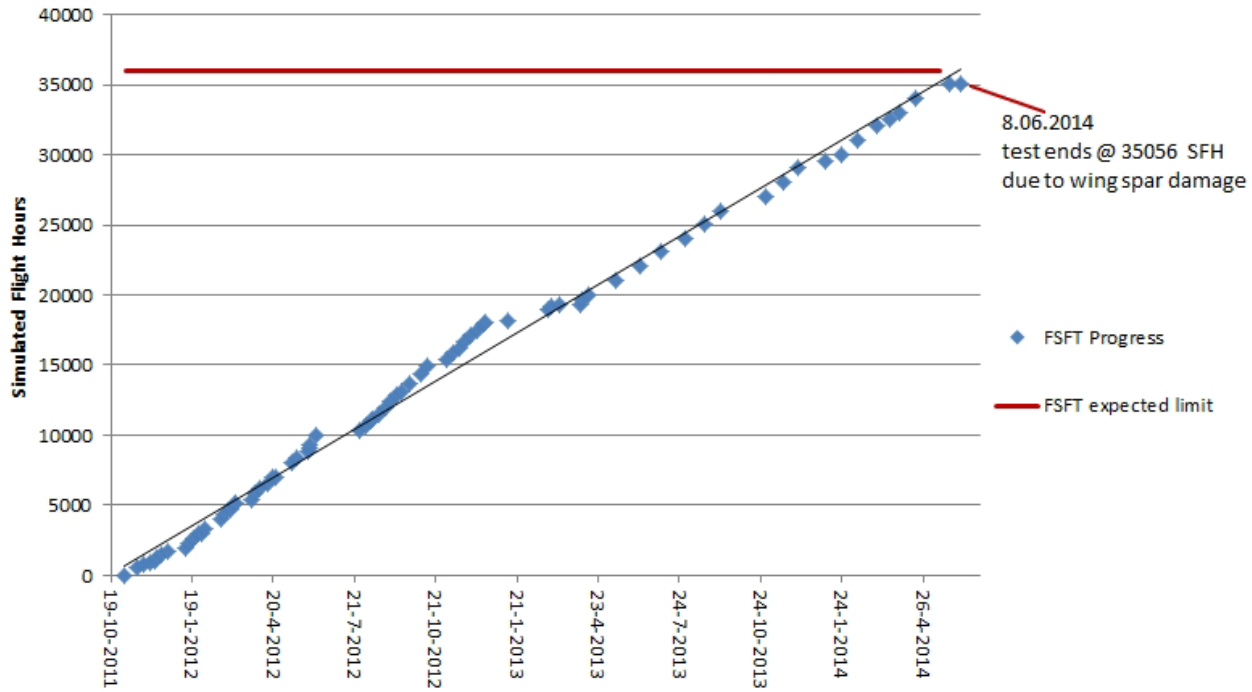


Figure 11-4: Full-Scale Fatigue Test Progress Chart.

Figure 11-5 presents two graphs depicting the location where damage was found by percentage as well as a chart describing the types of damage found.

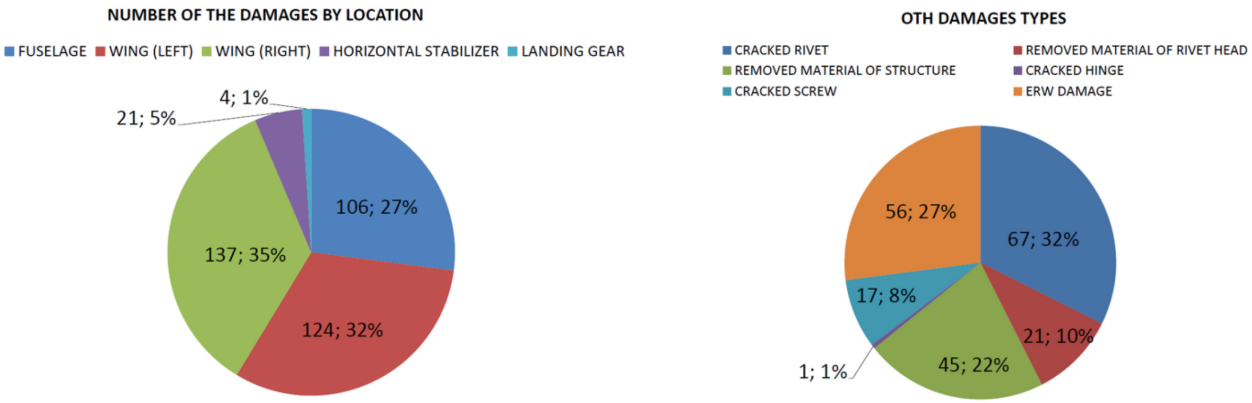


Figure 11-5: Distribution of Damage Found Throughout the Structure and by Type of Damage.

Rivets were one of the more common failing items during the test. During inspections, some damages were found in the early stages, when a crack was propagating within a rivet; some were found only when the rivet had failed due to fast damage development. The left side of the Figure 11-6 shows a group of rivets located on the fuselage left front side. Damaged rivets were found during 29 500 SFH Level 2 inspection. Additional rivets were defined as being damaged on the right side of the fuselage during 33 000 SFH Level 1 inspection.

The right side of Figure 11-6 shows the final damage number 818, that caused the test to terminate. The critical damage occurred at 35056 SFH although several smaller damages (failed rivets and small cracks) were detected in this region from 33 000 SFH.

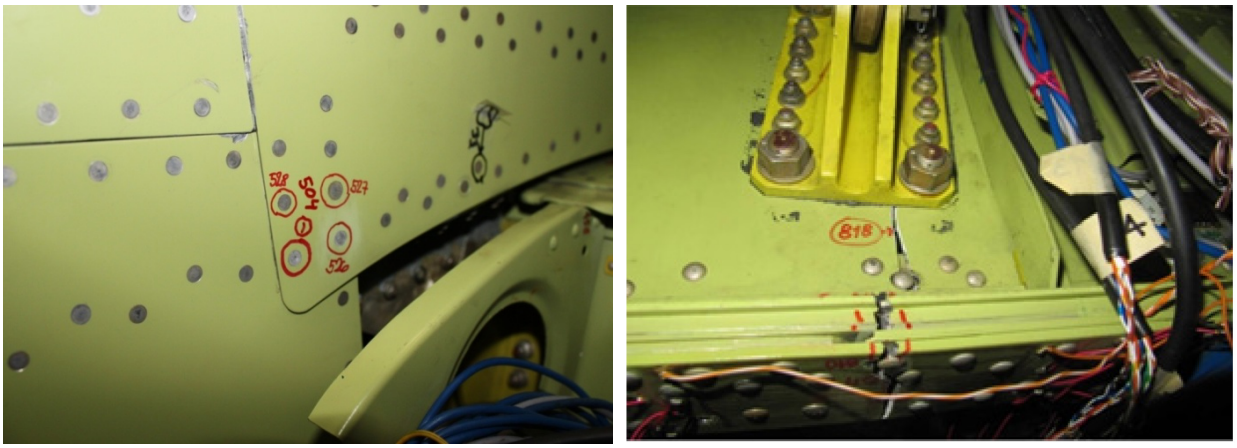


**Figure 11-6: Example of Damage Found During the Test.
Failed rivets and final critical spar damage.**

11.5 TEARDOWN INSPECTION (TI)

After finalization of the test, the final NDI was performed by VZLU and the final report issued after which the test rig was disassembled, and the test specimen taken out from the test rig and shipped back to Poland.

Teardown Inspection (TI) of the PZL-130 TC-II after FSFT was carried out by disassembling the aircraft structure down to separate parts [6] and performing versatile NDI in order to both examine the elements which were inaccessible during the test, as well as to verify damages which were reported during the test [6]. Figure 11-7 shows the process of disassembling the wings. After additional analysis of the wing's outer surface using the MAUS V automated system, the skin sheeting was carefully removed by drilling out the rivets thus allowing access to the inner wing structure.

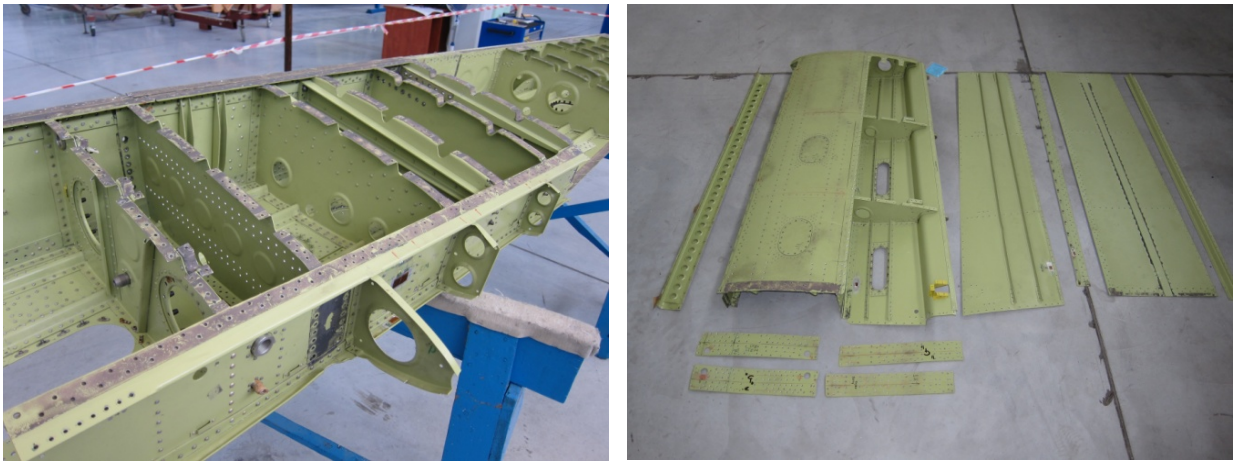


Figure 11-7: Teardown Inspection of the PZL-130 TC-II Wing.

During TI, many new damages were found, the majority of which were located in the wings, since the wing inner structure was inaccessible during the test. Like the results of NDI during FSFT, the damages were of different types, ranging from failed rivets, through partial cracks, up to elements cracked completely through.

After, the TI selected cracked elements (both with through and closed cracks) were examined with Philips XL30 Scanning Electron Microscope in order to identify fatigue markers, which were introduced in the modified load spectrum [2], [7], [8]. A total of 23 samples were examined from various damages found in the wing-fuselage connection area. During the study, a magnification range of 10-500000x was used. Nucleation, fatigue fracture and final overload areas were clearly visible on the samples crack surfaces and fatigue fracture areas of coupons tested before FSFT [2], [4]. Although the FSFT aircraft samples showed similarities, it was not possible to define the fatigue marker bands caused by the reordering of the load spectrum.

11.6 INDIVIDUAL AIRCRAFT TRACKING PROGRAM

An example of implementation of the SEWST (Introduction of Damage Tolerance Based Operation, SEWST) results to a maintenance system is the Individual Aircraft Tracking program (IAT). According to the IAT, the structural loads acting on aircraft structure are to be monitored for each aircraft in the fleet. All PZL-130 aircraft operated by Polish Air Force are equipped with digital flight data recorders which, among all the recorded flight parameters, record values of *g* factor.

A dedicated software was developed for analyzing and maintaining captured data. For each recorded flight, the intensity factor, as well as the number of equivalent flight hours, are calculated. The intensity factor is defined as the proportion of equivalent and actual flight hours for a single flight or set of flights. The technical issue for the intensity factor is to compare the real load spectrum accumulated by an aircraft structure during a flight with the defined spectrum used for the FSFT. This comparison is calculated based on fatigue damage caused by both spectra. The fatigue damage is calculated according to S-N curve methodology and uses the S-N curve defined in Ref. [9].

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Chapter 12 – SU-22 FIGHTER-BOMBER AIRCRAFT SERVICE LIFE EXTENSION PROGRAMME SUPPORTED BY OPERATIONAL LOAD MONITORING IMPLEMENTATION

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12.1 INTRODUCTION

In-service usage monitoring is an important airworthiness requirement for maintaining aircraft safety. Fatigue load spectra change during operational use, especially for military aircraft, due to different tactical requirements, new missions, advanced aircraft configurations (e.g., higher masses) and different environments [1]. During recent decades, load and usage monitoring has grown from a simple *g* counter to a highly complex and intelligent on-board system with the ability to monitor various locations in real time.

The modern approach to aircraft utilization is inseparably connected with the concept of material fatigue. More than 100 years ago, at the beginning of aviation, hazards associated with material fatigue were poorly recognized. The aviation industry in 1930 – 1940, when the first fully metal aircraft structures were developed, simply didn't deal with the material fatigue phenomenon. At that time, planes were designed focusing mainly on the problem of static strength of the structure. In the following years, the development of aircraft structures due to World War II, as well as the rapid evolution of public air transportation, caused increased awareness of the phenomenon of material fatigue. From that point, combination of static strength and fatigue life was taken into account during aircraft design [2], [3].

The development of aircraft design and operation techniques continues to this day, contributing to an increase in safety and extending the life of aircraft. Unfortunately, the main "milestones" [4] in consciousness regarding the phenomenon of structural fatigue, occurred after fatal aircraft crashes, e.g., de Havilland Comet in1954, F-111 in 1969, Boeing 707 in 1977 and Boeing 737 in 1988.

The rational use of an aircraft, i.e., use in accordance with its tactical and technical characteristics, is possible only in the case of a functioning operating system, which ensures the optimization of aircraft usage. The quality of the operating system is mainly determined by the maintenance and repair methods, as they contain a set of regulations specifying the scope and frequency of service, control the level of reliability and technical condition of the aircraft. Regarding the above, Individual Aircraft Tracking (IAT) by use of an Operational Load Monitoring (OLM) system is essential to ensuring the implementation of the maintenance and utilization strategy [5]. Moreover, OLM allows the determination of significant life extension potential for the aging aircraft, which, after performing the necessary repairs and modifications, will enable their further operation according to their technical condition [6], [7].

The case study of the Su-22 "Fitter" aircraft OLM system implementation is presented in this paper as a part of the latest Service Life Extension Program (SLWP).

12.2 SERVICE LIFE EXTENSION PROGRAM FOR SU-22

The Su-22 "Fitter" variable-sweep wing fighter-bomber aircrafts entered Polish Air Force service in 1984 to 1989 in two variants: Su-22M4 single-seat version and the Su-22UM3K twin-seat trainer. The original service life established by the manufacturer was set to 1500 Flight Hours (FH) / 2300 landings in 20 years,

which were prolonged in 1998 to 2000 FH / 3000 landings in 20 years for Su-22M4 and 2000 FH / 4000 landings in 20 years for Su-22UM3K. For both versions, the first general overhaul was scheduled after 800 FH in 12 years, and inter-renovation overhaul for 700 FH / 10 years. After the expiration of these resources, the operational use of those aircrafts was carried out on the basis of the provisions of the operational bulletin, which assumed a phased service life extension every two years or 200 FH as part of the maintenance. The additional diagnostic and control works were carried out, determining the final service life of 3000 FH / 3000 landings in 30 years for Su-22M4 and 3000 FH / 4000 landings in 30 years for Su-22UM3K.

However, in 2014 the Polish MOD decided to continue the operation of the aging Su-22 “Fitter” for another 10 years, after successful confirmation of structural integrity by a Structural Service Life Extension Program (SLWP). The SLWP included [8]:

- Ground and flight tests for a separate aircraft;
- Flight Data Recorder (FDR) archives analysis for the period of 5 years of operational use of the whole fleet;
- Full-Scale Durability Test (FSDT) of a retired aircraft; and
- Operational Loads Monitoring (OLM) system implementation for all Su-22UM3K.

The double-seated trainer version was of special interest because it accumulated significantly more landing-take-off cycles in their lifetime than the combat variant, and is threatened with experiencing more severe loading spectra, both during flight and landing.

Ground and flight tests were performed to determine total loads on wings, and fuselage as well as landing gear elements. During ground static tests, as well as 10 flights with a total duration of 8 hours and 25 landings (including 15 touch-and-go landings), the load spectra were obtained by measuring actual strains in selected Critical Points (CP) from more than 40 strain gauges. The sensors were installed in locations that enabled easy determination of the total wing bending moment acting in the wing attachment points as well as the variable-sweep pivots. In addition, strain gauges mounted on the fuselage enable determination of the total fuselage bending moments. A third group of sensors was installed on elements of the landing gear and the landing gear attachment points. Other aircraft regions were omitted as the program focused on landing gear and wing structure.

Thanks to the flight data records kept at the institute, fleet-averaged, as well as individual service profiles were developed for the Su-22s. The M4 and UM3K variants were compared. The individual profiles are now used in IAT activities that is a part of the SLWP. For the presented extension program, data from the previous five years were used (2009 – 2013), as the service profile changed significantly through the years. A period of five years was considered to be sufficient for obtaining a usage profile, and in addition, a statistically significant number of flight hours had been recorded. The usage profiles were based on the vertical acceleration (g-force) signal Nz, whereas the usage due to landings was calculated based on the product of mass and vertical acceleration m × Nz. The rainflow method of cycle classification was used for cycle calculation. The calculated usage cycle values have been distributed into bins of 0.25Nz width, taking the maximum value in the range as the bin value. The usage profiles were calculated for an average 1000 FH period. To determine the landing load profile, recorded landing histograms were created. Landing mass at landing was determined based on the assumed empty aircraft weight (taking the aircraft variant into account). This baseline was than corrected by adding the recorded fuel remnant. The installed armament weight was not taken into account, due to lack of data.

Data from the ground and flight test as well as from FDR archives analysis were used to determine the load distribution and correlation between flight parameters (mainly vertical overload) and strain prior to the Full-Scale Durability Test (FSDT). The FSDT was conducted on a taken out of service aircraft which had already experienced 3127 landings and 1583 Flight Hours between 1985 and 2003. The test was designed to

prove the desired 3200 EFH (Equivalent Flight Hours), durability of 6500 landings with a safety factor of 4, as well as the total durability of the aircraft structure. The detailed description of that activity is presented in Chapter 25.

12.3 OLM SYSTEM DESIGN AND IMPLEMENTATION ON SU-22UM3K

Part of the SLWP program for the Su-22 was the implementation of an Operational Load Monitoring System on-board of six Su-22UM3K combat-trainer aircrafts during their overhaul, which consisted of stain gauges and a 3-axis wide bandwidth accelerometer sensor network. The purpose of the OLM System was to assist twin seated Su-22UM3K operation and enable their controlled and safe operation within a period of prolonged service life above 3200 flight hours and 6000 landings.

The main system element is an airborne multi-role recorder with integrated data acquisition, which manages signal acquisition and archiving from a permanently bonded strain gauges sensor network and accelerometer. Periodical analysis of aircraft structural loading for each aircraft is performed off-line on the Ground Station, and suitable conclusions are drawn regarding further operational usage. A block diagram of the OLM system is presented in Figure 12-1. The Data Acquisition Unit is an SSR-500 multi-role recorder manufactured by Curtiss Wright Control Avionics & Electronics, with adequate analogue and digital user modules to acquire data from 8 strain gauges, 11 parameters from Built-in Test for supervising the operation of the device, 13 GPS parameters and a 3-axis accelerometer. One user slot is filled with a dummy module presently, and is ready for use in any future upgrade for a chosen type of sensor and measurement task, as the recorder has a modular architecture and can be reconfigured as needed (Figure 12-2). The MT-1 is a custom-made and tested additional unit for strain gauges bridge completion as well as for shunt calibration of strain gauge measuring channels of SSR-500 DAU. A DC to DC converter is implemented to stabilize voltage from the on-board DC power supply, to prevent under- or over-voltage during powering of other installed equipment.

The main data source for OLM is an integrated network of 8 strain gauges, mounted on predefined structural critical points for monitoring the operational loading both during flight and landing to determine load exceedances, e.g., harsh landings. A 3-axis, wide bandwidth Microelectromechanical System (MEMS) accelerometer is used for load determination. Additionally, parameters like power-up and time-on counter, internal voltage values on buses for e.g., sensor excitation and digital components, error counter, chassis and internal temperature and chassis status, as well as GPS navigation data are acquired.

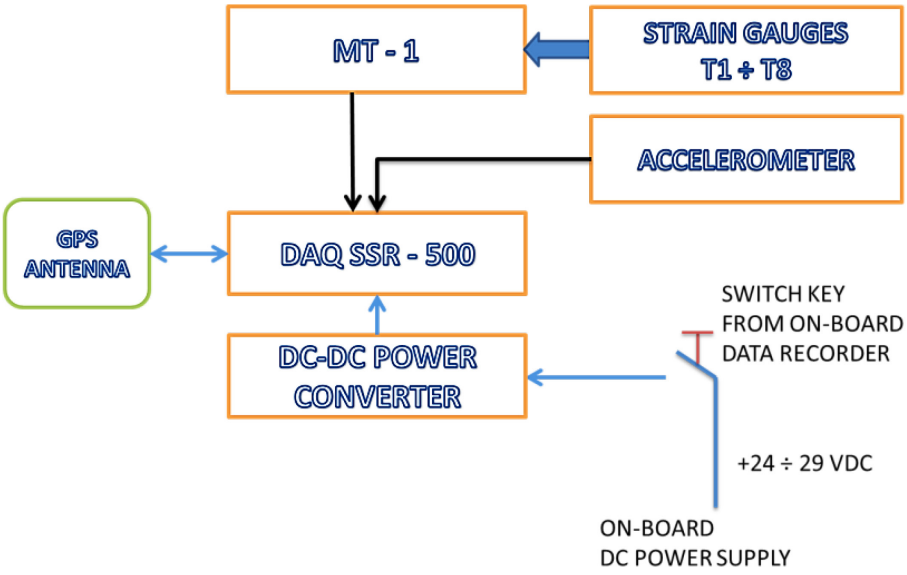


Figure 12-1: Block Diagram of OLM System [9].

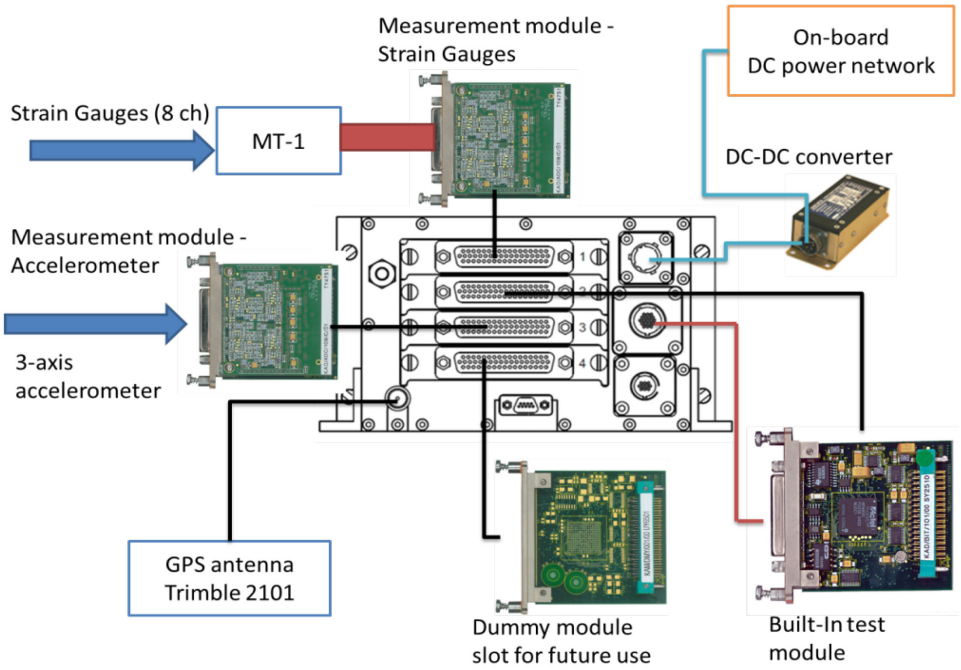


Figure 12-2: Measurement Configuration of OLM System.

A pair of strain gauges (T1 and T2 on the Left Hand (LH) side, T5 and T6 on the Right Hand (RH) side) are bonded on the bottom and top flanges of the wing main spar, near the wing main attachment point. Measurement from those channels are used during flight to determine loading in certain manoeuvres and aircraft configurations. For exceedances during landings, one sensor is installed on the main landing gear strut (LH side – T3, RH side T7) to measure longitudinal loads, and second sensor (LH side – T4, RH side T8) is bonded on the gear-wing connection to measure lateral loads. The sensors are installed symmetrically on both sides of the aircraft to be sensitive for asymmetrical loading as well as for redundancy (Figure 12-3).

The accelerometer is located near the centre of gravity point on the top of the fuselage. Main components like DAQ SSR-500, MT-1 and DC-DC converter are located on top of the first technical hatch of the aircraft.

12.4 IN-FLIGHT LOAD DETERMINATION

The OLM system provides information about loads in critical aircraft areas using strain gauges. In a basic approach, each flight consists of start, flight, with manoeuvres and landing. Due to the design assumptions, the OLM sensors are mainly subjected to compressive loads during operation. In this case, there is no risk of fatigue or static damage by direct tearing of the monitored elements. However, these records provide indirect information about the overall load level in the structure. The characteristic load features during the flight are shown in the diagrams in Figure 12-4.

The outlined characteristic parts of the flight are:

- A – Aircraft start;
- B – Flight with significant changes in vertical overload Nz;
- C – Circles above the runway and touch-and-go landings; and
- D – Full stop landing.

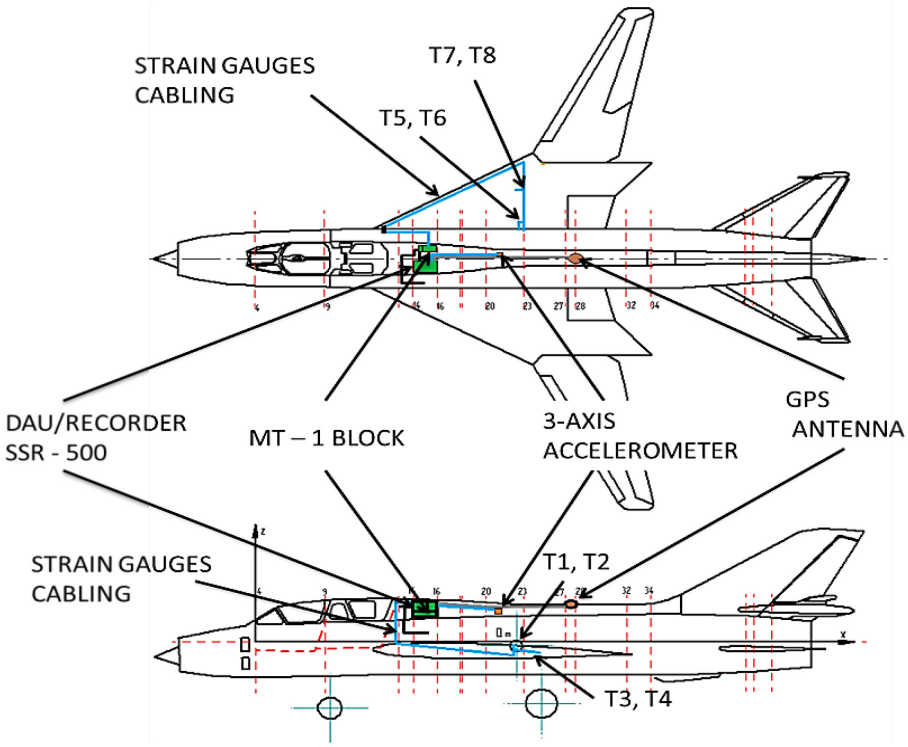


Figure 12-3: Location of the Elements of OLM.

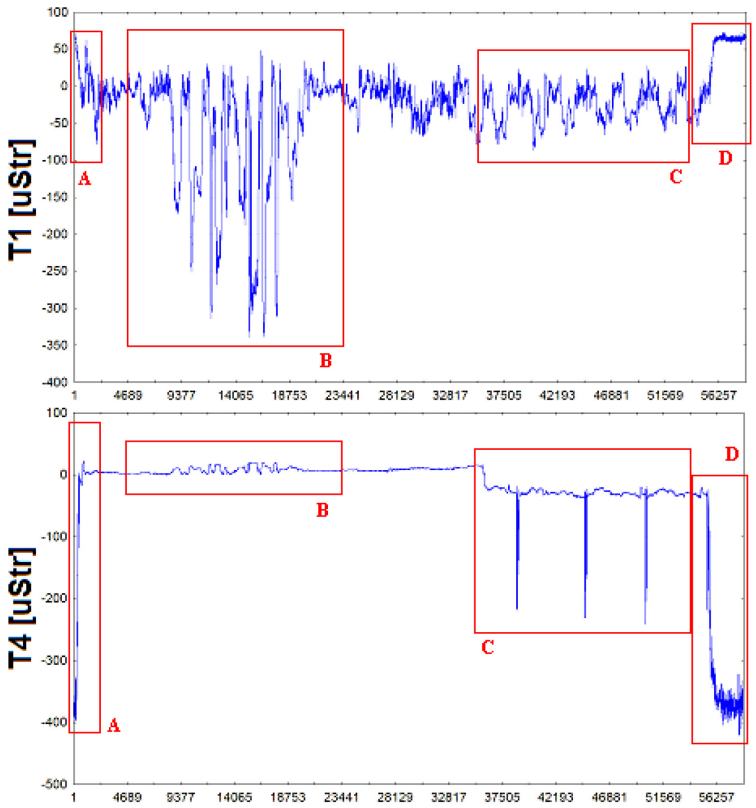


Figure 12-4: Loads from Strain Gauges T1 and T4 During Typical Parts of the Flight.

Figure 12-4 shows changes on T1 (LH side top flange of main spar) and T4 (LH side main landing gear – wing connection point). It can be seen that particular flight phases are easily distinguishable even only by strain gauges. Correlation and synchronization of the data from OLM and on-board data recorder give enough information for individual tracking of a particular aircraft.

The main "added value" of having an OLM system implemented on-board the aircraft is the ability to detect exceedances of operational use both during flight and landing. Those exceedances can have a meaningful influence on fatigue parameters, like fatigue usage, operational intensity factor and equivalent-to-real flight hours ratio. Moreover, parameters e.g., time of acceleration during start, detachment speed, speed during closing the landing gear, touchdown speed, touchdown g-level, maximum peak-to-peak strain value during touchdown. Based on OLM data, one should be able to detect e.g., harsh or asymmetric landing and quantify its influence on aircraft usage [10].

12.5 SUMMARY

Operational load monitoring is a next step toward operational usage optimization of the aircraft. The need for an accurate and reliable fatigue usage monitoring system is of increasing importance to ensure the safe and economical utilization of aircraft, especially regarding aging aircraft, which are now expected to last much longer than first envisaged. At the moment, implemented OLM allows for counting and determination of operational load exceeds both in the air and during landings for the twin seated version of the Su-22 aircraft. Overloads can have significant influence on airframe strength due to high mechanical strain occurrence. Data analysis based on the Flight Data Recorder enables specifying usage profile values as operating intensity factors and equivalent flight hours for each monitored aircraft.

Activities in progress within the SLWP program are now focused on parallel utilization of the direct strain gauge data for the aircrafts equipped with the OLM system for individual tracking and determination of usage profile values as operating intensity factors and equivalent flight hours for each monitored aircraft.

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Chapter 13 – AIRCRAFT STRUCTURAL INTEGRITY MANAGEMENT ACTIVITIES IN FINLAND

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13.1 INTRODUCTION

This chapter provides a brief review on aircraft structural integrity management activities in Finland from the Finnish Defence Forces (FDF) viewpoint.

The national approach to aircraft structural integrity management was initiated by the Finnish Air Force (FINAF) during the late 1990s and early 2000s, following the identification of the severity of the operational usage compared to the design spectra. Aircraft Structural Integrity Program (ASIP) was implemented for the FINAF F/A-18C/D Hornet fleet according to MIL-STD-1530 [1]. Lately, the ASIP approach has also introduced for the FINAF BAE Hawk.

The FDF ASIP has evolved as a primary means to manage structural integrity in order to maintain safety and availability of aging systems and ensure economic service life of the fleets. From the fleet management perspective, effective ASIP processes provide data for the following objectives:

- Allow required number of aircraft to remain in service until the planned out-of-service date;
- Keep maximum number of aircraft available, and enable prediction of necessary repairs or modifications;
- Instruct deployment of the fleet in terms of severity of usage; and
- Instruct decommissioning of the fleet beginning from the most stressed individuals.

13.2 IN-COUNTRY CAPABILITIES

In-country engineering and design capabilities have been instrumental in the maintenance of the airworthiness and mission capability of the FDF aircraft through maintenance, repair, overhaul and modification programs that are tailored for the national requirements and based on the actual use of aircraft. This work has been done in close co-operation with other users of the same aircraft type by openly sharing information. The work is being carried out under the supervision of the Finnish Military Aviation Authority (FIMAA) that sets a regulatory basis for such activities and requirements for different organizations as well as approves these organizations.

The FIMAA has delegated authority to FDF Logistics Command (FDFLOGCOM) to act as a Type Certification Holder (TCH) and Continuing Airworthiness Management Organization (CAMO) for the Finnish military aircraft, with the following tasks:

- Develop airworthiness criteria, and processes and means to show compliance with the airworthiness criteria;
- Develop and sustain a maintenance program and a structural integrity plan for each type; and
- Maintain a system for data collection, assessment, analysis and reporting related to failures and defects that pose risks for maintaining airworthiness of the aircraft.

The FDF's TCH does not have an organic design capability and is typically supported by OEMs and the domestic partners.

As Finland has its unique operating environment, tasks and usage spectrum, the FDF must have its own capability to:

- Assess effects of the usage spectrum on the service life and structural integrity of individual airframe and systems;
- Implement changes and repairs needed to the structure due to differences in actual usage vs. design usage spectrum; and
- Adjust maintenance requirements and intervals to maintain optimal availability with minimized costs.

Furthermore, the national capability should enable re-certification of the fleet (component) when extension of the service life is deemed necessary.

Regarding new fleet acquisition programs, a requirement for comprehensive structural integrity management capability places a request for the OEM to provide a sufficient data package along with a need for contractual agreements to enable access to engineering data when the need arises during the sustainment. A requirement for an independent design capability necessitates the most complete set of engineering data, including material and process specifications, numerical models (CFD, FEM) and fatigue test reports with test spectrum and load data package.

13.3 ASIP ACTIVITIES

This section gives a brief review of ASIP principles and practices implemented particularly for the FINAF F/A-18 fleet. Although initiated during the sustainment phase, the program has been intended to cover all of the Tasks I-V defined in the MIL-STD-1530. Particularly, the aim has been to identify all the information related to design and development phases (Tasks I-III) and incorporate them into the program, providing the basis for structural integrity management activities throughout the sustainment phase.

Task IV (Certification and Force Management Development) involves the activities to develop the basis for Task V. The list of activities (not exhaustive) includes:

- Identify the certification basis and requirements: design standards, certification criteria, etc. and related guidance material, as well as verification compliance documents;
- Develop systems and processes to perform Operational Loads Measuring (OLM) and Individual Aircraft Tracking (IAT);
- Establish a structural maintenance plan for each of the critical structural components/locations;
- Define the national policy for preventive structural inspections, modifications and repairs;
- Estimate fatigue lives for the critical structural components/locations based on the data from monitoring/tracking systems;
- Decide on the primary measures of structural life consumption for fleet management and maintenance scheduling;
- Evaluate and maintain the structural inspection program in order to ensure sufficient safety and availability levels with minimized costs; and
- Decide on additional measures especially concerning structural management of aging aircraft, e.g., fleet leader inspections and structural teardown programs as the two most common concepts, which provide also means to evaluate effectiveness of ASIP.

Task V (Force Management Execution) embodies the actual fleet monitoring and structural integrity management tasks, based on collecting usage data by the HOLM and IAT systems and assessing identified usage changes and damage findings from structural inspections (including information from other operators).

The usage data collected by the HOLM and IAT systems is further utilized to determine a baseline operating spectrum for fatigue analysis, to adjust timing and intervals for structural inspections and modifications, as well as to detect other types of events that affect the structural service life.

All the relevant information and actions are documented in the ASIP book, compiled in accordance with the MIL-STD-1530 standard and updated on regular basis. The ASIP book consists of two volumes: Volume I describes the principles of integrity management, identifies the design and development data, and determines life targets and limits, whereas Volume II includes the actual, detailed management plan for the fleet.

The effective ASIP execution is based on continuous collaboration and communication within the FDF and strategic partners. The ASIP status is communicated regularly to engineers and managers responsible for the fleet management. The status reports include decided service life goals and applied fatigue indices, fleet fatigue overview and trends, projections for end of life, and operational guidance for the individual aircraft based on the fatigue indices.

An overall effectiveness of ASIP is evaluated regularly and an action plan is prepared based on the evaluation in order to improve the identified focus areas. The evaluation is applied for each critical structural detail and then individual evaluations are compiled to get the overall ASIP status. The evaluation addresses at least the following essential questions:

- What is the actual level of implementation of the ASIP activities?
- Do the activities contribute to achievement of the service life goal?
- What is the operational risk level now / projected for the end of life?
- Does the certification represent the current perception?

13.4 DAMAGE TOLERANCE AND LIFING POLICIES

A recently initiated national activity aims at establishing harmonized damage tolerance and lifing policies for the FDF aircraft, both for the legacy and future fleets. The aim is to address and clearly determine detailed practices and guidance at least for the following topics:

- Acceptable risk levels (probability of catastrophic failure);
- Analysis criteria and factors: scatter factors, life improvement factors, failure criteria, crack growth criteria, critical crack lengths;
- Test spectra and criteria for fatigue, damage tolerance and durability tests;
- Fatigue test representativeness and fleet experience correlations;
- NDI requirements, inspection thresholds and intervals;
- Fatigue tracking and individual aircraft monitoring, data requirements, results and post-processing;
- Fatigue analysis methods and tools; and
- Minimum data requirements regarding the engineering data.

As the F/A-18 ASIP already addresses most of the topics, the objective is to document the best practices experienced with F/A-18 and define policies applicable to other FDF fleets as well.

The current lifing practices for F/A-18C/D and BAE Hawk Mk. 51/51/66 form a generally good basis to be followed. Those lifing practices are based on activities within Finnish industry, as OEMs were not required to establish ASIP programs per MIL-STD-1530 or per any other similar standard.

For other FDF aircraft, OEM practices, especially in those aircraft certified in the Federal Aviation Regulations (FAR)/Certification Specifications (CS) 25 category, may be similar but unknown. There are no ASIP programs.

Aircraft certified in the FAR 23 category generally do not follow lifing policy principles at all. The same applies for rotorcraft airframes in the FAR 27 category.

13.5 NATIONAL R&D ACTIVITIES

As soon as the newly acquired BAE Hawk and F/A-18 Hornet fleets were identified as susceptible to structural fatigue problems, the FINAF initiated national R&D activities in order to develop knowhow, analysis capabilities and tools to investigate structural problems to support the overall aircraft life management activity.

The R&D activity has been carried out as subsequent multi-annual programs conducted by the FDF, involving a collaborative network of industrial partner companies, universities and the VTT Technical Research Centre of Finland (VTT). The main areas of R&D activity during the 2010s with some highlights are briefly described in Sections 13.6 and 13.7.

Operational loads and structural stresses for the aircraft has been determined by use of nationally developed capabilities for Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) supported by flight simulation capability. Examples of recent activities include:

- Enhancing the CFD model of the Hawk and applying the model to predict aerodynamic load distributions for the tail plane in different flight conditions, to be utilized in a domestic fatigue test for a component;
- Modelling the flow field around NH90 fuselage and other developments in helicopter flow simulation model and computations;
- Further CFD method development especially related to time-accurate simulations and fluid-structure interactions;
- Determining load spectra for F/A-18 major components and interfaces, in order to perform more accurate fatigue life assessments for critical structures in FINAF usage; and
- Developing crack growth analysis capability in order to implement damage tolerance approach; for that purpose, studying limit load cases for FINAF F/A-18 to determine critical crack sizes, necessitating evaluation of aerodynamic limit load distributions for the whole aircraft in critical design load cases.

OLM and IAT systems provide the fundamental means for collecting actual operational usage data for structural integrity management. National R&D activities have been carried out on this area during the last two decades, featured by development of OLM and IAT systems for the F/A-18 aircraft.

The systems currently applied for the structural integrity management of the FINAF F/A-18 Hornet are briefly described below:

- SAFE (Structural Appraisal of Fatigue Effects) is the OEM's fatigue tracking system that measures strains in the structural locations considered the most critical and calculates Fatigue Life Expenditure (FLE) for those locations. The SAFE system provides IAT capability and primary measures for monitoring fatigue life consumption of the FINAF F/A-18 aircraft [2].
- The HOLM (Hornet Operational Loads Measurement) programme has been running since 2006 with the goal of quantifying the effects of operational usage on the structure of F/A-18 Hornet aircraft. The programme was initiated by the FINAF while the SAFE system was considered incomplete for the FINAF life management purposes in terms of sampling rates and coverage of the structure. The programme is based on two F/A-18C aircraft equipped with relatively high number of strain gauges and a few accelerometers, measuring loads on various structural locations during actual operation in squadron usage and providing an ability to predict fatigue damage accumulation on various structural locations. The data captured from the two HOLM aircrafts is available as input data for different types of service life assessments and for verification of numerical models (CFD, FEM) [2].
- The parameter-based fatigue life analysis is an IAT method developed by Patria to meet the demand to evaluate structural life consumption of the whole fleet without any modifications to the aircraft systems. The analysis makes use of the flight parameter data, stored by standard aircraft systems, and artificial neural networks that have been trained by the measured strain gauge data from the HOLM flights. The neural networks are utilized to generate virtual strain gauge data, which allows calculating predicted fatigue lives for each individual aircraft [2].

Non-Destructive Inspection (NDI) technologies have been investigated nationally and new methods implemented to monitor the integrity of structural components of the FINAF aircraft. As the damage tolerance approach has been introduced, a need has emerged to quantify the reliability and performance of each NDI method in order to validate the NDI-based decisions, such as determination of inspection intervals. For this objective, the statistical method called Probability of Detection (POD) has been applied in a couple of studies, increasing understanding of aspects related to performance of NDI and realizing the importance of POD assessment [2].

National capability for designing and performing structural repairs and modifications has involved investigating fatigue characteristics on different materials and components by experimental testing, developing processes of carrying out repairs on composite materials and structures [2].

13.6 INTERNATIONAL CO-OPERATION

The FINAF has actively participated in the F/A-18 International Structural Integrity Forum (FISIF) and Composite Repair Engineering Development Programme (CREDP) together with the United States Navy (USN) and countries operating the F/A-18.

The scope of the FISIF is to assess the structural integrity of the F/A-18 aircraft and constituent parts. The scope of the CREDP is to investigate, develop, and expand repair techniques for structural components of the F/A-18 by conducting research and engineering tasks.

Participation in the FISIF and CREDP has been extremely valuable for national structural integrity management. Direct data exchange with other operators has provided the FDF with information on inspection findings, new inspection methods, fatigue tracking data, structural repairs and modifications. The received data have promoted flight safety and enabled the FDF to plan and implement structural refurbishment programmes needed for securing adequate structural service life.

13.7 CONCLUSION

The FDF ASIP has evolved as a primary means to manage structural integrity in order to maintain safety and availability of aging systems and ensure economic service life of the fleets.

Although initiated during the sustainment phase, the FDF ASIP is intended to cover all the tasks defined in the MIL-STD-1530. Design and development (Tasks I-III) information is to be identified as far as possible and incorporated into the program, to be assessed when the need arises during the sustainment.

The overall effectiveness of ASIP is evaluated regularly, and an action plan prepared in order to improve the identified focus areas. As regards lessons learned, the FDF experience suggests early initiation of ASIP, particularly establishing national certification and lifing policies and validating the structural life of aircraft as exactly as possible. An important action is to perform POD assessment to validate NDI-based decisions. Furthermore, an effective ASIP execution necessitates continuing alertness within the organization, in addition to capable analysis tools and available repair capabilities.

Continuous and collaborative R&D programs focused on aircraft structural integrity management have been considered crucial to develop in-country engineering and design capability on implementing ASIP. With fairly limited R&D and engineering resources within the FDF and its domestic partners, focusing on the most effective and efficient activity is important.

Regarding new acquisition programs, a requirement for comprehensive structural integrity management capability places a request for the OEM to provide a sufficient data package and a need for contractual agreements to enable access to engineering data when the need arises during the sustainment.

International co-operation is highly acknowledged by the FDF, particularly the information exchange and collaborative actions within the F/A-18 user community that has greatly improved understanding and knowledge within the FDF and domestic partners. Using the common standard base has helped to share information and adopt ASIP practices from other users.

Increasing structural issues with the aging aircraft pose risks and challenges to meet requirements for operational availability and economic service life. Major concerns include crack findings on fracture critical structures for which there is no “full life” modification available and findings on structures that allow very small critical crack sizes. In addition, exceedance of certified safe life for some components may necessitate either significant re-certification activities or introduction of new structural inspections to further add to the increasing workload. These are examples of structural issues that justify the necessity to maintain a responsive and effective ASIP through the remaining service life.

13.8 REFERENCES

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Part 3: AIRCRAFT PROPULSION SYSTEMS



Chapter 14 – AIRCRAFT PROPULSION SYSTEMS (UNITED STATES)

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14.1 INTRODUCTION

This section will address the United States Air Force's (USAF) approach to propulsion continued airworthiness as expressed in our fielded engine life management approach. The methods and practices used to assure engines are being supported with the proper technical activities to provide the service life for the required safety levels and maintenance costs will be discussed. Engine life management concepts have been developed and have evolved within the propulsion community to provide a roadmap of activities that must be considered for the support of the engines in the field. The Propulsion System Integrity Program (PSIP), as described in MIL-STD-3024, offers a methodical systems engineering approach to the full life cycle management of propulsion systems and the key elements of sustainment and airworthiness will be described.

14.2 HISTORICAL PERSPECTIVE

In the post-World War II era, initial capabilities for gas turbine engines were approximately 25 hours of life, governed primarily by hot section limitations. By the early 1950's this had increased to 160 hours of life. Engine procurement requirements, however, were deficient in sufficiently describing structural durability requirements and omitted essential elements like duty cycle definition and mission related testing. The institution of a 150 hour qualification endurance test was an incremental improvement, but still did not adequately reveal service related problems. The late 1960's and early 1970's saw the advent of improved criteria, initially added to the A-10 and B-1 propulsion specifications. Unanticipated failures persisted and in 1976 a Scientific Advisory Board (SAB) was convened to determine any systemic root causes, resulting in the creation of the Engine Structural Integrity Program, or ENSIP [1], [2], and [3]. Some of the lessons learned are as follows:

- It is unrealistic, and possibly dangerous, to assume defect-free structures in safety-of-flight components;
- Critical parts and potential failure modes must be identified early and appropriate control measures implemented;
- Internal thermal and vibratory environments must be identified early in engine development;
- Predicted analytic stresses must be verified by test for complex components;
- Materials and processes must be adequately characterized; and
- Design stresses, component tests, and engine test spectra must be based on actual or anticipated service usage.

This focused effort also highlighted additional overall factors affecting engine durability, specifically the roles of design, manufacturing, maintenance, and operations. Design factors identified were failure modes attributed to low cycle fatigue, wear, crack propagation, creep/stress rupture, dynamics, thermal environment, materials, and usage. Manufacturing contributors were the roles of quality, inspection, misassembly, and methods/techniques. Maintenance factors were items such as spares, tech data,

inspections, repairs, and training. The area of operations included usage, environment, foreign object damage, tactics, and parts tracking.

ENSIP broke down the propulsion life cycle into five sequentially ordered tasks:

1) Task 1: Design Information;
2) Task 2: Design Analysis, Material Characterization & Development Tests;
3) Task 3: Component and Core Engine Tests;
4) Task 4: Ground and Flight Engine Tests; and
5) Task 5: Engine Life Management.

ENSIP is an organized and disciplined approach to the structural design, analysis, development, production, and life management of gas turbine engines with the goal of ensuring engine structural safety, increased service readiness, and reduced life cycle costs. The application of ENSIP introduced two concepts:

1) The introduction of fracture mechanics based design and life management system (damage tolerance); and
2) The use of Accelerated Mission Testing (AMT) to assess durability. It should be noted that not all failure modes are equally exercised during an AMT.

For engines entering development since 1978, damage tolerance has been incorporated into the acquisition program as prescribed by ENSIP, with existing engines receiving a Durability And Damage Tolerance Assessment (DADTA). Damage tolerance concepts are used in ENSIP to define critical part inspection requirements:

- Where to inspect;
- When to inspect; and
- How to inspect.

This enhances safety, reliability, and quality assurance through defining intelligent inspection requirements.

The first four tasks are a building block approach to produce a knowledge base supporting the sustainment or life management task where closed loop force management techniques are utilized to address actual usage.

14.3 ADVENT OF PROPULSION SYSTEM INTEGRITY PROGRAM (PSIP)

The initial release of ENSIP was as a military standard, MIL-STD-1783. As part of the evolution of Department of Defense (DOD) acquisition philosophy, the military standard was revised and converted into a handbook and the requirements incorporated into the Joint Service Specification Guide. The migration from standard to handbook did not diminish the focus on structural life prediction of gas turbine engine turbomachinery components, particularly the rotating ones. A renewed emphasis on systems engineering principles within the DOD provided the perspective that the singular focus promulgated by ENSIP was insufficiently holistic and a top level integrated approach embracing other disciplines and component groups was necessary. A traditional product integrity process focused nearly exclusively on structural/material integrity issues was not inherently adaptive to reflect the emergence of other integrity initiatives, namely the Mechanical Equipment and Subsystems Integrity Program (MECSIP) and the Avionics Integrity Program (AVIP). This recognition spurred the DOD to address not only structural integrity but mechanical/electrical systems integrity as well as performance/operability and functional integrity disciplines. The result was a comprehensive systems engineering approach to all engine components including rotating turbomachinery, static structures, externals, plumbing, and mechanical/electrical controls. Program activities are defined and

scheduled to place an early emphasis on the definition of proper design criteria, to perform detailed structural analyses before hardware is fabricated, and to conduct component verification testing at realistic operational loads. The overall objective of the mechanical integrity program is to enhance engine safety and reliability by improving component durability, damage tolerance, and quality. An important by-product of this program is the reduced cost of ownership that is realized when the production engine system is deployed for use.

In recognition of and response to this overarching approach, a new document emerged to address all aspects of the propulsion system called PSIP. It was also decided that the significance of this effort warranted elevation back to a military standard which permitted it to be contractually referenced by the DOD. This approach successfully unifies all the propulsion elements of ENSIP, MECSIP, and AVIP into one governing document describing the system integrity at the whole engine level. Additionally, recognition of the increasing interdependence and integration of the propulsion system within the overall weapons system is addressed across all phases of development with emphasis on a rigorously controlled Interface Control Document (ICD). The ICD is a formalized agreement between propulsion system provider and the weapon system contractor establishing physical and functional definitions and responsibilities. This can range from routine definition of a common coordinates system (x, y, and z planes) to incoming inlet distortion patterns at the aircraft interface plane.

14.4 MECHANICAL INTEGRITY REQUIREMENTS OVERVIEW

Expanding beyond the categories of rotating turbomachinery and other large structural components, PSIP actively integrates the components and functions of an engine's subsystems. These include the following:

1) Sensors, actuators, and databases;
2) Electrical power components;
3) Ignition;
4) De-ice and anti-ice;
5) Fuel;
6) Externals;
7) Gearbox; and
8) Bearings, sumps, and lubrication circuit.

The five pillar construct originally envisioned for turbomachinery now encompasses the controls and subsystems components, bringing rigor and consistency across the whole spectrum of life cycle management. The urgency of embracing this approach became apparent with the progressing complexity of current and future propulsion systems and the ever increasing integration and dependency among previously segregated hardware entities. This unified approach harnesses the following elements across the entire propulsion system:

- Design based on mission usage profiles and expected service life exposure;
- Durability capabilities that account for failure modes such as low cycle fatigue, high cycle fatigue, and creep;
- Adherence to the component classification process describing safety-critical, mission-critical, durability-critical, and durability non-critical categories;
- For safety-critical and mission-critical designations, appropriate damage tolerance compliance actions are defined;
- Materials and process characterization;

- Definition of the internal and external environments, including aerothermal and vibratory influences; and
- Demonstration of robustness is accomplished by engine testing and AMT.

The activities listed, along with many other elements of the engine development process, form an essential building block of knowledge when transitioning to full production status and sustainment.

14.5 CONTINUING AIRWORTHINESS FOR USAF PROPULSION

The central governing tenet for continuing airworthiness in propulsion systems after receiving their Military Type Certificate (MTC) from the Technical Airworthiness Authority (TAA) is the concept of Operational Safety, Suitability, and Effectiveness (OSS&E). OSS&E preserves the capability of Air Force systems by ensuring that operational use, configuration changes, maintenance repairs, aging, part substitutions, and similar activities and events do not degrade baselined characteristics of the systems. Continuing airworthiness matrixes within the safety element and the propulsion enterprise utilizes a large toolset of approaches to ensure all the elements of OSS&E are executed proficiently. Two of the core elements within propulsion that enable this are the gas turbine engine flight safety risk management process and the Engine Life Management Plan (ELMP). The latter establishes a robust framework to prevent or minimize the occurrence of failure events while the former defines the approach when such events happen. Key elements of the ELMP that support these objectives are:

1) Lead the Fleet (LTF) engines;
2) Analytical Condition Inspections (ACI);
3) Mission surveys and usage updates; and
4) Component Improvement Program (CIP).

The goal of an LTF program is to accelerate operationally relevant exposure on a series of engine assets by prioritizing their insertion into flying aircraft. Careful coordination with the using command is essential to ensure their support of this objective while minimizing the impact on mission readiness. The intent is to use this select population to encounter any failure modes and buy reaction time for the larger fleet with spares, repair techniques, or redesigns if necessary.

Embedded within an LTF program are scheduled ACIs, where the engines are completely disassembled and methodically inspected. Non-destructive inspection techniques are used to assess the wear and durability characteristics of the hardware and then documented for the program office engineers. This progressive approach that accompanies the flying accumulation provides the engineering community with quantifiable data on wear out modes, hot section distress progression, and other leading health indicators on the individual components.

Engines are designed to an initial set of expected aircraft missions in the development phase of acquisition. As the aircraft are fielded and get operational experience it's essential to update the mission usage attributes and issue component life updates reflecting actual usage. Personnel from the government program office and engine OEM interview pilots, acquire and review significant engine parameters from either on-board or offboard sources, to create new mission profiles. Additionally, these new profiles are used to generate new mission definitions for conducting any subsequent AMTs, ensuring any exposure testing has the greatest relevance to the fleet experience.

When the most suitable remedy for a discovered safety-related shortfall is a redesign, that component becomes a candidate for CIP to fund the necessary engineering activities for redesign and test. CIP is an

ongoing program for engines within the Air Force portfolio to execute design solutions and designate engine assets for full-scale AMTs as required to evaluate the effectiveness of the changes.

Safety-related events are governed by a process described by propulsion's best practice titled "Aircraft Gas Turbine Engine Flight Safety Risk Management Process". This document describes the methods and practices used to actively track flight safety issues and apply sound engineering principles to eliminate or significantly reduce the technical risk of encountering engine failures. Figure 14-1 provides an overview of the process while the rates and consequences are governed by Engine Related Loss Of Aircraft (ERLOA) and Non-Recoverable In-Flight Shut-Down (NRIFSD) metrics. Program office engineers track the progress real time with thrice yearly senior engineering leadership reviews for all the engines within the Air Force portfolio.

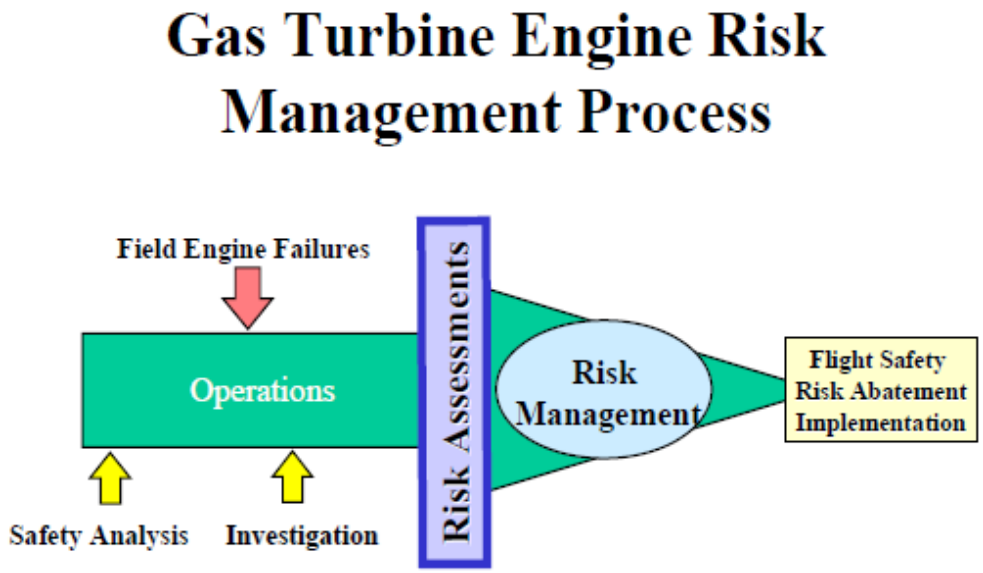


Figure 14-1: Propulsion Risk Process.

14.6 SUMMARY

Continuing airworthiness is best ensured when rigorous systems are in place to establish baseline capabilities of gas turbine engines and then manage and monitor their actual usage. Unplanned and unexpected exposure or failures are swiftly identified, assessed, and management plans laid in place as remedies are developed. Robust monitoring of the fleet and agile responses with sound systems engineering principles have proven to be effective at keeping the US Air Force fleet always postured to be safe, effective, and ready.

14.7 REFERENCES

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[2] Holmes, R., RTO Technical Report 28 "Recommended Practices for Monitoring Gas Turbine Engine Life Consumption", Chapter 2, 2000.

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Chapter 15 – US ARMY PROPULSION – CONTINUING AIRWORTHINESS

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15.1 EXECUTIVE SUMMARY

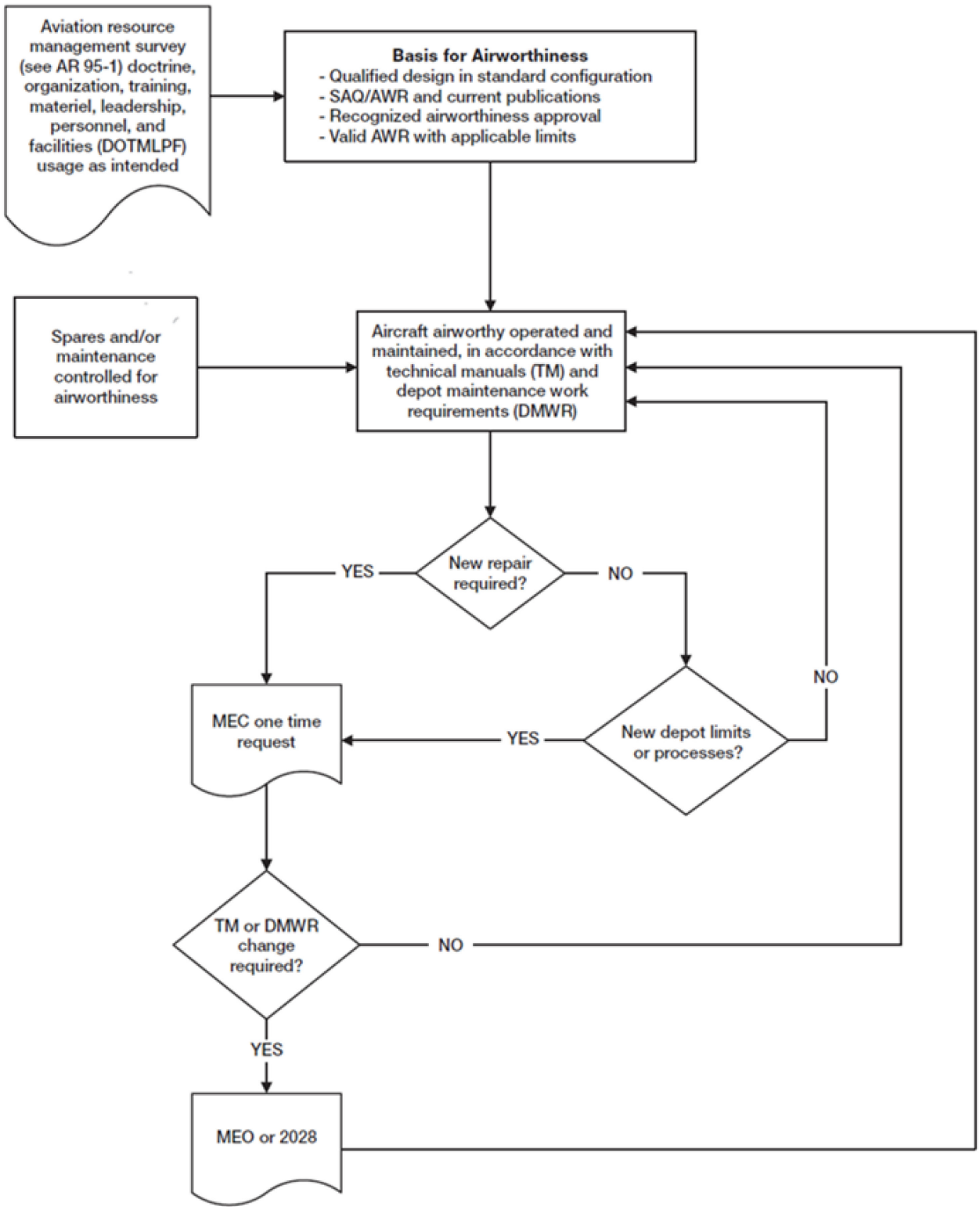
The US Army has not been effective in developing and fielding new aircraft systems for a variety of reasons. As a result, several of the aircraft systems are being operated many years beyond original expectations. The US Army has implemented various modernization concepts to address the lack of replacement aircraft for three of its major aviation weapon systems. Many UH-60A aircraft were remanufactured to the same UH-60A configuration with newly refurbished dynamic components as well as many structural modifications. Subsequent programs upgraded the UH-60A to the UH-60L configuration for increased capability and commonality to the fleet. The Apache and Chinook programs have inducted older model aircraft and output current configurations at the aircraft manufacturer's facility as part of their modernization plan. The truly aging systems, such as the UH-60A and AH-64A, have been (or will be very shortly) removed from the US Army inventory.

This paper will share the US Army's approach in maintaining airworthiness of these older systems from a propulsion perspective. The methods used in establishing initial airworthiness of drive systems will be discussed as well as the ongoing efforts to sustain those systems through additional testing and usage spectrum updates. The two primary turboshaft engines used in these platforms, T55-GA-714A and T700-GE-701D engines, are military qualified engines with ongoing programs to maintain their airworthiness as well. Additional information regarding the T700 life management will be provided to share how the US Army has evolved its philosophy toward using current fleet usage instead of prescribed mission profiles. The benefit of other Army aviation enterprise programs that monitor new part manufacturing as well as component condition throughout its life cycle are described.

15.2 FUNDAMENTAL APPROACH

The US Army approach for continued airworthiness is established in Army Regulation 70-62, Airworthiness of Aircraft Systems. There are three airworthiness processes beginning with the design airworthiness process which focuses on the airworthiness qualification plan, analyses, design reviews, inspections and test data generated to verify compliance with the applicable requirements. The second process is the production airworthiness process; it adds production readiness reviews, physical configuration audits, and process control, as well as post-production modification considerations. The third process is the continued airworthiness process, depicted by Figure 15-1. Once the basis for airworthiness has been established, the aircraft must be operated and maintained in accordance with technical manuals and depot maintenance work requirements.

The "Basis for Airworthiness" includes analysis and testing during product development. Many propulsion components are deemed 'on condition', whereas the component may remain in service an indefinite period of time as long as it meets inspection requirements. Some components have a prescribed retirement life (aka, life limit) due to a limitation in capability, such as Low Cycle Fatigue (LCF). These life limits are established to maintain safe operation of the component based on data and analyses available at that time. As the fleet matures into production and fielding, the basis for those life determinations must be reviewed periodically. Several potential changes that impact the life limit may have occurred, including material processing, changes in design, and analysis tool revisions, as well as field experience and mission requirements.



MEO – Maintenance Engineering Order
MEC – Maintenance Engineering Call
SAQ – Statement of Airworthiness Qualification
AWR – AirWorthiness Release

Figure 15-1: Continued Airworthiness Process Flowchart [1].

15.2.1 Drive Systems

US Army rotorcraft operating today were originally designed and qualified decades ago. UH-60, AH-64, and CH-47 airframes including their propulsion and drive systems have been in service for over thirty years. In consideration of potential issues with an aging aircraft fleet, the airworthiness of US Army rotorcraft drive systems is maintained through a combination of efforts including the original design and qualification, load surveys, health and usage monitoring, and fatigue life management.

Rotorcraft transmissions are designed to the drive system Maximum Continuous Power (MCP) rating specified for that particular platform. The components are sized for operating at MCP 100% of the time. Stress analysis of gear shafts verifies that static strength requirements are met and peak fatigue stresses are below the material endurance limit. Gearbox bench testing is conducted to demonstrate that gear teeth have infinite life in tooth bending. Bearings are required to have a minimum rolling contact fatigue life of 4500 hours at 75% of the drive system MCP rating or cubic mean power. Gearbox endurance and overstress testing is conducted to ensure there are no wear or other failure modes that would limit the service life of gearbox assembly (as well as to verify the gearbox capability to operate for some limited power excursions above MCP). This results in most gearbox components having an unlimited fatigue life which allows for maintenance based ‘on condition’ and hence components are only removed for cause. US Army rotorcraft gearboxes also include debris detection, temperature, and/or vibration sensors to identify excessive wear or other impending failure modes before airworthiness is affected. Many drive system components also have required periodic maintenance inspections, servicing, and/or scheduled overhaul intervals to ensure safe operation. Barring any appreciable increase to the drive system MCP rating or other system performance requirements, this overall approach results in continued airworthiness throughout the service life of aircraft.

There are other drive system components that are not designed by torque alone. For example, the critical loading and design of main and tail rotor drive shafts and some gearbox housings is also impacted by aircraft flight loads, and their fatigue life may not be unlimited. These components are subject to fatigue testing as part of the original design and qualification. The fatigue life analysis includes conservative assumptions regarding material strength, aircraft usage, and flight loads which are used to compute a retirement time with six nines of reliability. To maintain this level of reliability, it is important to periodically reassess aircraft usage. Assumptions used to develop original usage spectra can become outdated due to changing mission requirements, training, aircraft upgrades, and piloting techniques. US Army Fatigue Life Management, as defined in the Aeronautical Design Standard Handbook ADS-79E-HDBK, Condition Based Maintenance System [2] for US Army Aircraft includes detailed guidance for updating aircraft usage. This involves using regime recognition tools, health and usage monitoring data, and pilot surveys. Partial updates to the usage spectrum are also conducted that focus on certain damaging regimes in an effort to evaluate published retirement time for specific components. Any potential airworthiness concerns for these components in an aging fleet are mitigated by the original design and qualification requirements, field maintenance, periodic updates to usage spectra and component retirement lives.

15.2.2 Turboshaft Engines

The Army’s predominant turboshaft powered fleets use the T55-GA-714A or T700-GE-701D engine. The structural integrity and continuing airworthiness of those engines are maintained by adherence to the operator’s manuals, maintenance manuals, addressing safety/maintenance bulletins, and accurate tracking of critical life-limited components.

The T55 engine operating limits are defined in the aircraft operator’s manual and the maintenance procedures required to ensure proper engine operation are defined in the maintenance manuals. Daily pre-flight checklists describe actions such as ensuring that the inlet is free of debris, the engine filter status indicators are clear, there are no oil/fuel leaks, all attachments are secure, etc. In addition, engine overhauls are performed at 2,800 hour intervals. During an overhaul, the engine is removed from the aircraft and sent

to an approved overhaul facility (Corpus Christi Army Depot (CCAD) or Honeywell's Greer, South Carolina facility). At the overhaul facility, a complete teardown and rebuild of the engine is performed. Any component at or near its life limit is replaced, the compressor and turbine blades are replaced and any other issues addressed.

General issues affecting the fleet are communicated to the field by safety or maintenance information messages. These messages notify the operators of issues identified by the technical community and describe the actions required to mitigate these issues.

The T55 engine component cyclic/fatigue life consumption is tracked by cycle counting algorithms that are part of the Electronic Control Unit (ECU). These algorithms track the life for seven critical rotating components based on changes of engine rotor speed. Component life cycles are computed for each flight and are summed with previous counts to establish the total life cycle count. The total life cycle count indicates the fatigue life consumed. A safe life fatigue limit for each critical component has been established by testing and analysis. The component is removed from service when the total life cycle count, as determined by the ECU algorithms, is equal to the established fatigue life limit.

15.2.3 T700 Life Management

The T700 life limits were originally developed by General Electric (GE) Aircraft Engines and updates to those life limits have been in accordance with their life management process. An assessment is completed that determines the consequence of cracking of a given part as well as the confidence in the component's lifing analysis. The confidence in the analysis is based on operating conditions, heat transfer and stress analyses tools, materials data, and life analysis, as well as operating experience. Two of those elements, operating conditions and operating experience, lean heavily on the Service's ability to provide current and useful information.

The T700-GE-700 life limits were originally developed by GE Aircraft Engines, using a prescribed mission mix from the engine model specification. There were a total of 10 missions anticipated for the UH-60A platform; including troop assault, resupplying units in combat, troop extraction, sling load, and training. These missions provided the operational input as to how the engine was expected to operate. However, over a period of time, many changes to that mission mix are noted. Aircraft tend to gain weight over time, which increases the power required across most of the mission service operational spectrum. Changes in tactics, training and procedures often impact the duration of missions as well as the 'mix' of the missions. Therefore, it is very important to provide the engine manufacturer with current information regarding how the engine is operated.

During the 1990s, there were various engine data recording devices available to install on aircraft. The US Navy uses variants of the T700 engine that shares many parts with the T700 engine used by the US Army and was successful in installing recording devices and obtaining fleet representative data which was screened and eventually provided to GE. These mission updates were then used by GE as part of the life management process with eventual updated life limits made available to the US Navy. The US Army was unsuccessful in installing the same devices due to electromagnetic interference concerns. As a result, the 10 mission mix was slightly adjusted based on the increased power available of the T700-GE-701C engine; that updated 10 mission mix was the basis for the T700-GE-701C life determinations.

Upon completion of the T700-GE-701C life analysis, the recommended life limits were substantially lower than expected. One means to assess the accuracy of the newly calculated lives was to perform a validated life analysis. The CT7 turboprop engine had a similar hot section configuration and significant cumulative operating experience and a substantial database of field inspections including more than 200 eddy current inspections. Using the newly updated analysis toolset as well as operational experience from the GE CT7 turboprop engine, GE performed a validated life analysis. The analysis indicated that the predicted lives were inconsistent with field experience. While there were no known cracking events in the field, the analysis

predicted that several events should have occurred. This analysis allowed the US Army to risk manage the fleet, instead of extensive field removals and their associated impact on readiness and cost. It also emphasized the substantial benefit of inspecting high time parts and maintaining a database on inspection results.

During the development of the T700-GE-701D, emphasis was placed on understanding the engine's LCF capability from a "double hump" cycle perspective, an example of which is shown in Table 15-1. Many helicopter applications have missions that require a major cycle (i.e., engine start through maximum rated power) as well as minor cycles. The severity as well as the sheer volume of minor cycles is important to properly assess as the damage accrued during these minor cycles can be a significant contributor to the calculated life limits of a component.

Table 15-1: LCF Engine Test Cycle [3].

Approximate Total Time (Minutes)	Approximate Schedule Time (Minutes)	Event
0.5	0.5	Start engine
2.5	2	Run at idle
2.6	0.1	Accelerate to maximum power
5.1	2.5	Run at maximum power
5.2	0.1	Decelerate to idle
8.2	3	Run at idle
8.3	0.1	Accelerate to maximum continuous power
10.8	2.5	Run at maximum continuous power
10.9	0.1	Decelerate to idle
12.9	2	Run at idle
13.5	0.6	Shut-down
Contractor to insert	Contractor to insert	Cool down

Due to this emphasis on the double hump cycle, GE Aircraft Engines performed a finite element model based LCF Analysis of the T700-GE-701D engine with the double hump cycle and reported a minimum life for each analyzed component in terms of cycles. The US Army manages components in terms of hours so an additional assessment was required to convert the cyclic lives to hours to support the logistical capabilities of the current system. By this time, the US Army had accomplished installing recording devices on aircraft and was then able to obtain actual fleet data that could be utilized in some fashion during a lifing analysis. The assessment was performed by the US Army and utilized simplified lifing algorithms developed by US Army personnel to calculate fatigue damage based on the available fleet data.

Fundamental engineering principles (e.g., stress as a function of speed squared) are used to define a mathematical relationship that estimates the stress for a given speed range. Information provided by GE Aircraft Engines in the T700-GE-701D LCF Analysis was utilized with this relationship to define constants that are unique for each feature and component assessed. With these constants now defined, the relationship can be used to determine the stress for any other speed range given. The life for a given speed range can then be calculated and fatigue damage calculated as the fraction of life consumed for the given speed range. The damage from all identified speed ranges for a flight data record is summed to calculate the

mission life in hours. For a set of flight data, the same process is followed to determine individual mission lives and damage. The individual mission damage and individual mission duration is summed for all flights of the data set and used to calculate the component life limit in hours.

These algorithms described above are packaged in a single analysis tool which is able to reduce the size of actual flight data files to rotor speed peak/valley points by eliminating duplicate and intermediate points. The tool then performs rainflow cycle counting and the damage summation for all peak/valley points of the recorded mission. These algorithms enable the US Army to no longer rely on mix of anticipated missions, as was the case with the 10 mission mix, but on the actual missions being flown by the warfighter today.

The initial life limits published for the T700-GE-701D engine utilized the aforementioned US Army "Cycles-to-Hours" lifing algorithms to assess roughly 21,000 flight records of T700-GE-701C and -701D usage. Due to the infancy of the -701D fleet at the time, a decision was made to leverage the -701C usage data and apply correction factors to the -701C calculated life developed from statistical analysis of the competing fleets. The correction factors applied to differences in average mission duration and power turbine speed for various airframes.

Several years later, this assessment was performed again but with a much larger data set of flight data records and additional airframes that had been upgraded with recording equipment since the initial analysis. Roughly 90,000 flight records compiled across three airframes were assessed for the revised life limits and due to this analysis, increased volume correction factors no longer needed to be applied. Additionally, newly developed analysis tools by US Army personnel enabled the data set to be quickly filtered, segregated, and statistically analyzed to give the US Army a better understanding into actual engine usage and the similarities and differences inherent between airframes. Finally, the typical removal cause and previously established removal limits were considered to ensure that the new life limits were supportable from a logistics perspective. These analysis tools developed during the lifing assessments of the T700-GE-701D engine have now been adapted and used for other engine families in the US Army inventory.

Lastly, the T700 Product Office has taken a proactive approach to remove the T700-GE-700 and -701 models from inventory as well as reducing the number of 701C models. The T700-GE-701D will be the single T700 configuration. The initiative was pursued from a logistical and cost perspective but provides many airworthiness and safety benefits as well. The T700-GE-701D has benefitted from almost 40 years of improvement and has an In-Flight Shut-down (IFSD) rate of less than 0.1 failures per 100,000 flight hours. Therefore, the main focus from an engine airworthiness perspective is to maintain vigilance over changing operating environment, new product quality and adherence to field and depot maintenance practices and procedures.

15.3 AVIATION ENTERPRISE PROGRAMS

The US Army aviation enterprise has multiple programs that exist to ensure airworthiness of its fleet, including the Critical Safety Item (CSI) program as well as Production Lot Testing (PLT) on selected newly manufactured parts. The CSI program is executed in accordance with public law and various higher level guidance. Its intended purpose is to identify critical parts whose failure could cause a catastrophic or critical event resulting in the loss of or serious damage to the aircraft, to determine the critical characteristics of that part and to increase the quality assurance surveillance to ensure part is manufactured and maintained as intended by the design authority. The engine and drive system manufacturers have been involved in the establishment of the CSI list of parts as well as their associated critical characteristics (i.e, non-destructive inspection, hardness, nital etch, etc.). This collaboration between the design authority and airworthiness organization results in products and processes that are valuable in promoting flight safety. Acquisition processes as well as depot maintenance work requirements have been revised to ensure that the criticality of various inspections and processes is maintained throughout the part's life cycle.

The PLT program established limited examinations for airworthiness assurance of both Critical Safety Items (CSI) and non-CSI items that require testing and which are used on Army Aircraft. The inspections are focused on safety, performance, form, fit and function as well as forward and reverse traceability. PLT encompasses both non-destructive and destructive testing of CSIs (as well as key component features) to verify that the parts have the proper characteristics and meet key drawing requirements subsequent to the manufacturing process.

Future systems are envisioned to take advantage of significant growth in processing capability and analytics such that life-limited components will be retained in service based on their actual usage. Each serial numbered part will have its unique retirement life based on how it was operated in the field. Substantial physics-based analysis and correlation testing will be required to ensure adequate safety margin exists for this approach. Changes in the US Army's record keeping and reporting systems will be necessary to accommodate this drastic departure from current practice that has the same component life for every part. Initiatives to create longer periods of maintenance free operations will require improved diagnostics and prognostics.

15.3.1 Quality Deficiency Report (QDR)

The US Army also uses QDRs to identify issues associated with fielded hardware. These reports are submitted by the aircraft user and are categorized as either safety-related or quality related. Safety-related QDRs are given priority and usually result in a formal investigation to determine root cause of hardware failure. Any confirmed safety issue results in action being taken to address the risk of failure. Action can include special field inspections, additional field maintenance or even part removal. The QDR reporting system is one additional way to address issues associated with an aging fleet of aircraft.

15.3.2 RIMFIRE

As mentioned previously, one of the key knowledge points to properly managing the propulsion systems is understanding the condition of the hardware once it is returned to the depot. The Reliability IMprovement through Failure Identification and REporting (RIMFIRE) program was established to document the condition of T700 engines upon initial disassembly of the engine at depot. Its approach was to accurately record component condition and any relevant failure mode data, develop a web-based database with a user friendly interface, conduct engineering assessments and provide reliability reports to identify key opportunities for component improvement. The intent was to make informed decisions on prioritizing component improvements to maximize safety of flight, engine time on wing and cost reductions. The program was extended to other Army engines, drivetrain components, rotor blades and other flight critical components.

The RIMFIRE program has evolved into the predominant source of identifying and quantifying the component failure mode data for Propulsion components. During the process of inspecting components and noting their condition, unexpected hardware condition and configurations were documented. The original program was subsequently expanded to include Special Inspections, whereas specific inspections can be conducted on a particular problem area. For example:

- The use of incorrect common fasteners installed by field units at a critical location was discovered during inspections. A special inspection was put in place to quantify the number of occurrences, which was the basis for a determination on the need for further field action;
- Manufacturing discrepancies have been detected and quantified for a number of engine and gearbox assemblies. Once again, special inspections were established and statistical analyses performed to estimate the suspect population size;
- Special inspections were instituted to measure the effect of a shaft surface condition due to a quality escape. The data was used to determine the expected impact on fielded hardware that justified no further field action;

- Data gathered during engine disassembly was used to correlate the location of component weep holes to determine is a major source of oil leakage could be attributed to the alignment of those weep holes; and
- Bearing damage, high cycle fatigue failures, and improper balance grinding are some of the over 34 types of failures that RIMFIRE has detected that could have caused In-Flight Shutdowns (IFSD).

While many subject matter experts focus on maintaining appropriate Low Cycle Fatigue (LCF) life limits on critical rotating parts as a primary means to maintain continued airworthiness of our aging fleets, the RIMFIRE program has illustrated that a comprehensive inspection program at the depot is essential in maintaining airworthiness while minimizing field actions that affect readiness and cost.

One item under consideration is the development of a database that contains the listing of components that have finite life limits (retirement lives), as well as their final disposition upon retirement. A database that includes the final inspection results is critical to ensure that our predicted life limits are appropriate as well as establishing a database for any future lifing validation tasks. This initiative should ensure components are being inspected at the time when any crack formation is most likely (near their retirement life) to be detected.

15.3.3 Engine Component Improvement Program (CIP)

Aircraft Engine CIP funds are programmed in the Research Development Test and Evaluation (RDT&E) appropriations to provide for continuing improvements in the realm of safety, reliability, maintainability, durability, correction of service revealed difficulties and extend time between overhaul. The DOD recognizes that the operational and support environments change over time and a program is required to address the resultant shortfalls. Deficiencies found during field operations are analyzed and correction actions identified, redesigned products are qualified and incorporated in the engine production and fielded configurations. Engine CIP is an essential element of the airworthiness process.

15.3.4 Summary

The Commanding General, US Army Aviation and Missile Command, is the US Army's airworthiness authority. He has delegated that authority to the Combat Capability Development Command (CCDC), Aviation and Missile Center's (AvMC) Aviation Engineering Directorate (AED). The AED develops airworthiness criteria, standards and methods of compliance so that the necessary analyses and test data can be generated and approved to provide the basis for airworthiness. Continued airworthiness of the systems requires cognizance of the material, operational, maintenance and environmental changes inherent to aircraft systems as well as an ability to determine the airworthiness impact of those changes. Such an endeavour requires extensive design knowledge of the product, proactive data gathering of the product's current condition and an awareness of probable future changes.

15.4 REFERENCES

[1] US Army Regulation 70-62, Airworthiness of Aircraft Systems, Figure 2-3 Continued Airworthiness Process Flowchart, 11 May 2016.

[2] US Army Aeronautical Design Standard Handbook ADS-79-HDBK, Condition Based Maintenance System for US Army Aircraft, Appendix A, Fatigue Life Management, 8 Feb 2016.

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Chapter 16 – ENGINE STRUCTURAL INTEGRITY PROGRAM (ESIP)

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16.1 INTRODUCTION

A number of high profile catastrophic or near-catastrophic instances of uncontained failure of critical engine components provide graphic illustrations of the need to maintain the structural integrity of engines. Various studies suggest incremental improvement with successive generations of engine design. Several Royal Canadian Air Force (RCAF) aircraft types continue to operate with engines that do not benefit from these improvements.

A causal factor for loss of structural integrity of engines is inaccurate usage tracking due to changing mission profiles. If increased usage severity is not captured by programmatic review and update, inadvertent exceedance of life limits may occur; conversely, if usage severity has fallen, then critical parts may be retired prematurely.

From an aging aircraft perspective, there is increased potential difference between the actual engine usage and the assumption-based design (or baseline) engine usage as the aircraft ages. Therefore, it is essential to ensure the engine critical component life limits and associated assumptions are re-assessed throughout the life of the engine to ensure they are reflective of actual usage [1].

16.2 PROGRAM REQUIREMENTS

The Engine Structural Integrity Program (ESIP) requires each Weapon System Manager to maintain defined program to, at regular intervals [2]:

1) Reassess and document actual usage conditions;
2) Compare actual usage conditions against design usage conditions; and
3) Determine life consumption based on actual usage (of critical components, as a minimum) accordingly.

Guidance is provided defining these activities as follows:

16.2.1 A Defined Program

The set of ongoing activities constituting the “defined program” as documented in the ESIMP. The program may be conducted, and the ESIMP developed, by the Weapon System Manager (WSM) or by another organization in the WSM’s Weapon System Support Network (WSSN).

16.2.2 At Regular Intervals

The reassessment of actual usage and comparison with the design usage (baseline usage) conditions should be based on the role of the aircraft and the likelihood that usage can change over time. Normally, an interval not to exceed five (5) years would be acceptable to the Technical Airworthiness Authority (TAA) for the low risk of change situations and, more frequently, where there is a potential for significant variation in usage;

any change to the Statement of Operating Intent (SOI), change to the Aircraft Structural Integrity Program (ASIP) baseline usage spectrum, or similar change identified by the WSM should trigger a review of usage.

16.2.3 Reassess and Document Actual Usage Conditions

The reassessment of usage conditions must define the usage spectrum to which the engine has been exposed, so that it may be compared to the baseline usage spectrum. This requires the recording and analysis of operating data:

- Recording. There must be some means of recording usage parameters. Parameters may be recorded by hand or digitally, but digitization is necessary for analysis. Parameters must be recorded on a per flight basis, but on-board recording systems may provide useful real-time recording capability. Engine Original Equipment Manufacturer (OEM) requirements should define the minimum data recording requirement (i.e., parameters and sampling frequency) for usage monitoring; and
- Analysis. The collected data should be reduced to a statistical data set that is technically representative of the usage spectrum. An OEM or engineering support contractor who performs the comparison should also perform the data reduction analysis.

16.2.4 Compare Actual Usage Against Design Usage Conditions

This is the comparison of the recorded actual usage spectrum against the baseline usage spectrum. If the recorded actual usage spectrum does not fall within the baseline, the baseline usage spectrum must be updated so that the rate of component life consumption may be accurately calculated:

- The design usage conditions are the assumed baseline usage spectrum when an engine enters into service on a particular platform, used to determine both life limits and the way in which life consumption is calculated. Given that there are a number of assumptions made during the design stages, the actual usage of the engine may vary from the design usage conditions. Initially, the baseline usage spectrum should be established using the information in the SOI. The SOI may not be updated unless a formal re-role of the aircraft occurs. Usage must therefore be monitored to assess the validity of the baseline;
- The engine OEM should be engaged to perform the analysis comparing actual usage to the previous baseline using all recorded usage data (no data reduction) and with reference to any previous usage assessments. If necessary, the OEM will make recommendations on any need to alter the life consumption rate or life limits as appropriate. If OEM support is not possible, the WSM may employ other elements of the WSSN to perform this analysis; and
- The process and engineering methodologies used to establish and maintain the baseline usage spectrum must be documented in the ESIMP. The baseline usage spectrum established for the ASIP provides some useful data for the engine baseline, but additional information is required to assess engine usage.

16.2.5 Determine Life Consumption Based on Actual Usage (of Critical Components, as a Minimum) Accordingly

If it is found that there has been a change to the baseline usage spectrum such that either the life limits or the calculation of life consumption changes, the results must be incorporated into the approved maintenance program. If a reduction to life limits is identified, fleet records are to be reviewed to determine if any in-service components exceed life limits as a result.

In order to facilitate programmatic execution and technical review and assessment of the program, supporting documentation is also required.

16.3 OTHER REQUIREMENTS

The ESIP also mandates issue tracking: safety-related issues are managed through the Record of Airworthiness Risk Management (RARM) process documented elsewhere in this report (Chapter 2, Section 2.6), which is not a propulsion-specific process.

Involvement in Component Improvement Programs (CIP): several RCAF fleets are members of a CIP, which provides access to and collaboration with other users as well as a forum to identify and address common problems with OEM and other stakeholder involvement.

IVHM (Integrated Vehicle Health Management): under the ESIP, IVHM systems are not required; any practicable means of capturing adequate data to ascertain parts life consumption is permitted, and automated data recording systems are not required.

Several fleets make use of Engine Health Monitoring (EHM) and/or Health and Usage Monitoring System (HUMS) data for limited trend monitoring and operational or maintenance planning purposes. The use of such systems is not programmatically driven, and is fleet-specific based to a great extent on OEM offerings; legacy fleets may not have robust means for automated data recording for the purposes of EHM or usage monitoring.

Several fleets also make use of Oil Analysis (OA) programs: RCAF OA providers standardize against Joint Oil Analysis Program samples. The use of OA is not programmatically driven (i.e., as a component of an across-the-board IVHM requirement), and is fleet-specific based on legacy or OEM maintenance program requirements.

16.3.1 Reliability Tracking

Under the ESIP, reliability tracking is recommended, but not mandated. Specifically, the ESIP guidance includes the following note:

> *The use and documentation of performance metrics are highly recommended, although not required by the TAM. The In-Flight Shut-Down (IFSD) Rate provides a good indication of the airworthiness of the engine type. Tracking the rates on both a 12-month and 5-year rolling average will provide a trend indicator on engine airworthiness. With low operating hours, the 12-month rolling average may have too much variability to identify trends. The 5-year rate, while making the trend more visible, is slower to register both positive and negative changes. Both rates, as a result, should be monitored and a narrative provided on a periodic basis to explain any resulting changes. Additionally, a Pareto chart listing the top IFSD causes should be developed and updated on a periodic basis. This information is highly useful for monitoring the frequency and severity of occurrences and for establishing resource priorities.*

16.4 OUTCOMES

It is not yet possible to ascertain the effectiveness of the ESIP, as compliance with the regulation is not required until 30 Jun 2019. Review of fleet in-service programs has in several instances not identified a clear chain of analysis linking RCAF-specific usage rates to parts life consumption. It is understood this does not necessarily imply a safety concern, but unless such a chain of analysis exists parts life consumption must be based upon conservative assumptions in order to ensure adequate safety, which may be substantially sub-optimal economically for the RCAF. Further, whereas reviews of usage rates for engine critical components have been conducted ad hoc, the ESIP mandates a periodic review. Reassessment of the cyclic exchange rate (low cycle fatigue major cycles consumed per flying hour) of one RCAF fleet, performed shortly before the release of ESIP requirements, found that evolutionary changes in role and mission mix had resulted in significant increases in life consumption rate, on the order of 20 – 30 % per flying hour, since the last time such an analysis was carried out. This case is representative of the rationale for the ESIP.

16.5 REFERENCES

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Chapter 17 – AIRCRAFT ENGINE STRUCTURAL INTEGRITY MANAGEMENT ACTIVITIES IN FINLAND

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17.1 INTRODUCTION

This chapter provides a brief review on the approach and activities related to aircraft engine structural integrity management in Finland, from the Finnish Defence Forces (FDF) viewpoint. In addition to this chapter, the report includes dedicated chapters for aircraft structures (Chapter 13) and mechanical systems (Chapter 21).

The FDF have not implemented a systematic, comprehensive approach for aircraft engine structural integrity management. However, many related activities have been conducted within the FDF and its industrial partners, especially for the engines of the F/A-18C/D Hornet fighters and the BAE Hawk jet trainers operated by the Finnish Air Force (FINAF), as well as the NH90 rotorcraft operated by the Finnish Army. In addition to national activities, there are life management programs established by the OEMs and the FDF's involvement in international user groups and programs, which has provided important fora to share information with other users as well as allowed to participate in collaborative research and development efforts.

Along with engine Maintenance, Repair and Overhaul (MRO), a capability for demanding repairs and component manufacturing have been developed in country with Patria as a strategic industrial partner. During in-service operation with the FINAF Hornet and Hawk fleets, a significant number of repairs and modifications have been developed nationally – with very limited design and certification data. The lacking data and design capability have been partly patched up by national R&D activities.

The impact of national R&D and repair development efforts have been acknowledged, especially in the remarkable cost savings achieved. Experimental research has enabled the FDF to extend the recommended component life or the engine maintenance/overhaul intervals. Nationally developed repair schemes have been implemented successfully for several life-limited and expensive parts. In some cases, repair development has been extended to redesign and manufacturing of new parts.

17.2 ENSIP APPROACH

In general, the FDF have identified a need for investigating implementation of a systematic, comprehensive approach for aircraft engine structural integrity management, with the intention of avoiding duplication of effort by examining generally known standards such as the MIL-STD-1783 (ENSIP) [1].

The ENSIP standard is organized into five basic tasks of which Tasks I – IV relate to engine design, development and testing/certification, whereas Task V is dedicated to engine life management, which is apparently the most essential from the FDF perspective.

The initial review of ENSIP tasks suggest the following major elements when considering implementation of the standard:

- Identification of the Tasks I – IV information and engineering data required for the development/execution of the engine life management (Task V) capability;
- Determination of the component's life limits;

- Monitoring and collecting data on the actual usage (loads / environment and engine performance parameters);
- Individual engine / component tracking program and life assessment; and
- Engine structural maintenance plan.

The life limits determined for the components, as well as the required maintenance actions (i.e., Engine structural maintenance plan) are to be reviewed and updated based on the actual monitoring of usage and continuous inspections/assessments.

An example of recent enhancement of the national monitoring and data collection capability is the engine health monitoring system implemented in the FINAF Hawk Mk66 fleet. The system measures operational engine parameters and stores them on-board, to be downloaded after the flight to the embedded life assessment system which counts the cycles accumulated for each life-limited part.

The development of data analytics is a key technology area in order to exploit the growing amount of collected data, providing Continuing Airworthiness Management Organization (CAMO) with tools for life cycle planning, fleet management and maintenance planning/scheduling.

17.3 REPAIR DEVELOPMENT AND COMPONENT MANUFACTURING

The FDF jet engines MRO is assigned primarily to Patria as a strategic industrial partner. The in-country MRO capability along with advanced repair capabilities for components have been created mainly through engine assembly programs as well as continuous investments in development of new techniques.

Spare parts' availability and cost issues have been the usual drivers behind the repair development projects or the establishment of capabilities in component manufacturing. Besides the application of manufacturing techniques, some cases have necessitated a design change for a component due to insufficient reliability or performance.

In addition to developing solutions for urgent problems occurring within the fleet sustainment, Patria is continually exploring new methods of manufacturing and repairing aircraft parts. Special techniques, such as the application of thermal coatings and electron beam welding, are widely used today. Patria's work on 3D printing (additive manufacturing) technology achieved an important milestone in January 2018 with successful completion of the first 3D printed part installed and flying in the F/A-18 Hornet. The part was designed in accordance with the MDOA approval granted to Patria and was manufactured from the Inconel 625 superalloy. MDOA approval refers to Military Design Organization Approval in accordance with European Military Aviation Requirements (EMARs) and granted by the Finnish Military Aviation Authority (FMAA).

17.4 EXPERIMENTAL R&D ACTIVITIES

Engine related R&D has been mainly conducted within larger aircraft structural integrity research programs funded by the FDF. The overall goal of the national R&D activities for engine integrity has been to improve in-country capabilities related to jet engine integrity assessments in a proactive manner, before the life limits of certain engine components are reached. Besides retaining aircraft availability and securing the life cycles, a main economic driver for the research investment is the potential to achieve significant cost savings by extensions on life limits of the engine components for with there is conservatism in terms of the replacement intervals recommended by the OEM.

Special emphasis has been on the experimental methods (e.g., creep tests and associated metallographic investigations) focused on certain turbine blades and the possibility for associated life extension, with the following examples:

- Analysis of the FINAF F/A-18 Hornet low pressure turbine blades [2];
- Analysis of the FINAF F/A-18 Hornet high pressure turbine blades [2];
- Microstructural degradation of a single-crystal gas turbine blade [3];
- Guideline – turbine blade failures [3]; and
- The effect of volcanic ash on gas turbine blades and vanes [3].

The experimental research projects typically include the following tasks:

- Investigation of the flown components for failure mechanisms (initiation and propagation);
- Assessment of the failure criticality (presence of life-threatening features);
- Performing a series of inspections and other experiments; and
- Estimation of life extension potential based on the results of experiments.

Experimental research support from VTT Technical Research Centre of Finland (VTT) has enabled the FDF to increase the operational life (flight hours) of the high pressure turbine blades of the FINAF F/A-18 engines. The 10% increase in life yielded approximately 3 million USD in savings to the taxpayers, with a nearly hundred-fold Return On Investment (ROI).

An analysis of the FINAF F/A-18 Hornet low pressure turbine blades ordered by the FDF from the VTT is briefly described in the ICAF 2017 review [2] from which some direct quotes are made in the following paragraphs:

- Three FINAF F/A-18C Hornet Low Pressure Turbine (LPT) blades were received for investigation that aimed to determine in-service effects such as coating condition, microstructural degradation, cracking and attachment wear, and also to determine the 3D and cross-section geometry of the blades. Two of the blades were removed after 2496 EFH (Engine Flight Hour) and 3890 EOT (Engine Operation Time) after reaching the end of their nominal life. The third blade had seen 1363 EFH and 2130 EOT in an engine that had sucked in snow when the aircraft incidentally veered off the runway [2].
- The blades were photographed, 3D laser scanned (dimensional geometry), inspected (stereo microscopy) and then sectioned at selected locations for subsequent metallographic investigations [2].
- The crystallographic orientation did not show significant deviations from the expected status. No obvious life-threatening damage in terms of coating condition, thermal blade material degradation or cracking was observed in any of the inspected LPT blades. The fully served blade included one 0.1 mm deep crack in a location and orientation that was not threatening the blade integrity [2].
- In the blade with the snowbank incident (rapid in-service cooling), there was some limited coating delamination at the base plate and on the blade root area. The observed modest microstructural degradation of the blades was not considered to indicate life-threatening damage either [2].
- The dovetail area of the blades investigated showed some wear marks at the contact surfaces and deformation of the base material under the contact surfaces and some lamellar cracking, but there was no indication of fatigue cracking developing from these lamellar cracks or from the outer surface of the waist of the blades. Therefore, a modest extension of operating hours could be justified [2].

An analysis of the FINAF F/A-18 Hornet high pressure turbine blades ordered by the FDF from the VTT is briefly described in the ICAF 2017 review [2] from which some direct quotes are made in the following paragraphs:

- Three of the FINAF F/A-18C Hornet High Pressure Turbine (HPT) blades flown the extra 10% were removed from service and subsequently subjected to metallographic investigation to compare the blade condition after 3160 EOT against the condition of previously studied blades which had been used up to a nominal life of 2800 EOT. The main effort on damage characterization was concentrated on overheating on the concave side of the blade, microstructural degradation and depth of cracks at the leading edge [2].
- The concave side's overheating did penetrate the blade's wall in one of the three inspected blades and thus exceeded the acceptance criteria. Nevertheless, the overheating damage does not seem to threaten the blade life and can be easily monitored by visual inspection. Only in one blade some cooling holes at the blade tip were blocked by debris, but this was not believed to be life-threatening either [2].
- The maximum crack depth at the leading edge after 3160 EOT did not exceed that of previously assessed blades after nominal 2800 EOT. Also, the gamma prime (γ') depleted zone inside the cracks was continuous up to and within the crack tip which suggests sufficiently slow crack growth to justify the previous decision to extend the blade life from 2800 EOT by 10% [2].

17.5 CONCLUSION

The FDF has identified a need for investigating the implementation of a systematic and comprehensive approach for aircraft engine structural integrity management, with the intention of avoiding duplication of effort by examining generally known standards, such as the MIL-STD-1783 (ENSIP). Another standard to be considered is the MIL-STD-3024 Propulsion System Integrity Program (PSIP) as it provides a comprehensive system engineering approach addressing structural/mechanical/electrical systems integrity (see Chapter 14). The establishment of integrity management processes along with associated critical capabilities is considered crucial to supporting the FDF's Type Certificate Holder (TCH) and Continuing Airworthiness Management Organization (CAMO) functions.

The initial review of ENSIP tasks suggests the following major elements when considering implementation of the standard:

- Identification of the Tasks I – IV information and engineering data required for development/execution of the engine life management (Task V) capability;
- Determination of the component life limits;
- Monitoring and collecting data on the actual usage (loads/environment and engine performance parameters);
- Individual engine/component tracking program, life assessment; and
- Engine structural maintenance plan.

Regarding best practices, the experience gained from implementing Aircraft Structural Integrity Program (ASIP) may provide some applicable practices when considering implementing an Engine Structural Integrity Program (ENSIP). For example:

- Identify all the information related to the engine design and development phases, and incorporate them in the ENSIP to be assessed when the need arises during the sustainment;

- Develop and maintain an up-to-date ENSIP plan/database for the fleet, documenting all the relevant information and actions; and
- Evaluate regularly the overall effectiveness of the ENSIP and prepare an action plan to improve the identified focus areas.

The national activity related to aircraft engine structural integrity is highlighted by the repair development and R&D achievements enabling significant life cycle cost savings while assisting in securing the required levels of aircraft availability and flight safety. From that experience, the following can be recommended to support the aircraft engine structural integrity management program:

- Establish repair development programs and manufacturing capabilities in country, with the potential to provide feasible and cost-effective solutions for engine component obsolescence/availability issues;
- Invest in R&D on jet engines to create knowledge and capability within the domestic research community to be utilized as basis for engine component life assessment/extensions and other structural integrity management activities; and
- Promote active collaboration with the OEMs and participation in international user groups, which provides access to other users' findings, sharing best practices and technology advancements along with actual collaborative research efforts.

17.6 REFERENCES

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Chapter 18 – AGING OF ENGINE STRUCTURES

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18.1 ENGINE MATERIALS FAILURE MODES

Critical components of gas turbine engines include the major rotating parts, discs and shafts, and other structural components subjected to high loads. Typically safe operating lives are defined for these critical components. In addition to the major components, other components in the rotating assemblies, such as spacers, cover-plates and seals, may also be designated as critical. Following the safe life philosophy, to avoid unacceptable risk of catastrophic failure, it is necessary to monitor the life usage of those critical components and retire them from service before their allocated life has been exceeded [1], [2], [3], [4].

A thorough understanding of the failure mechanisms affecting gas turbine components is essential if the failure modes, the safe life, and the life usage of each component are to be accurately determined and safely monitored [2]. Typical failure mechanisms summarized in Table 18-1 [3] are:

- Low Cycle Fatigue (LCF);
- High Cycle Fatigue (HCF);
- Thermomechanical Fatigue (TCF);
- Creep (C);
- Overstress;
- Corrosion (Cor);
- Hot Corrosion (HC);
- Erosion (ER); and
- Fretting and Wear (WR).

Table 18-1: Failure Modes and Life-Limiting Properties for Turbine Engine Components [3].

Engine Section	Component	Failure Mode
Compressor	**Blades**	ER-COR, HCF
	Vanes	ER-COR, HCF
	Discs	LCF, C, HCF
	Spacers	LCF, C, HCF
Turbine	**Blades**	TMF, C, HC, LCF, HCF
	Vanes	TMF, C, HC, HCF
	Discs	LCF, C, HCF
	Torque rings	LCF
Combustor Cases		LCF, C, HCF

Engine Section	Component	Failure Mode
Shafts		LCF, WR
Compressor Discharge Cases (Diffusers)		ER, LCF, COR
Rotating Seals		LCF, C, HCF

Legend:

ER	Erosion	LCF	Low Cycle Fatigue
C	Creep	HCF	High Cycle Fatigue
COR	Corrosion	HC	Hot Corrosion
TMF	Thermomechanical Fatigue	WR	Wear

The ability of a component to resist the effects of these failure mechanisms is a function of the material properties, the component design and manufacture processes and also the component operating environment. These features of the component are fixed by the design and application of the engine and cannot be affected by the method in which the engine is operated or maintained. Conversely, there are external factors which also have an influence on the rate of component life consumption but which can be reduced during engine manufacture, operation and maintenance [2]. The external factors affecting life usage rate are:

- Manufacturing methods and material defects;
- Build and maintenance errors;
- Foreign Object Damage (FOD); and
- Limit exceedances during operation. [2]

These four engine damage sources are effectively controlled by engine manufacturers, operators and maintainers therefore they could be described as avoidable. However in reality, in operational practice, this is difficult to achieve.

Failure and failure modes:

- Failure of a gas turbine engine component is defined as any change in the size, shape, or mechanical properties of the component that makes it unable to satisfactorily perform its design functions. The term may also mean that all of the life is used up; and
- Failure mode is defined as a physical or chemical process or processes, which take place or combine their effects to produce component failure [3].

During long-term service in an extreme environment under high stresses and at high temperatures, turbine engine components such as discs, blades or vanes suffer from cumulative damage, which gradually degrades their mechanical properties and could lead to a component failure or even loss of engine structural integrity.

Engine components can be subjected to both surface and internal damage:

- Surface damage due to erosion, corrosion, oxidation, wear, fretting or impact can promote crack nucleation and subsequent crack initiation at stress concentration areas. These cracks can then propagate under the influence of mechanical and thermal cyclic loads during service and eventually cause component failure; and
- Internal damage is related to microstructural changes that occur slowly at a rate which is strongly influenced by service temperature and stresses, which in turn depend greatly on user practice. These microstructural changes can be associated partly with plastic damage accumulation and partly with

metallurgical aging. Depending on the component, alloy composition and service condition, the plastic damage may be due to creep, Low Cycle Fatigue (LCF) or creep-fatigue interactions. As internal damage builds up, the resistance of components to deformation under static (creep) or cyclic (LCF) loading is reduced. Extensive loss of resistance to plastic deformation can lead to cavitation and internal cracking under creep conditions or ductility exhaustion and crack initiation under LCF or TMF conditions. Both lead to failure.

A summary of all basic failure modes for gas turbine engine components is shown in Table 18-1. The primary failure modes that are assessed for life usage purposes are LCF and creep [3].

LCF damage is dominant in bores, bolt hole and fillet areas of compressor and turbine discs. It is caused by stress cycling associated with engine start-up and shut-down and with RPM excursions during service. While the driving force for LCF damage accumulation in compressor discs is primarily mechanical, in hot section areas of the engine it may also be associated with thermal cycling. In addition, TMF damage in vanes and high-performance blades is often a life-limiting factor in modern gas turbine engines.

The component service temperatures are usually high enough to cause aging of the material, which results in loss of tensile and creep strength and therefore its load bearing capacity.

Creep damage is usually predominant in the mid-airfoil section of a turbine blade and in some cases in rims of turbine discs, where the stresses and temperatures may be sufficiently high to cause time-dependent plastic deformation.

Engine designers expend a great deal of effort to establish life limits for components whose deterioration may threaten operational safety. The lifing procedures employed to establish life limits vary with components and the mode of damage. In modern turbines, discs and spacers are normally designed to withstand LCF and burst due to overspeed as well as creep for the hot section side of the engine. Turbine blades and vanes are designed to withstand creep as well as thermomechanical fatigue and High Cycle Fatigue (HCF).

The life limits for these components are initially established based on service estimates of damage accumulation rates. They are then revised as field experience is accumulated. Typical lifing procedures can be grouped as follows:

- For rotating components the most common lifing procedure employed to establish safe life limits follows a time or a cycle to crack initiation criterion, which is factored down to represent a minimum property component;
- For turbine blades and vanes, life limits may or may not be prescribed by engine designers. In particular, turbine blades and vanes in aerospace gas turbine engines are seldom lifed because of the difficulties associated with predicting the service behaviour of complex alloy systems under operational conditions that vary widely with user practice; and
- In the case of coated components, these difficulties are compounded due to coating-substrate interactions, which are usually not well understood. A “Life-on-Condition” approach is sometimes employed, where, for instance, creep growth or untwist of airfoils is measured and distortion limits are used as retirement criteria.

As indicated, rotating parts such as compressor and turbine discs are usually life-limited due to LCF damage accumulation. The most common and traditional lifing method employed for these parts follows a “cycles-to-crack initiation” criterion, where a minimum life capability is defined statistically for simulated service conditions through extensive coupon testing and component test verification in spin test rigs. The statistical minimum is usually based on the probability that no more than 1 in 1000 components will

have developed a detectable crack (typically chosen as a crack of 0.8 mm in length). It should be mentioned that the value "1 in 1000" is chosen arbitrarily. Various engine manufacturers use different values, e.g., 1 in 980, or 1 in 750 components [3].

This approach has been criticised as being overly conservative and costly because in this lifing approach critical rotating components, such as discs, are usually discarded with significant amounts of useful residual life. There are two major concerns when a cycles-to-crack-initiation rejection criterion is used to life rotating parts. The first one is that, by implication, 99.9% of the components will be retired before any detectable crack has formed and it is possible that these parts may be capable of significantly longer service before they develop a detectable crack (actually 0.8 mm in length). The second concern is that the discarded components may be capable of tolerating crack of sizes much greater than the 0.8 mm typically used. This limit actually reflects the sensitivity and reliability of current Non-Destructive Evaluation (NDE) methods rather than the mechanical tolerance of a particular part for cracks. For example, crack detectability by dye penetrant methods depends on crack length, whereas crack depth is the critical factor for lifing purposes [3].

Because many modern components have demonstrated high levels of resistance to crack growth, and modern materials have different characteristics, alternative lifing procedures based on damage tolerance and the application of fracture mechanics principles, are now in use. The philosophy behind these alternative lifing procedures assumes that the component may be capable of continued safe operation during crack growth, providing that the cracks grow sufficiently slowly during service to allow their growth to be reliably detected and perhaps even monitored through regularly scheduled inspections.

In their most elementary forms, these alternative damage tolerance based lifing procedures, which are also known as Life-On-Condition, Retirement-for-Cause or simply fracture mechanics lifing, assume that the fracture critical locations of a component contain cracks of a size that lie just below the detection limit of the Non-Destructive Inspection (NDI) technique used to inspect the component. The crack is then assumed to grow during service in a manner that can be predicted by linear elastic fracture mechanics, or any other acceptable method, until a predetermined dysfunction limit is reached beyond which the risk of failure due to rapid crack growth becomes excessive [3].

The accuracy of the process for determining safe component life and the monitoring of its consumption have a major impact upon the safety of the engine or on its life cycle cost. Engine design-features and operational environments that undermine safety the most or are very costly, both in direct cost or in maintenance efforts, must be identified. Only then can managers assess the potential benefit of proposed modifications to the design or changes to operating practices. Even minor changes to operating practice, which may have little or no operational impact, can significantly lower life usage rates and bring the benefits of higher availability and reduced life cycle cost [2], [3].

For Damage Tolerance (DT) based procedures to be successful, supporting methodologies must be developed. These supporting technologies include:

- Non-destructive inspection;
- Mechanical testing of test coupons and components;
- Structural analysis;
- Mission profile analysis; and
- Condition monitoring of components.

Particularly, extensive material testing involving room and elevated temperature crack growth rate data must be performed for the application of deterministic and probabilistic fracture mechanics based life prediction concepts.

Not all components are candidates for life usage management to damage tolerance limits. Two examples are:

- Components made out of material with a short crack propagation life; and
- Components in a situation when the engine parts cannot be inspected.

Few, if any, mature engines that are currently in service were designed with damage tolerance methodologies, though some may be viable candidates for damage tolerance management.

18.2 DAMAGE TOLERANCE APPLICATION METHODOLOGY FOR AGING ENGINES

The initial life of a gas turbine engine is developed and applied by the Original Equipment Manufacturer (OEM) at the engine design stage. The lifing methodology includes analyses and testing of various life-limiting locations in critical components. The lifing process applied to civilian engines is governed by requirements of regulatory agencies, such as Transport Canada or Federal Aviation Authority (FAA) in the USA. Civilian engine operators have to adhere to strict life limits established by the OEM, but in a military environment, weapon system managers or life cycle managers have airworthiness authority. That is, they can decide on engine overhaul policies and the possibility of flying them beyond OEM recommended life. These airworthiness decisions have to be made on the basis of sound technical data and proper risk assessment. Therefore, lifing of critical components of aerospace gas turbine engines has a significant effect on the safety and economics of operation for both military and commercial fleets. The need to balance risk and escalating maintenance costs explains the growing interest in the application of life extension technologies for safely extracting maximum life out of life-limited parts, [1], [5], [6], [7], [8], [9]. Unfortunately, gas turbine component lifing methodologies are treated by the OEM as proprietary information and these methods are strongly protected. Consequently only limited information is available on life prediction methods used by the OEM [10], [11].

Basic damage modes, such as Low Cycle Fatigue (LCF), Thermomechanical Fatigue (TMF), creep or High Cycle Fatigue (HCF) have been identified for all critical components of gas turbines. Characterization and understanding of these damage modes acting separately are generally well-developed. However, components in service are subjected to a combination of these damage mechanisms induced by the effects of mechanical forces, temperature and environment. Therefore the major challenges in life prediction and life extension of gas turbine engines are to understand the complexity of multiple damage modes and their interactions. Often, a linear cumulative damage model is used to count damage induced by fatigue, creep and creep-fatigue interaction, even though there is a lack of a physical rationale underlying this rule [9].

The fatigue damage accumulation process in structural components can be broken into crack nucleation, small crack growth and large crack growth stages. A life obtained from material coupon testing supported by spin rig verification is usually regarded as the “safe life” of a component, which implies that it is defect-free until the end of its prescribed life. This safe life approach was the sole lifing philosophy until the advent of fracture mechanics, which provided the theory and methodology to deal with crack growth behaviour in materials. The lifing methodology that takes into account the period of crack growth is referred to as the “damage tolerance” philosophy [10], [11], [9], [12].

In general implementation of lifing procedures for critical components, there are key questions that need to be addressed to practically life a given component. Some of these questions include: “What is the definition of crack nucleation?” “What are initial cracks?” “What is the crack growth rate?” and also “how can cracks in structural components be detected before they become critical?” Addressing these questions poses great challenges to engineering implementation of the lifing procedures. In addition, at the theoretical level other issues, such as models that can bridge the crack nucleation and crack growth stages, must be addressed. These include physics-based modelling of fatigue and creep crack nucleation, with their applications to life

prediction of aerospace components [9], [12], [13], [14]. In addition, efforts were made to develop diagnostics, prognostics and health management systems for gas turbine engines, as described in Refs. [10], [11], [15], [16].

Damage tolerance concepts for gas turbine engines have emerged due to the limitations of the traditional safe life design concept, where only 1 in 1000 components is expected to develop a small fatigue crack at the end of a safe life period, Figure 18-1. The remaining 999 components are needlessly retired in a crack-free condition with a large amount of potential life still available. Many critical rotating components, such as turbine discs and spacers, are treated in this wasteful manner.

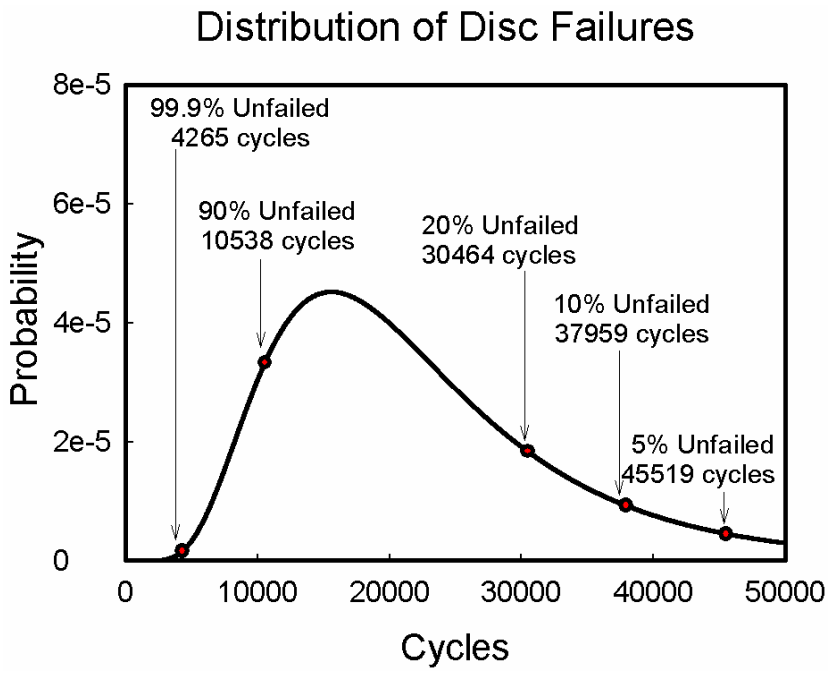


Figure 18-1: Probability of Failure in the Safe Life Approach.

By applying a safety-by-inspection life cycle management approach, which relies on predictions of crack growth life and Non-Destructive Evaluation (NDE) of components at overhaul, safety of these components can be assured and significant cost savings can be realized. This is often referred to as the Damage Tolerance Based Life Cycle Management (DTLCM) concept, which is illustrated in Figure 18-2. It is shown that at the end of a Safe Inspection Interval (SII), all components are inspected and then the components in which cracks indications were not found can be returned to service for another SII. This procedure is repeated until a crack is found. In this approach the components are retired based on their individual condition. DTLCM procedures assume that:

1) Flaws exist in manufactured parts;
2) They are located in the fracture critical locations of the components; and
3) Their sizes are just below the detection limit of the NDE technique used to inspect the components [10], [11].

The flaws are predicted to grow during service at a rate governed by the local stress distribution and operating environment for the parts in a manner that can be predicted by Linear Elastic Fracture Mechanics (LEFM). A dysfunction limit is determined, beyond which the risk of failure due to rapid crack growth becomes excessive. The process of crack growth from an initial size (a_i) to a dysfunction crack size (a_d) in a

component is usually established numerically, based on the best estimates of the service loads and material properties. The results generate a Crack Propagation Interval (CPI), which forms the basis for SII:

$$SII = CPI / Safety\ Factor \tag{18-1}$$

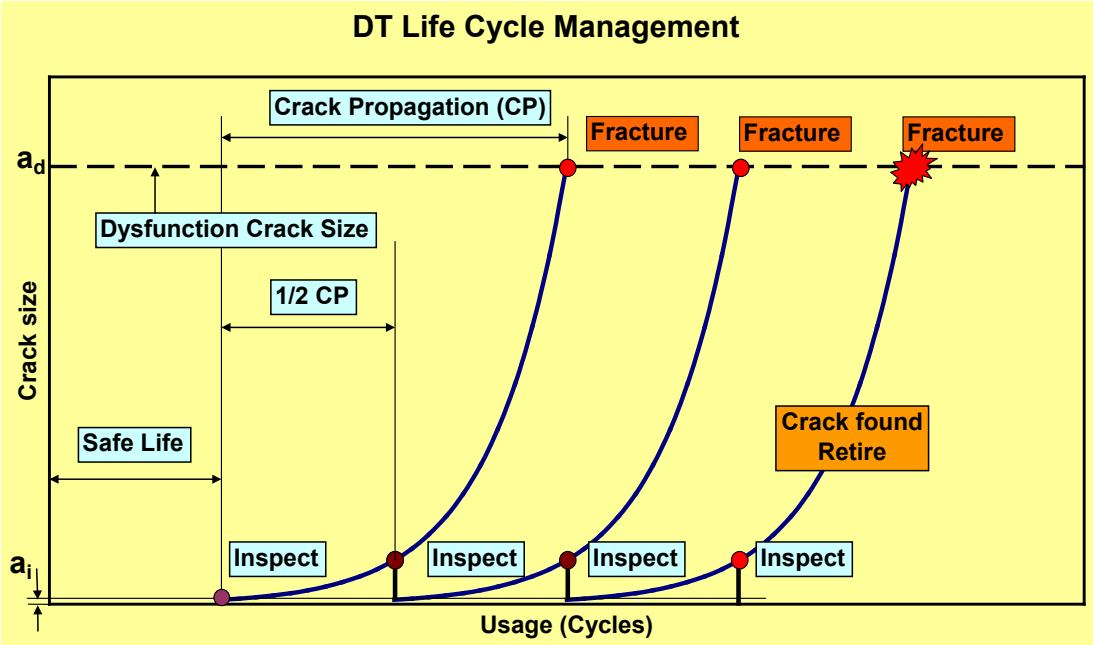


Figure 18-2: Schematic Representation of the Damage Tolerance Based Life Cycle Management Approach.

The US ENSIP damage tolerance approach [17] uses quantitative measures of the maximum crack size that may be missed during depot level inspection as the starting point for damage tolerance analysis. Probability Of Detection (POD) information is also considered in the damage tolerance analysis. The initial surface crack size used in the analyses usually corresponds to 90% POD with 95% confidence (90/95 POD) for NDE techniques. In addition, the Probability Distribution Function (PDF) of size for cracks missed during inspection is used as the starting condition for each simulation, which is the initial crack size a_i. [10], [11].

Deterministic Fracture Mechanics (DFM) calculations, which represent a worst case scenario, are used to predict SII. Accordingly, Probabilistic Fracture Mechanics (PFM) is used to quantify risk, by simulating the consequences of missing a crack during inspection. The PFM approach uses the LEFM principles for calculating a , but input parameters such as initial crack size, dysfunction crack size, and constants of the Paris equation are treated as random variables.

A flow diagram of the DFM/PFM methodology is presented in Figure 18-3. These procedures, based on DFM and PFM, take into account material data, POD and distribution of initial crack sizes missed by particular NDE techniques. In addition, curves describing the Stress Intensity Factor (SIF) vs. crack size are used. Simulation of the crack growth from an initial crack size to the dysfunction crack size is performed and simulation results are fitted with probability distribution functions [10], [11].

Each set of simulated failure data obtained in PFM analyses is evaluated statistically. Two or three parameter Weibull, lognormal or gamma distributions are used as Probability Distribution Functions (PDF) candidates which fit the simulated data. Probability-plot-correlation-coefficient plots are used to initially estimate shape parameters for Weibull or gamma distributions. This determines which specified distribution family provides the best fit to the simulated failure data. Next, three distributions are fitted to the data using both the least

square and the maximum likelihood methods. Finally, the Anderson-Darling goodness-of-fit test is performed for fitted PDF curves. This test is a modification of the Kolmogorov-Smirnov (K-S) test which gives more weight to the tails than the K-S test [18], [19]. In-house software packages are used to perform disc failure simulations, while MATLAB® and in-house statistical analysis software are used to analyse the simulation results [10], [11].

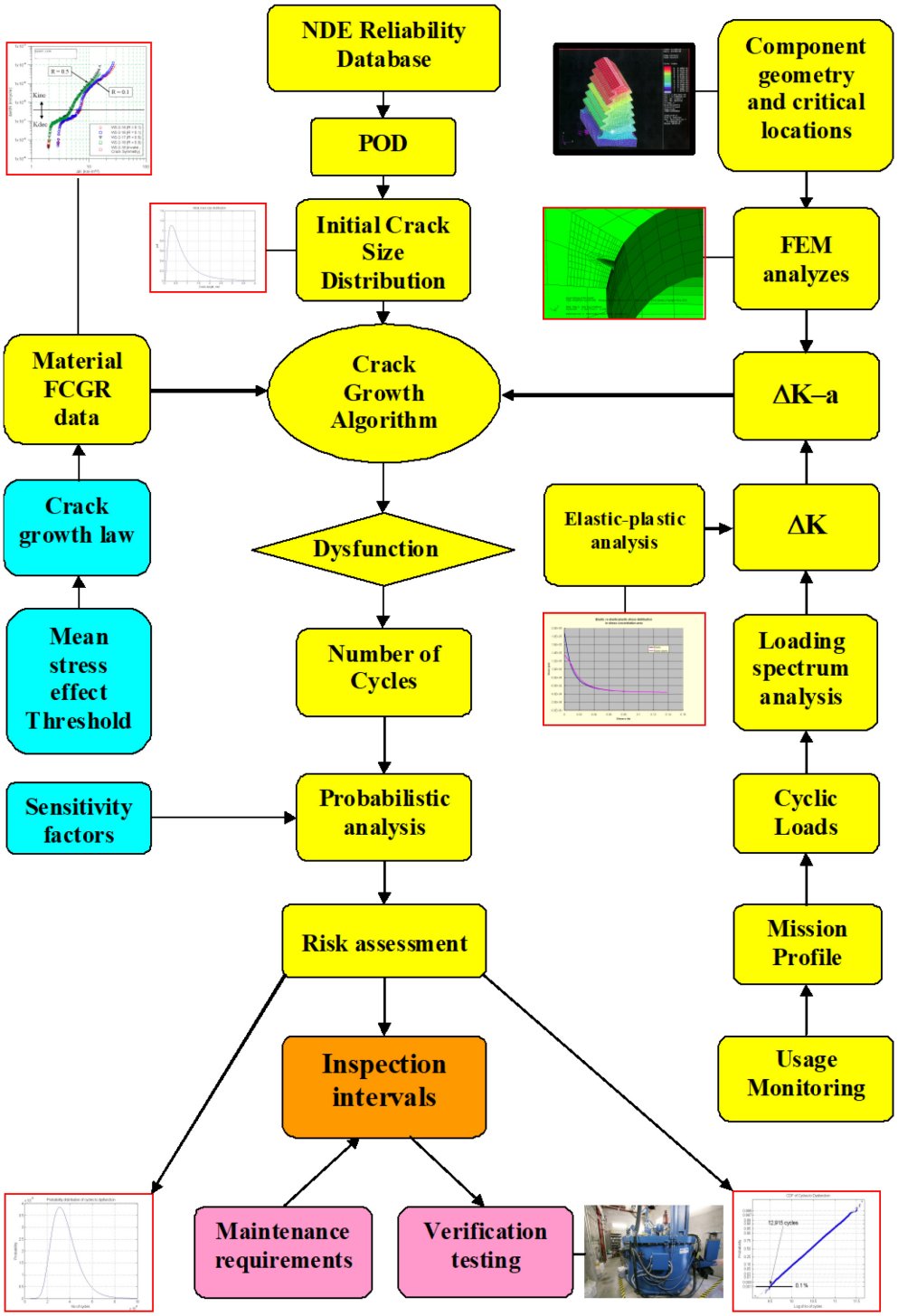


Figure 18-3: Flow Diagram of the Damage Tolerance Assessment Algorithm [10], [11].

Both types of analysis, DFM and PFM, require the stress and thermal analyses of components, which are performed at NRC-Aerospace using commercial Finite Element (FE) packages such as MSC.Nastran, MSC.Marc and ABAQUS. Meshing for the FE analyses is prepared with MSC.Patran and Femap. Following linear elastic calculations, elastic-plastic analyses are performed to establish the redistribution of stresses under operational loads. In other companies and research organizations, different software and different methods are used to perform component lifing analyses, and damage tolerance analyses, e.g., Refs. [20], [21], [22], [23], [24], [25], [26] and [27]. Material data is obtained using material testing performed on service exposed materials using appropriate test methods, e.g., [28].

Some assumptions have to be made in the damage tolerance assessment of old hardware due to a lack of detailed technical data. In the approach reported here it is assumed that:

- Cracks in the component are large enough to grow according to the Paris relation;
- For 2D calculations, growth of the three-dimensional cracks is governed by the stress intensity factor at the deepest point;
- Only a one dimensional stress state is driving propagation of the crack (mode I);
- Effect of minor cycles can be neglected;
- Temperature distribution in a component can be inferred from known operational temperatures;
- Only cracks emanating from surfaces are allowed to grow; and
- Effects of compressive residual surface stresses can be neglected.

Conservative safety factors are used during the analysis to compensate for these simplifying assumptions. In addition, for the practical application of DTLCM in the field, a final safety factor on predicted SII is also defined. This safety factor is based on confidence in the analysis, material property data, engine usage, and inspection capability. The value of the safety factor is based on an overall confidence in the entire DT process, and is typically between 2 and 5 [10], [11].

The Applied Vehicle Technology (AVT) Panel of NATO Science and Technology Organization (NATO STO) prepared a number of reports and conference proceedings on gas turbine engine lifing, damage tolerance and required instrumentation, [28], [29], [31], [32], [33].

Using these algorithms, damage tolerance analyses were performed at the NRC-Aerospace for several components of gas turbine engines operated by Royal Canadian Air Force (RCAF). Deterministic Fracture Mechanics (DFM) methods were used to assess damage tolerance of a part containing a crack at the detection limit of the inspection techniques used in the field, while Probabilistic Fracture Mechanics (PFM) methods were used for assessment of the risks associated with the application of various inspection strategies. Components from a few engines powering military aircraft, among them J85, Nene X and T56, were assessed, [10], [11], [34]. The damage tolerance methods developed were transferred to the RCAF airworthiness authority for military aircraft, who have implemented some of the recommendations for the maintenance and operation of the military gas turbine engines. The damage tolerance methods developed contributed to the Canadian Engine Structural Integrity Program (ESIP) requirements promulgated for the RCAF [35], [36].

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Part 4: AIRCRAFT MECHANICAL SYSTEMS, AND OTHER SUB-SYSTEMS



Chapter 19 – AIRCRAFT MECHANICAL EQUIPMENT AND SUBSYSTEMS

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19.1 INTRODUCTION

This section will address the United States Air Force's (USAF) approach to continued airworthiness for aircraft mechanical equipment and subsystems. The USAF uses a structured systems engineering process as described in MIL-STD-1798 [1] to manage aircraft mechanical equipment and subsystems. The majority of program offices execute a Mechanical Equipment and Subsystems Integrity Program (MECSIP). MECSIP is a cradle-to-grave task-based approach with the goal of achieving the desired level of safety and aircraft availability at the most economic cost across the life cycle of the weapon system. In addition to MECSIP, key elements of sustainment and airworthiness make up the current state of subsystems management practice in the USAF.

19.2 HISTORICAL PERSPECTIVE

The successful Aircraft Structural Integrity Program (ASIP) as described in MIL-STD-1530 [2], combined with the desire to avoid mishaps related to mechanical failures, gave rise to MECSIP. The proven ASIP approach, which had previously been applied to the development of other integrity programs such as those for avionics and engines, also provided a framework for developing the mechanical equipment and subsystems integrity program. All of USAF's integrity programs use the ASIP pattern and all have similar types of tasks [3]. MECSIP is governed by MIL-STD-1798, which was first published in 1988 and updated in the early 2000s with more robust sustainment tasks. As it stands today, each task in the standard builds cumulatively toward optimizing integrity all the way through sustainment.

Prior to 2005, though the MECSIP standard existed as an available method for subsystems management, it was not called out as a requirement in USAF directive publications and it lacked sufficient detail for effective sustainment. In 2005, Air Force Instruction (AFI) 63-101/20-101 began requiring each program office to execute integrity programs for their aircraft. Only recently developed aircraft from the mid-2000s to today had a MECSIP requirement in development. In contrast, almost all USAF aircraft in use today had a requirement for ASIP from the start. The MECSIP requirements are primarily a collection of best practices, the result of individual program lessons learned on subsystems management before MECSIP was a requirement.

MECSIP has grown to incorporate the roles of materials, design, manufacturing, testing, usage, personnel, and repair/overhaul factors, providing sufficient insight into component failures to enhance readiness, safety, and sustainment cost for the USAF.

MECSIP includes five sequentially ordered tasks, which are summarized below and described in detail in MIL-STD-1798 [1]:

1) **Task I: Preliminary Planning** – The purpose of Task I is to scope the tailoring, planning, and development strategy for applying MECSIP;
2) **Task II: Design Information** – This task encompasses the efforts required to identify and understand all technical criteria that apply to the initial design, development, materials, manufacturing processes, and production planning for each specific system or equipment

application. A key effort within Task II is the classification of components and identification of appropriate control mechanisms for all safety-critical components and those mission-critical components which must not fail in service;

3) **Task III: Design Analysis and Development Tests** – Analyses and development tests support the Design Control Activity and verify compliance with performance, functional, and integrity requirements;

4) **Task IV: Component Development and System Functional Tests** – These tests are intended to verify the subsystem integrity performance and to validate design verification analysis. Test scope includes subsystems or individual components, in simulated subsystem installation environments or during flight and ground testing; and

5) **Task V: Sustainment, Force Management** – Force management includes those actions necessary to ensure that the performance, safety, reliability, and durability requirements established in Tasks I through IV are met and maintained throughout the entire life of the weapon system.

MECSIP addresses the unique characteristics of subsystem components while borrowing some successful program elements and organization from ASIP. Like ASIP, MECSIP uses a task-based approach and requires identification and management of safety-critical components to prevent catastrophic failures. MECSIP also takes it a step further, incorporating a focus on improving management of non-safety-critical components to reduce aircraft downtime (approximately 40% of aircraft downtime is attributable to mechanical equipment and subsystems). A second major difference between MECSIP and ASIP is the high number of failure mode types that are characteristic of subsystem components as compared to crack and fracture characteristics in aircraft structure. Understanding of the relationship between component usage, maintenance, overhaul, and cost often lacks the level of precision necessary to prevent unscheduled maintenance on non-critical components. While Reliability-Centered Maintenance and Condition Based Maintenance Plus are helping in this area, progress is hindered by a lack of Item Unique Identification technologies for parts marking and tracking across the USAF enterprise. Historically, the chief focus of integrity programs has been to identify, manage, and prevent failure of safety-critical parts, defined as those parts whose proper functioning is essential to safe aircraft operation. MECSIP goes further by positively impacting aircraft availability and sustainment cost through management tasks for all mechanical equipment and subsystem components regardless of safety-critical priority.

19.3 ADVENT OF MECHANICAL EQUIPMENT AND SUBSYSTEMS INTEGRITY PROGRAM (MECSIP)

MECSIP expanded the product integrity process from its original structural/material integrity focus as applied in ASIP and ENSIP to include mechanical/electrical systems, performance/operability, and functional integrity. MECSIP is a comprehensive systems engineering approach to managing all aircraft subsystem components.

The initial release of MECSIP guidance was as a military standard, MIL-STD-1798, in 1988. As part of the evolution of DOD acquisition philosophy, the military standard was revised and converted into a handbook in 1997, then converted back to a military standard in 2008.

In the mid-1990s, the KC-135 program, along with a few other transport aircraft programs, suffered component failures that resulted in catastrophic mishaps. In response, the Functional Systems Integrity Program (FSIP) emerged as a comprehensive integrity process with the objective of proactively ensuring operational safety, suitability, and effectiveness of aircraft functional systems. The FSIP concept combined standards from existing, standalone integrity programs, mainly MECSIP and the Avionics Integrity Program (AVIP), and added sustainment tasks to meet this new purpose.

In the mid-2000s, catastrophic mishaps on T-38s and a B-52 prompted a greater emphasis on sustainment in the mechanical equipment and subsystems integrity domain. For reference, in 2004 more than 50% of major programs had no formal subsystems management plan. Those programs with formal plans used five different types of plan. In 2009, USAF engineering began annually reviewing all aircraft programs against MIL-STD-1798 regardless of program origin or status.

In addition to reviews, the USAF began hosting an annual conference targeted at creating cross communication and best practice sharing opportunities among USAF aircraft program offices, industry, other USAF organizations (using commands, logistics, etc.), and other services to foster growth and innovation in the MECSIP community.

Management of mechanical equipment and subsystems has continued to evolve over the past decade. In 2010, MIL-STD-1798B incorporated sustainment tasks as used by transport aircraft FSIPs. In 2013, MIL-STD-1798C expanded the sustainment requirements for mechanical equipment and subsystems to encompass aircraft availability and cost in addition to the traditional focus on safety [1].

In 2018, the Air Force clarified and strengthened the requirement in AFI 63-101/20-101 that all programs must apply and tailor MIL-STD-1798 [4]. Over time, programs are shifting their management processes to align with MECSIP even though the majority of them originally included no MECSIP requirements. Today, nearly all USAF programs have a MECSIP manager and MECSIP master plan integrated into their mechanical equipment and subsystems management processes. Through the review process, programs are encouraged to comply with the latest revision of MIL-STD-1798 within two years of publication. All new programs entering development are required to include MECSIP requirements for all phases from development through sustainment. The class A and B combined mishap rate for manned aircraft due to mechanical equipment and subsystems causes has steadily declined for more than a decade.

19.4 MECHANICAL INTEGRITY REQUIREMENTS OVERVIEW

MECSIP actively integrates the components and functions of all aircraft mechanical equipment and subsystems. See Table 19-1 for a list of all MECSIP systems.

Table 19-1: List of All MECSIP Systems.

Cockpit and Fuselage	Electrical Power Supply
Landing Gear	Electrical Multiplex
Flight Control	Lighting System
Helicopter Rotor System	Hydraulic and Pneumatic Power Supply
Escape Capsule	Fuel System
Aerial Recover System	Oxygen System
Vertical or Short Take-off and Landing Power and Control Transmission System	Indicating/Recording
Auxiliary Power Plant	Miscellaneous Utilities
Electrical Wiring Interconnection System (EWIS)	Emergency Equipment
Ice and Rain Protection	Personnel and Miscellaneous Equipment
Air Conditioning, Pressurization, and Surface Ice Control	Explosive Devices and Components

Figure 19-1 shows the steps required for completing the five MECSIP tasks. The MECSIP master plan is the foundation of each MECSIP, documenting what the program is doing to meet the requirements of MIL-STD-1798. Updates to the MECSIP master plan occur regularly throughout the life of the system. Plan updates occur during each task of engineering development. In sustainment, plan updates are precipitated by various events such as changes in design, usage, or sustainment philosophy, and MIL-STD-1798 revisions. The MECSIP master plan is tailorable by determining requirement-by-requirement applicability for each aircraft. Any requirements judged non-applicable must have appropriate justification for exclusion from the MECSIP plan.

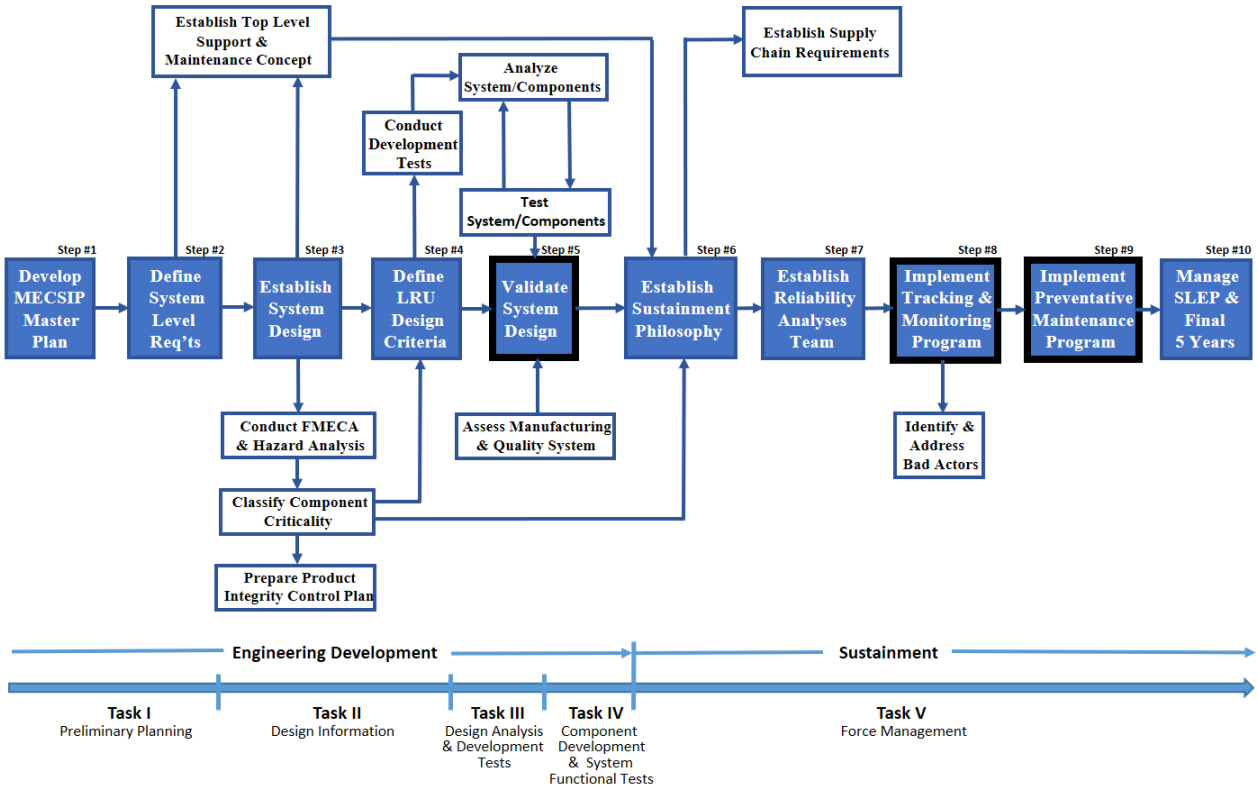


Figure 19-1: Steps Required for Completing the Five MECSIP Tasks.

Effective mechanical equipment and subsystems component management enables programs to optimize aircraft integrity and availability. The MECSIP tasks classify components according to safety-, mission-, and cost-criticality. These categories have implications for aircraft safety, usage, and availability, as well as sustainment cost and maintenance/repair procedures and timelines. Key enablers are engineering data availability; component tracking infrastructure and monitoring; data collection and analytics capabilities; field and depot maintenance documentation; and effective reliability analysis.

USAF programs have made significant progress in the past decade in all areas mentioned above by implementing functional systems integrated database software solutions that provide the program office with a software layer for managing mechanical equipment and subsystems issues. The database solutions facilitate effective documentation and management of maintenance data, fleet configurations, and technical requests, among other capabilities. Currently, there are three major database solutions in use across the USAF, with varying governance processes. One very successful database solution has grown rapidly recently as a result of a shared approach for funding upgrades. The aircraft program leaders voluntarily meet monthly and work ongoing projects funded by program office money. Program offices share the cost of Cybersecurity and

storage. This governance process results in government-owned software modifications being made available to all participating programs. It has proven to be a very dynamic, responsive, and successful approach to building robust functional systems integrated database solutions while sharing the cost through collaboration. In the future, the USAF plans to manage these database applications at the enterprise level through an ongoing database consolidation, which will make them more accessible to all aircraft programs.

19.4.1 Programmatic Issues

19.4.1.1 Aircraft Availability Cost

The USAF does not currently assign a monetary value to aircraft availability. Aircraft programs have annual availability standards that are expressed as the percentage of usable aircraft out of the total population for each mission design series. Mechanical equipment and subsystem components tend to have more of an effect on aircraft availability than on safety. Safety issues tend to get higher priority in a fiscally constrained environment. MIL-STD-1798 includes a requirement to establish a method for evaluating return on investment in terms of aircraft availability. The Air Force is unable to express the value of aircraft availability based on a profit-making motivation; however, aircraft availability impacts ability to support operations and readiness levels. Existing facilities, labor levels, and numbers of procured aircraft are in place to support defined operations and readiness levels. One method proposed derives a value for an hour of availability based on the cost to achieve the present availability rate. The value varies per aircraft based on actual costs. Using this method, the Air Force can express the value of aircraft availability by acknowledging that continuous investments in aircraft maintenance, facilities, labor, etc. are required to support the present level of availability. If the Air Force were to stop investing, then the availability rate would decline, ultimately converging on zero available aircraft. If a monetary value were placed on aircraft availability, then return on investment justifications could objectively include the impact of a change on aircraft availability. Some non-safety-related projects would receive increased priority based on positive contribution to aircraft availability.

19.4.1.2 Database Accuracy

Reliability programs (Reliability-Centered Maintenance, Condition Based Maintenance Plus, MSG-3) rely upon collecting and processing accurate maintenance data. Maintenance data, particularly data in the Reliability and Maintainability Information System (REMIS), often requires extensive “scrubbing” to make it usable for accurate reliability analysis. Improvements in the maintenance data entry process will make it easier for maintainers to enter accurate data. On the back end, improvements to automatic data post-processing can help identify common issues and indicators even from imperfect data. A recent change to the work unit code structure added a system code for the Electrical Wiring Interconnection System to allow more accurate coding and tracking of wiring type failures. This change will enhance visibility of wiring issues to aid in discovering wiring maintenance trends. The USAF’s general practice before this change was to code wiring failures against the functional system component it supports. A functional system consists of “those units which make up a system without regard to whether the units are hydraulic, electrical, pneumatic, electronic, or mechanical in nature.” [5] The Electrical Wiring Interconnection System code was added because the functional system concept failed to recognize the difficulty in discovery of related failures through maintenance data that has been coded against multiple interconnected functional systems.

19.4.1.3 Serialized Component Tracking

The USAF requires serial number tracking on items whose failure can result in catastrophic consequences. There are a few other cases where serialized tracking is required, but the underlying assumption is that serialized tracking imposes too much of a burden in terms of cost and labor to be applied across-the-board. The majority of aircraft components do not have adequate unique item identification markings to enable use of technology solutions for tracking. Any new parts management philosophy that is reliant upon markings

will have limited utility until already installed components are marked, since the unused portion of life for those components will remain unknown, clouding insight into future events. In the long term, however, the Air Force would benefit in the safety, aircraft availability, and cost domains for mechanical equipment and subsystems by implementing a system analogous to the Individual Aircraft Tracking System used to good effect by the Aircraft Structural Integrity Program.

19.4.2 Technical Issues

19.4.2.1 Life Prediction/History

Lack of life prediction and component history is a persistent barrier to improving aircraft availability and reducing costs for the USAF. Mechanical equipment and subsystem component life history needs better tracking and higher fidelity. Components that are overhauled often have criteria for removal from the supply parts pool. Removals from aircraft may be failure driven or time change driven to avert safety implications. In the safety domain, the Air Force has robust controls in place to minimize catastrophic consequences of failure. In the aircraft availability and cost domains, the Air Force could improve its knowledge of component failure characteristics through robust component tracking. The Air Force is in the process of implementing Condition Based Maintenance Plus principles that attempt to use various strategies and algorithms that add a layer of rigor to the component management process beyond standard removals, shifting the emphasis from reaction to prediction. Strategic component replacement and overhaul can be used to balance the competing goals of maximizing component life vs. probability of mission completion.

19.4.2.2 Wiring Health

The USAF is putting greater emphasis on wiring health today than ever before. Implementation of robust Electrical Wiring Interconnection System inspections is gaining momentum in the wiring community. The MECSIP standard references Electrical Wiring Interconnection System MIL-HDBK-525 [6] for optimizing the integrity of aircraft wiring systems. In addition, the development of non-invasive inspection techniques and technologies has reached a level of maturity that has been helpful on some programs.

19.5 MAINTENANCE/SUSTAINMENT FOR USAF MECHANICAL EQUIPMENT AND SUBSYSTEMS

United States Air Force sustainment practices play a major role in aircraft safety, cost, and availability. Other than the obvious role of keeping aircraft serviceable, maintenance actions provide opportunities for insight into system integrity through maintenance data, which helps make adverse maintenance trends discoverable. Reliability-centered maintenance analysis is one key strategy promoted by MECSIP for the purpose of enhancing system integrity. Maintenance data reveals poorly performing components and supports the decision-making process used to plan component replacement and redesign efforts. The program office, however, must rely to varying degrees on the logistics community to take action to correct deficiencies found. AFI 63-101/20-101 [4] emphasizes managing and documenting relationships and responsibilities of organizations that support or interface with systems managed by the program manager.

For example, when a program office identifies an item of concern in a commodity division, they must have a point of contact in order to pursue a solution to the problem, since it resides outside their control and chain of command. This is a growth area for the USAF and a point of interest for MECSIP effectiveness. Identifying a point of contact who is knowledgeable, possesses the appropriate level of authority, and is willing to act is a critical first step toward solving day-to-day problems efficiently. ASIP has excelled in this area and has multiple avenues for delineating roles and responsibilities across the USAF, as opposed to MECSIP's single focus on program office responsibilities.

19.6 CONTINUING AIRWORTHINESS FOR USAF MECHANICAL EQUIPMENT AND SUBSYSTEMS

MECSIP places emphasis on practical integrity requirements such as operational service life, usage, and natural and induced environments (including maintenance and support) as a basis for design, qualification, and airworthiness certification. MECSIP Tasks I-IV work in concert with the airworthiness approval process [1].

The USAF uses a design-based airworthiness process with the following basic characteristics as described in AFI 62-601 [7]:

1) The airworthiness process is a higher-level process for new aircraft design and reportable (high-risk) design changes, but is not recurring on a regular basis;
2) The Technical Airworthiness Authority, which is independent of the program office, approves flight operation of an air system configuration and the conditions of that operation. The Technical Airworthiness Authority issues Military Type Certificates (MTC) and other flight releases;
3) Once the Airworthiness process is completed and the MTC or other flight release issued, the program office has Systems Engineering responsibilities (Operational Safety, Suitability, and Effectiveness (OSS&E)) for the subsystems;
4) The program office assesses airworthiness of minor design changes; and
5) Aircraft program offices manage aircraft subsystems in sustainment. The Technical Airworthiness Authority retains authority over major design and operation changes during the lifecycle of the system.
    a) Reportable design modifications;
    b) Major modifications or changes to flight envelope and planned usage;
    c) Hazards identified through mishap investigations; and
    d) Discrepancies found during airworthiness audits.

19.7 SUMMARY

The United States Air Force uses a design-based airworthiness process that factors in the intended mission, usage, and operating environments. Throughout the lifecycle of a system, the program office is responsible for its operational safety, suitability, and effectiveness. MECSIP is the Air Force's process for ensuring integrity of mechanical equipment and subsystems throughout the lifecycle of the aircraft from early acquisition through disposal. MIL-STD-1798 includes five MECSIP tasks that support airworthiness certification during the development phases and long-term integrity of the system in sustainment.

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Chapter 20 – AIRCRAFT MECHANICAL SYSTEMS INTEGRITY PROGRAM IN CANADA

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20.1 INTRODUCTION

This chapter discusses the development and implementation of an Aircraft Mechanical Systems Integrity Program (MSIP) for Canada's Royal Canadian Air Force (RCAF) aircraft fleets. Requirements for MSIP were first formally introduced in Canada's Department of National Defence's (DND) Technical Airworthiness Manual (TAM) [1] in 2015. In 2018, a Technical Airworthiness Authority (TAA) Advisory [2] was developed to provide further guidance on MSIP implementation to the various RCAF aircraft fleets. This Advisory was published in February 2019. In general, MSIP covers the entire lifecycle of an aircraft: acquisition, in-service, and fleet life extensions if applicable.

20.2 HISTORICAL PERSPECTIVE

Current RCAF aircraft fleets are supported in a variety of methods, from near complete in-house DND fleet management and engineering support to fleets that rely heavily on aircraft Original Equipment Manufacturer (OEM) or in-service support contracting framework. Therefore, the nature of in-service support is not uniform, and the level of technical data readily available to DND on aircraft mechanical systems varies from fleet to fleet. Prior to the introduction of MSIP, MSIP-like goals were managed through the fleets' maintenance programs and ensuring that these maintenance programs were effective and improved as required. Formalization of MSIP ensures the awareness level of mechanical systems integrity and monitoring is kept at the forefront for all RCAF fleets.

20.3 MSIP OVERVIEW AND APPLICABLE SYSTEMS

Canada's MSIP applies to all DND-owned fixed and rotary wing aircraft. The focus of Canada's MSIP is on reducing the occurrence of mechanical system in-service difficulties through preventive maintenance and appropriate system health monitoring activities. An in-service difficulty is defined as a failure or malfunction of, or defect in, an aircraft system or component that affects, or if not corrected, is likely to affect the safety of an aircraft, its occupants or any other person. Maintenance inspections are the primary means for detecting in-service degradation. The preventive maintenance schedule and associated inspection tasks contained therein are, as a result, critically important to maintain the level of safety established at initial certification. The preventive maintenance schedule and tasks are initially developed without the benefit of in-service experience; it may therefore be necessary to amend the preventive maintenance schedule and tasks as a result of operating experience. It is common to discover new failure modes and unanticipated degradation as a result of in-service experience throughout the life of the aircraft.

MSIP has three broad measures of success:

1) Adoption of appropriate design standards for initial certification and in-service design changes for mechanical systems;
2) Incorporation of best practices for aircraft preventive inspection programs; and
3) Ability to identify, track, and remedy mechanical systems in-service difficulty trends.

Mechanical Systems covered by MSIP, as identified in the TAM, are as follows:

1) Fuel, including fuel tanks, pumps, lines, etc.;
2) Hydraulic, including reservoirs, pumps, lines, etc.;
3) Oxygen, including reservoirs, pumps, lines, regulators, etc.;
4) Environmental control;
5) Flight Controls, including pulleys, cables, rods, attachment points, etc.;
6) Propellers and rotor blades;
7) Pitot-static;
8) Undercarriage / landing gear mechanism (non-structural aspect);
9) Wheels, tires and brakes;
10) Pneumatic (bleed air, anti or de-icing, pressurization, etc.);
11) Fire protection, fire walls, detection/extinguishing, lines, etc.;
12) Transmission/drive components;
13) Aircraft interior, seats, ejection seats and restraints; and
14) Aircraft stores suspension equipment (pylons, racks, launchers, non-releasable stores, etc.).

20.4 MSIP METHODS OF COMPLIANCE

MSIP provides guidance on three phases of an aircraft's lifecycle: Initial Aircraft Procurement Phase, In-Service Phase, and Estimated Life Expectancy (ELE) Extension Phase (if applicable). Compliance guidance, formalized within the MSIP TAA Advisory and communicated by letter from the Directorate of Technical Airworthiness and Engineering Support to the fleet Type Certificate Holders, was released in April 2019.

20.4.1 Initial Aircraft Procurement Phase

When new RCAF aircraft fleets are procured, the fleet sustainment contract must include an aircraft mechanical systems integrity monitoring program, either as a stand-alone program, or integrated within a larger aircraft systems monitoring program.

The maintenance program developed for the new aircraft acquisition must be robust enough, in terms of aircraft mechanical systems. This includes the identification and tracking of the following:

1) Safety-critical components and systems;
2) Life-limited components;
3) Appropriate overhaul requirements (based on approved System Safety Analysis techniques and standards);
4) Appropriate inspection requirements for components and aircraft zonal areas; and
5) Corrosion prevention and control programs.

Proper installation of mechanical systems including routing and clearance of lines and fittings should also be confirmed. To accomplish this, an on-aircraft Enhanced Zonal Analysis Procedure (EZAP) is required to be carried out by DND personnel prior to 1st aircraft delivery. Any request to waive this requirement must have prior approval by the TAA.

20.4.2 In-Service Phase

As per the TAM, a mechanical systems integrity monitoring program will be maintained during aircraft in-service life by the Type Certificate Holder (TCH) of each aircraft fleet. It is acknowledged that the maintenance program may be controlled within DND or controlled by a contracted in-service support provider. It is also acknowledged that mechanical systems monitoring may be integrated within a larger-scope fleet monitoring program. Data collection methods are also flexible to the differing fleet sustainment (in-service support) constructs. In broad terms, the following items must be part of any fleet's in-service MSIP:

1) Maintain a component tracking monitoring program with the timely capability to determine in-service difficulty trends;
2) Ensure the fleet maintenance program is updated to remedy unforeseen mechanical systems in-service difficulties. Such unforeseen in-service situations include the following:
    a) Unanticipated failures or new failure modes are discovered, especially where there is either no inspection task or the task is ineffective;
    b) Component or system failure rates are significantly higher than that assumed in the original aircraft system safety analysis;
    c) Unanticipated consequences of failures such as cascade effects or secondary damage to other systems or structure may result;
    d) Latent failures also affect crew reaction or lack thereof. The flight crew's ability to cope with failures depends on correctly identifying that a failure has occurred. A lack of annunciation will increase the severity of the hazard for safety-critical functions; and
    e) Other unanticipated mechanical systems failures.
3) Capability to search effectively for mechanical systems in-service difficulty trends in the fleet's Maintenance Electronic Record Keeping System (ERKS);
4) Creation and execution of Corrective Action Plans to improve aircraft safety and airworthiness related to aircraft mechanical systems; and
5) When practical (such as during an on-aircraft second line periodic inspection), carry out an EZAP if one was not completed when the fleet was acquired. The TCH should ensure that any modifications completed during the aircraft fleet's in-service phase do not compromise the proper installation of any mechanical systems, including routing and clearance of lines and fittings, and interactions with electrical wiring.

20.4.3 ELE Extension Phase (if Applicable)

In certain cases, RCAF aircraft fleets need to extend the fleet ELE beyond the original length that was set when the aircraft fleet was acquired. In such cases, the aircraft OEM likely did not conduct engineering analysis on the aircraft systems and components beyond the original ELE. The following items must be considered when planning an ELE extension to a RCAF aircraft in terms of mechanical systems:

1) Review of life limits for safety-critical components that are not assigned a retirement or overhaul life. It can be assumed that when the OEM designed the aircraft, some safety-critical components that are not normally removed from the aircraft would not fail during the life of the aircraft, effectively assigning the planned aircraft operating life as the components' life limit. However, with an ELE extension, the durability of all of these components must be re-evaluated in order to decide on one of the following options:

a) The component's life can be extended to the new ELE date;

b) The component requires a maintenance inspection to be created and carried out to determine if the component's life can be extended to the new ELE date;

c) The component requires a new part replacement interval to be created and implemented; and

d) The component needs to be repaired and/or overhauled in order to last to the new ELE.

2) Ensure continuation of the in-service phase aircraft mechanical systems integrity monitoring program until the end of the new ELE;

3) Review of components that may become obsolete or unsupportable before the new ELE is reached;

4) Identify certification requirements that need to be met in order to support the ELE and then make findings of compliance against them. In other words, have a design change certification basis for the ELE; and

5) Consultation with other country users of the same aircraft fleet, if such countries have undergone a similar ELE extension or have been using the aircraft fleet longer than DND has.

20.5 RCAF FLEETS MSIP REPORTING REQUIREMENTS

TCHs are to provide MSIP updates in their Technical Annual Airworthiness Report (AAR(Tech)). This AAR(Tech) precedes an annual briefing by each aircraft fleet to the Airworthiness Review Board. MSIP topics to discuss in the AAR(Tech) include:

1) Updates to the capabilities of the fleet MSIP program since the last reporting period;

2) Deficiencies identified with the fleet MSIP program since the last reporting period; and

3) Corrective action plans currently in place or planned.

20.6 SUMMARY

Canada's Mechanical Systems Integrity Program (MSIP) is focused upon reducing the occurrence of mechanical system in-service difficulties through preventive maintenance and appropriate system health monitoring activities. The goal is to provide a means to improve aircraft fleet effectiveness and safety. MSIP is designed to provide flexibility to the varying in-service support contractors of the RCAF aircraft fleets, while still providing sufficient oversight and guidance.

20.7 REFERENCES

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Chapter 21 – AIRCRAFT MECHANICAL SYSTEMS INTEGRITY MANAGEMENT ACTIVITIES IN FINLAND

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21.1 INTRODUCTION

This chapter provides a brief review on the approach and activities related to aircraft mechanical systems integrity management in Finland, from the Finnish Defence Forces (FDF) viewpoint. In addition to this chapter, the report includes dedicated chapters for aircraft structures (Chapter 13) and engines (Chapter 17).

The FDF have not implemented a systematic, comprehensive approach for aircraft mechanical systems integrity management. However, many activities have been put into practice within the FDF and industrial partners to manage the integrity of the mechanical systems of the current fleets, especially the F/A-18C/D Hornet fighters and BAE Hawk jet trainers operated by the Finnish Air Force (FINAF), as well as NH90 rotorcraft operated by the Finnish Army.

21.2 IN-COUNTRY CAPABILITIES

Along with implementing integrity management programs, the FDF aims at maintaining and developing an independent capability that allows assessment and determination of the inspection/maintenance requirements as well as repairs on the critical systems/components.

In-country design and engineering capabilities have been instrumental in the maintenance of the airworthiness and mission capability of the system through maintenance, repair, overhaul and modification programs that are tailored for the national requirements and based on the actual use of aircraft. This work has been done in close co-operation with other users of the same aircraft type by openly sharing information. The work is being carried out under the supervision of the Finnish Military Aviation Authority (FIMAA) that sets a regulatory basis for such activities, the requirements for different organizations and approves these organizations.

The FIMAA has delegated authority to FDF Logistics Command (FDFLOGCOM) to act as a Type Certification Holder (TCH) and Continuing Airworthiness Management Organization (CAMO) for the Finnish military aircraft, with the following tasks:

- Develop airworthiness criteria, and processes and means to show compliance with the airworthiness criteria;
- Develop and maintain a maintenance program and a structural integrity plan for each type; and
- Maintain a system for data collection, assessment, analysis and reporting related to failures and defects that pose risks for maintaining airworthiness of the aircraft.

The FDF's TCH does not have an organic design capability and is typically supported by OEMs and the domestic partners. For aircraft like the F/A-18, a national design capability has been necessary.

As Finland has a unique operating environment, tasks and usage spectrum, the FDF must have its own capability to:

- Assess effects of the usage spectrum on the service life and structural integrity of individual airframe and systems;
- Implement changes and repairs needed to the structure due to differences in actual usage vs. design usage spectrum; and
- Adjust maintenance requirements and intervals to maintain optimal availability with minimized costs.

Furthermore, the national capability should enable re-certification of the fleet (component) when extension of service life is deemed necessary.

21.3 MECSIP APPROACH

During in-service operation with the FDF aircraft, especially the F/A-18 Hornet, several activities have been put into practice that are comparable with the tasks defined in the MIL-STD-1798C Mechanical Equipment and Subsystems Integrity Program (MECSIP) [1]. This section provides initial thoughts regarding implementation of MECSIP.

MECSIP is described as “a task-based approach with the goal of achieving the desired level of safety and aircraft availability at the most economic cost across the life cycle of the weapon system”. Regarding suitable phase to initiate a MECSIP program, it is stated that “it will be easier to comply with MECSIP Force Management tasks if the program enters the sustainment phase with a robust execution of MECSIP Tasks I through IV, but completing Tasks I through IV is not essential for a successful MECSIP sustainment program. Many aircraft programs will initiate their MECSIP Programs in the sustainment phase” [1].

MECSIP Tasks I – IV are by definition related to design, development and test phases; however, they comprise significant information, requirement base and practices to be applied during the sustainment phase. As an example, airworthiness certification is based on certification analyses which may need to be reviewed/updated during sustainment in order to solve integrity issues, particularly when differences are identified between certification analyses and actual behavior of the component (e.g., measured operational loads or performance). Considering implementation of MECSIP during sustainment phase, CAMO should collect all the available data related to the Tasks I – IV.

MECSIP Task V (Sustainment – Force Management) forms the basis for the implementation of MECSIP for the aircraft already in service, including “those actions necessary to ensure that the performance, safety, reliability, and durability requirements established in Tasks I through IV are met and maintained throughout the entire life of the weapon system” [1].

In general, considering possible implementation of the MECSIP standard or similar approach, the following are considered as the first steps:

- Identify the critical mechanical equipment and subsystems with respect to reliability/availability and remaining service life;
- Identify the kind of data and knowledge base required to manage integrity of the selected MECSIP parts; and
- Define processes and methods, as well as roles and responsibilities for MECSIP planning and execution.

The following sub-sections briefly review Subtasks 1 – 5 of Task V with regard to the existing and foreseen FDF activities.

Subtask 1: Data gathering and task planning can be considered primarily as the OEM and the main user responsibility. However, many of the subsequent tasks link back to the information, practices and requirements set at the initial stage. For example, "developing new MECSIP parts" (under the Subtask 3) will reach back to updating FMECAs and safety-critical component lists.

Subtask 2: Develop and utilize a functional systems integrated database can be associated with the FDF activity of developing and utilizing the in-country Logistic Information Management System (LTJ-system) for monitoring and tracking of components usage, condition and maintenance data. This subtask also refers to the fundamental task to determine component inspection and/or replacement intervals and criteria. Actually, the FDF logistic support system facilitate most of the "MECSIP functionalities" by the LTJ-system as it serves as a primary maintenance database and is utilized extensively for aircraft maintenance and fleet management actions. However, implementation of MECSIP within the FDF would obviously require the LTJ-system to be improved and/or accompanied with more active use of both in-country developed and OEM delivered (analysis) tools.

Subtask 3: Force management execution is described in the standard as "a roadmap on how the fleet's components will be managed" and comprises performing tasks through monitoring, risk assessment, analysis, and actual management of components. Furthermore, the subtask addresses development of new MECSIP parts and assessment of overall program.

From the FDF perspective, this subtask is essentially about performing assessment, analysis and tests to support decisions on airworthiness, reparability, service life, maintenance program, and overall fleet management actions. Considering implementation of MECSIP, a fundamental action at this stage will be to compile the MECSIP master plan, to be updated regularly, including essential planning and documentation of activities.

In addition to the monitoring systems and programs developed under the previous subtasks, an organization with sufficient personnel resources and knowhow is required for execution of this subtask. FDFLOGCOM Joint Systems Centre, Air Systems Division has been organized into responsibility areas covering:

- Life cycle planning;
- Maintenance planning;
- Sleet management; and
- Supply chain management.

The FDF is in the process of implementing the European Military Airworthiness Regulations (EMAR), particularly EMAR 21 MTCH and Part M CAMO.

Subtask 4: Preventative maintenance actions covers essentially performing MSG-3 analysis in order to review the maintenance requirements, actions and intervals, resulting in the updated aircraft maintenance program.

The FINAF F/A-18 Hornet's maintenance program has been maintained from its early years of service by setting up a maintenance system development working group, led by the FDFLOGCOM and represented by maintenance experts from the FINAF squadrons and the strategic industrial partner Patria.

The necessity of the most recent review/update of the maintenance program for the FINAF F/A-18 originated from the increasing maintenance workload due to high number of new structural inspection tasks

based on the main user's maintenance bulletins. The project aimed at an optimized maintenance program, determining inspection thresholds and intervals with a special objective to extend the depot level maintenance intervals that were considered as conservative.

The analyses have been performed following the guidance given in ATA-MSG3 document that defines the data as the foundation for the analysis for a certain system:

- Fault/failure history and other experience/data related to the system;
- OEMs test data;
- Information from other users/operators; and
- Engineering judgement made by an experienced working group, based on operational experience.

Regarding the basis for the analyses, the LTJ-system holds reported fault indications/findings recorded during flight or maintenance operations, as well as any performed measurements related to condition of a mechanical system (e.g., clearances). The failure data can then be assessed as trends over specified time, as well as distributions of data in terms of in-flight, daily maintenance, and depot level maintenance. There is also an in-country developed tool for reliability analysis that assists in processing the failure data and calculates reliability values such as MTBF for equipment/subsystems to be used as reliability parameters for analysis purposes.

Subtask 5: Manage service life extension and final five years prior to retirement relates closely to the activity that has been executed for the F/A-18 within the international user group collaboration, e.g., F/A-18 Subsystem Life Extension Program (SLEP) actions together with US Navy and other Hornet users.

21.4 NATIONAL R&D ACTIVITIES

Along with the FINAF funded R&D programs supporting the Aircraft Structural Integrity Programs (ASIP) there has been a series of individual R&D projects on engines and mechanical subsystems integrity. Those projects contribute to the objective of decreasing maintenance burden and increasing aircraft availability, as well as maintaining and developing national analysis and repair capabilities for critical systems. Extensive in-country test and repair capabilities are deemed essential in the view of security of supply (in Finnish terminology, the capability for extended independent support). The research can be divided into three main areas:

- Simulation and modelling;
- Experimental research (laboratory and field testing); and
- Condition control and monitoring.

Besides research towards larger scale scientific goals, some efforts have also been focused into problem oriented smaller scale research subjects. The main R&D topics on FINAF F/A-18 Hornet have been [2]:

- Aircraft component failure prognosis related Early Warning System (EWS);
- Modelling and simulation of the hydraulic system of the FINAF F-18 Hornet;
- Modelling and simulation of the main landing gear system of the FINAF F-18 Hornet;
- Detecting and eliminating the measurement error caused by free air in aircraft hydraulic system on-line particle counting;
- Aircraft hydraulic system fault finding and troubleshooting using on-line particle counters; and
- Process for evaluation and validation of non-original components for aircraft hydraulic systems.

Aircraft component failure prognosis related Early Warning System (EWS) is a project aimed at providing an extra tool for the maintenance personnel to support the Condition Based Maintenance (CBM) decision making process. The EWS project is briefly described as follows:

- In practice, EWS tries to forecast the subsystem failures of the FINAF aircraft systems. The starting point is the process data of the aircraft systems. Thus, what is done at a broad level is data analysis on the aircraft systems process data. The research of EWS is especially focused on the subset of data analysis methods called Machine Learning (ML) methods or vernacularly Artificial Intelligence (AI) methods [2].
- In the EWS project the software for independent operation on the FINAF servers is under development. Currently the tool is capable of mining relevant parameters out of the data, like landing gear times from take-offs and landings of the aircraft. Also, some conventional statistical reliability data analyses and spare part stock estimation with obsolescence aspect research are ongoing in the project [2].

Modelling and simulation of the main landing gear system of the FINAF F/A-18 is part of the efforts to find solutions for integrity issues with the landing gear. In general, the objective of modelling and simulation of certain mechanical systems/components is to better understand the functioning of the systems and their failures. The F/A-18 main landing gear is a good example of a critical mechanical system that has been a subject for intensive modelling and simulation efforts. The studies and results are briefly described as follows:

- The studies were initiated by the FINAF in order to investigate reasons for landing gear failures (so-called Planing Link failures) that had caused several aircraft landing mishaps in Finland and elsewhere. The research focused on creating a realistic simulation model to be able to assess the main landing gear function under different landing conditions and the effect of different landing gear components. The landing gear model consists of the nose landing gear and both main landing gears allowing asymmetric touchdown simulation capability. To achieve realistic approach flight path (including ground effect) and desired aircraft orientation, in-country developed flight simulation software with the F/A-18C Hornet aircraft model had been used in conjunction with the landing gear model [3].
- A conclusion from the studies was that there was not a single cause for Planing Link failures, but it was a combination of causes related to rigging, landing parameters and the condition of the MLG. The solution focused on reducing clearances of the MLG, to be achieved by incorporating in-country changes to wear limits and manufacturing tolerances of bushings and bearings, including in-country modified axle-lever bushings. The capability for machining the bushings was set up in the FDF's industry partner Patria to meet the tightened tolerances. Furthermore, periodic overhaul for the landing gears was implemented in order to reduce the risk of failures.
- More recently, the necessity of re-evaluating the landing gear simulation results has become apparent, as several upgrades/modifications have been completed on the FINAF F/A-18 Hornet fleet. The goals of the ongoing study are to find out the effect of mass distribution change on landing behavior, to improve the landing gear model realism by coupling it to a complex shock absorber model, and to find out stress concentration locations of three main parts: Trunnion, Lever and Lower Sidebrace [4].

21.5 CONCLUSION

The FDF is investigating implementation of a systematic, comprehensive approach for aircraft mechanical systems integrity management, with the intention of avoiding duplication of effort by examining the generally known standards such as the MIL-STD-1798 (MECSIP). The establishment of integrity

management processes along with associated critical capabilities is considered crucial to supporting the FDF's Type Certificate Holder (TCH) and Continuing Airworthiness Management Organization (CAMO) functions.

The initial review of MECSIP tasks suggests at least the following activities that could support the implementation and execution of the mechanical systems integrity management for the FDF fleets:

- Develop the integrated logistic information management system accompanied with analysis and reporting tools, in order to facilitate the MECSIP functions;
- Conduct the process to revise and update the aircraft maintenance program based on collected data and information from in-service operation, for example by using MSG-3 analysis and an experienced working group assisted with data analytics tools;
- Develop data analytics methodology and tools in order to exploit the increasing amount of collected data with a potential to provide automatized, intelligent and efficient support for decision making;
- Make use of modelling and simulation to improve the understanding of critical mechanical systems function/failures; and
- Promote active participation to international user groups and R&D forums in order to share best practices and technology advancements along with actual collaborative research efforts.

Regarding best practices, the experience gained from implementing Aircraft Structural Integrity Program (ASIP) may provide some applicable practices when considering implementing a Mechanical Equipment and Subsystems Integrity Program (MECSIP). For example:

- Identify all the information related to design and development phases, and incorporate them in the MECSIP to be assessed when the need arises during the sustainment;
- Develop and maintain an up-to-date MECSIP plan/database for the fleet, documenting all the relevant information and actions; and
- Evaluate regularly the overall effectiveness of the MECSIP and prepare an action plan to improve the identified focus areas.

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Chapter 22 – EWIS MONITORING PROGRAM IN CANADA

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22.1 BACKGROUND – ELECTRICAL WIRING INTERCONNECT SYSTEM (EWIS) MONITORING

Over the years, there have been a number of in-flight smoke and fire events where contamination sustained and caused the fire to spread. Transport Canada Civil Aviation (TCCA) and the Canadian Transportation Safety Board (TSB), together with the Federal Aviation Administration (FAA), the US National Transportation Safety Board (NTSB) and the Joint Aviation Authorities (JAA) have conducted aircraft inspections and found wiring contaminated with items such as dust, dirt, metal shavings, lavatory waste water, coffee, soft drinks and napkins. In some cases, dust has been found completely covering wire bundles and the surrounding area.

Research has also demonstrated that wiring can be harmed by collateral damage when maintenance is being performed on other aircraft systems. For example, a person performing an inspection of an electrical power centre or avionics compartment may inadvertently cause damage to wiring in an adjacent area.

In recent years, the regulatory authorities and industry groups have come to the realization that current maintenance practices may not be adequate to address aging non-structural systems. While age is not the sole cause of wire degradation, the probability that inadequate maintenance, contamination, improper repair, or mechanical damage causing degradation to a particular Electrical Wiring Interconnection System (EWIS) increases over time. Studies by industry and government agency working groups have found that, although EWIS management is an important safety issue, there has been a tendency to be complacent about EWIS (see paragraph 5 – *Related Reading Material* – in Ref. [1]). These working groups have concluded that there is a need to manage EWIS, so that they continue to function safely.

To address the effects of aging on EWIS, a recommendation on best maintenance practices was created to mitigate the effects of aging on electrical and wiring systems. As indicated by the acronym, it was based on a new maintenance philosophy that wire and its associated systems must be viewed as a complete system and not simply a means of connecting other independent systems. All aircraft are filled with miles of wiring and hundreds of wiring devices that connect and transfer power and signals to and from electrical components. Virtually all aircraft systems rely heavily on some type of wiring for safe operation. The health and integrity of the EWIS can be significantly compromised due to deterioration from aging, compounded maintenance, damage and the failure of wiring installation. It is integral to the overall maintenance and sustainment of all aircraft that the EWIS be treated as a system and afforded the same level of importance as the aircraft structure and other critical flight control systems.

As an example, In February 2012, CC130342 experienced an on-board fire, resulting in a Category A occurrence, due to routing and clamping deficiencies in a modification made to install ground test connections to the auxiliary hydraulic system. Chafing between the hydraulic pump motor power wire and a pressurized hydraulic flexible hose caused electrical arcing between the wire and the hose, which resulted in a pin-hole breach of the flexible hose, release of hydraulic fluid under high pressure, and initiation of the fire (Figure 22-1). This incident highlights the importance of ensuring EWIS best practices are applied during design and maintenance. The flight safety report for this accident can be found in Ref. [2].



Figure 22-1: CC130 Damage.

22.1.1 Technical Airworthiness Manual Amendment

To align RCAF continuous airworthiness with the latest EWIS guidance, the latest change to the Technical Airworthiness Manual (TAM) added the following requirement:

EWIS Monitoring Program. An EWIS monitoring program shall be implemented for every aircraft type on the DND register. This program will include, without being limited to, the following components:

1) Evaluation of the inspection schedule, to ensure that the EWIS inspection program has sufficient coverage of the potential EWIS hazards. This evaluation should ensure:
   a) Identification of EWIS within the inspection schedule;
   b) Appropriate inspection tasks for EWIS, where a system failure will cause a significant hazard to the aircraft resulting from close proximity to:
      i) Combustible materials;
      ii) Primary and backup hydraulic systems; and
      iii) Mechanical or electrical flight controls.
   c) Sufficient inspection tasks to evaluate EWIS condition for wear, wire bundle separation, cleanliness and proximity to physical objects, such as aircraft structure, rigid lines and Weapon Replaceable Assemblies (WRAs).

22.1.2 Compliance Guidance

A Technical Airworthiness Authority (TAA) Advisory [3] was published to provide compliance guidance for the EWIS Monitoring requirement, whose guidance can be summarized as follows:

- Evaluate the aircraft type using the Enhanced Zonal Analysis Procedure (EZAP), as detailed in Ref. [1]. Further EZAP guidance is available in Ref. [4]; and
- The currently approved maintenance program should be changed to incorporate the output from the EZAP assessment using the fleet approved EWIS maintenance manual as acceptable inspection criteria.

All RCAF aircraft fleets have a zonal inspection program within their approved maintenance program, so the EZAP process essentially was a gap analysis to update the inspection program to reflect current EZAP guidance.

To address design changes, guidance was also provided, the design change categorization process was amended to require further increased TAA oversight for any change that affected EWIS risk levels or conversely added mechanical systems that increased risk e.g., new flammable fluid lines. Ref. [1] provides guidance with respect to assessing any design change adding or modifying EWIS, that should include an assessment, to determine whether the modification has affected the zone EWIS attributes to warrant reapplication of the EZAP to the entire zone. Further guidance is available in Appendix B of Ref. [4].

22.1.3 Compliance Status

The EZAP process has been completed on three aging fleets, CC115 Buffalo, CP140 Aurora and CC130H, all triggering changes to their zonal inspection program.

22.1.4 Training and Experience

Due to trade restructuring it has been recognized that the enhancement of EWIS experience was required. The focus on EWIS has been augmented in basic trades training, and in-service units are integrating EWIS training into their unit training to facilitate technicians recognizing EWIS degradation risks and damage is a key part of the program. Instilling the mantra of clean as you go is also key – “Keep the work area, wires, and electrical bundles clean of metal particles or contamination when you use tools. Unwanted material, metal particles, or contamination caught in wire bundles can cause damage to the bundles.”

22.1.5 Reporting

Type certificate holders are required to report on their Electrical Wiring Interconnection System Monitoring Program at a minimum every two (2) years, with the end of the review schedule such that the review data and results are available for presentation to the Airworthiness Review Board (ARB) for that particular year.

22.2 REFERENCES

[1] Transport Canada Civil Aviation, Transport Canada Civil Aviation (TCCA) TP 14331E – Enhanced Zonal Analysis Procedures, 30 September 2005, https://www.tc.gc.ca/eng/civilaviation/publications/tp14331-menu-608.htm.

[2] Department of National Defence, DND Flight Safety Investigation Report – CC130342, 21 February 2012 http://www.rcaf-arc.forces.gc.ca/en/flight-safety/article-template-flight-safety.page?doc=cc130342-hercules-epilogue-flight-safety-investigation-report/hky1dmyy.

[3] Department of National Defence, Technical Airworthiness Authority Advisory http://materiel.mil.ca/assets/MAT_Intranet/docs/en/air-policies-procedures/taa-2018-01.pdf.

[4] Federal Aviation Administration. FAA AC25-27A – Development of Transport Category Airplane Electrical Wiring Interconnection Systems Instructions for Continued Airworthiness Using and Enhanced Zonal Analysis Procedure. https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/319197.

Part 5: SUMMARY ON BEST PRACTICE AND LESSONS LEARNED



Chapter 24 – BEST PRACTICES SUMMARY

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This report collected 23 chapters on high-level overview of Continuing Airworthiness (CAW) of various aging systems, they are documented in four Sections on CAW Policies and Approaches (Section I), Structural Systems (Section II), Propulsion Systems (Section III), Aircraft Mechanical Systems/Subsystems (Section IV). A number of chapters on case studies are also collected in Section IV, which provided more detailed technical procedures to maintain structural integrity, specifically through aircraft Operational Loads Monitoring (Chapter 25), Full-Scale Fatigue Testing (Chapter 26), NDT (Chapter 27 to Chapter 28), environmental sensing for corrosion (Chapter 29, and failure models and NDI of composite parts (Chapter 30 to Chapter 31). Overall many chapters provide some excellent references/sources for the readers to learn more in-depth information.

24.1 AIRWORTHINESS POLICY

Many countries operate similarly with respect to airworthiness policies and recognize each other's airworthiness authority. This may not be the case with all nations, especially outside of NATO, so significant improvement could be seen in the airworthiness area with regard to ensuring similar policies exist for all countries.

The United States Air Force (USAF) has numerous written policies and instructions that establish requirements for aircraft development, production, and sustainment phases. The overall policy is titled Integrated Life Cycle Management and requires the acquisition chain of authority to apply standard systems engineering processes and practices to ensure the integrity, mission assurance, operational safety, suitability, and effectiveness of each system throughout the life cycle from concept development through disposal. The USAF has issued written policy and instruction that establishes the requirements for formal airworthiness assessments to ensure that USAF operated aircraft are airworthy over their entire life cycle and maintain accepted levels of safety. An important aspect of the USAF policy is that it establishes the requirement for an independent technical airworthiness authority (outside the acquisition chain authorities) to make airworthiness determinations and issue flight certifications and authorizations [1]. The original USAF airworthiness certification requirements were primarily aimed at initial airworthiness certification only. A significant change was made in 2009 when the inclusion of service life limits in aircraft airworthiness certificates was mandated for all existing and future aircraft. This requirement led to the inclusion of additional airworthiness certification requirements, most notably in the aircraft structures section of the Airworthiness Certification Criteria Handbook. The USAF airworthiness process requires a continual evaluation of fielded aircraft throughout their life cycle to ensure that all aircraft are in a condition for safe operation, i.e., that they have not exceeded the approved service life limit, that environmental (e.g., corrosion) or other factors have not degraded airworthiness, that aircraft are properly maintained in accordance with approved maintenance documentation, and the aircraft are operated in accordance with the approved flight manual within the approved mission usage. The USAF recognizes that the initial service life limit is not a fixed value and the airworthiness process includes procedures for determining service life extension potential and for executing a service life extension program when desired and practical.

For the RCAF fleets, the technical airworthiness program, which is outlined in the Technical Airworthiness Manual (TAM), consists of three primary elements: Initial Airworthiness, Continuing Airworthiness, and Disposal. Initial Airworthiness includes the processes and activities necessary to ensure that aeronautical products are airworthy (including Type Certification and Equipment Certification), prior to their introduction into service. The framework of the RCAF CAW includes:

- Conduct and control of maintenance;
- Design change certification;
- In-service configuration management; and
- In-service monitoring program.

The key element of the CAW requirement is to establish an In-service Monitoring Program (ISMP). The RCAF experience with the Aging Aircraft Assessment (AAA) has shown that the assessment activity needs to be tailored for each fleet based on how the fleet is operated and maintained. There is a heavy reliance on the OEM for fleets that are operated in a predominantly civilian role, while a more active involvement is required for military role fleets. Thus, both military and civil airworthiness standards are used in the TAM. The level of effort to perform AAA is dependent on the strength of the integrity monitoring program, with a strong program requiring minimal effort to carry out the AAA. This highlights the importance of the integrity monitoring program.

The United Kingdom Ministry of Defence (UK MOD) has been undertaking Aging Aircraft Structural Audits (AASA) since the early 1990s. These audits were initiated following the well-known Aloha Flight 243, Boeing 737 pressure cabin failure in 1988. However, several civil accidents in the mid-1990s, including TWA Flight 800 and Swiss Air Flight 111, made the aviation community aware of the need to consider aging effects of electrical and mechanical systems alongside structural implications. For the UK MOD, the need to understand these aging systems issues was reinforced starkly by the loss of Nimrod XV230 over Afghanistan in 2006. Thereafter, the inclusion of aircraft systems aspects into the UK MOD's Aging Aircraft Audit (AAA) process was introduced. Lessons from these initial systems elements (Aging Aircraft Systems Audit (AASysA)) and Condition Surveys (CS), including programs conducted on the Nimrod, VC10, C-130, Sentry, Tucano and Historic Aircraft were collated, with gratefully acknowledged inputs from across the UK MOD and industrial support base. Common recommendations were identified under the categories of regulatory or policy issues, program conduct issues and wider airworthiness issues. Another interesting part is that UK developed a combined AAA approach for different systems (structures, propulsion, and other subsystems) with common and specific sections. It was proven to be a far more efficient approach, with an estimated 40% cost saving for the AAA process. Key recommendations from this study were incorporated into the UK MOD Regulatory Framework and are summarized below:

- To include a requirement to validate the effectiveness of integrity assurance methods by undertaking a detailed physical condition survey of a sample of aircraft from within each fleet;
- To reinforce the airworthiness requirements of the AAA, rather than the cost of ownership and availability issues;
- To include a requirement to address the effectiveness of emergency systems within the AAA; and
- To streamline the three independent audits (structures, systems and propulsion) into a single AAA.

From the Polish perspective, the basic Airworthiness (AW) principles are common for all military aviation stakeholders. However, the detailed approaches and ways of implementation in the particular systems differ between Nations and users. The Polish Air Force also faces the challenge to operate both post-Soviet and "western design" aircraft which are certified with different AW regulations. The European Defence Agency has initiated an activity aiming for development of a common (commonly understood by all EU Nations) system of AW requirements, and further on regulations, for European military aviation. The EDA Military

Airworthiness Authority Forum (EDA MAWA Forum) was established to achieve this goal, and a set of European Military Airworthiness Requirements (EMAR) was developed under the Forum umbrella. The importance of having a common approach to the AW issues in military domain is very well understood by all national military AW authorities (or their equivalents) and a process of harmonization, bilateral and multilateral recognition is continuously in progress. An interesting example is provided on the airworthiness system of the NE-3A fleet, including 18 early warning aircraft operating within multi-NATO nations. From the Polish standpoint, the challenge does not necessarily lie in the general understanding of EMAR requirements, but in the detailed implementation of distinct requirements in polish military airworthiness regulations in particular EMAR 145 and EMAR M (on CAW) planned for the near future.

24.2 AIRCRAFT STRUCTURAL INTEGRITY PROGRAM (ASIP)

The United States Air Force (USAF) established the Aircraft Structural Integrity Program (ASIP) in November 1958 in response to in-flight structural failures resulting in five destroyed B-47 aircraft from March through April 1958. The process to achieve initial airworthiness certification for the aircraft structure is established in the USAF ASIP MIL-STD-1530. The process requires establishing the design information, performing design analyses and development testing, performing full-scale ground and flight testing, and resolving findings that indicate one or more requirements are not satisfied. The culmination of these activities is the development of the force management approach. Supported by an excellent safety record (Figure 6-1), the ASIP MIL-STD-1530 standard is a best practice and used by many countries.

The Royal Canadian Air Force (RCAF) was an early adopter of ASIP MIL-STD-1530. An ASIP Master Plan was mandated for all RCAF fleets. The ASIP Tasks IV and V of the MIL-STD-1530 covered the Continuing Airworthiness (CAW) requirements for the aircraft structure. Around the same time, the Department of National Defence (DND) started to formalize their technical airworthiness program and the assembly of the Technical Airworthiness Manual (TAM). As it was understood that the DND would have very limited influence on and access to the design information (i.e., design analysis and full-scale testing), it was decided to NOT mandate the MIL-STD-1530 in its entirety. Rather, it was decided to focus on those tasks for which the DND had control and would affect the CAW of the aircraft. This was brought under the In-service Monitoring Program (ISMP) chapter of Part 3 – Continuing Airworthiness of the TAM. Several annexes were included to cover the various systems of the aircraft. One of these annexes is the Aircraft Structural Integrity Monitoring Requirements. Since the RCAF aircraft fleets have been certified using different airworthiness standards (ex. MIL-STD-1530 vs. DEF-STAN-0970) (Table 8-1), the RCAF also gained some experience to manage structural integrity using two major lifing methods, i.e., Safe Life and Damage-Tolerant, either in a separate or combined manner. Future challenges include assessing the health of the execution of the ASIP requirements due to the lack of aircraft engineering design data acquired with the new fleet acquisitions. Current mitigation is to build into the acquisition and in-service support contact the ability of the TAA staff to access the engineering data.

In Australia, a Joint Directive signed by Secretary, Department of Defence and Chief of the Defence Force established the Defence Aviation Safety Framework as of 30 Sep 2016. The framework required the implementation of a credible and defensible aviation safety framework that recognizes and supports compliance with statutory safety obligations. Where appropriate the framework was aligned with International Civil Aviation Organization (ICAO) principles and European Military Airworthiness Requirements (EMAR). As at 01 Jan 19, the Australian Defence Force (ADF) fully transitioned to the Defence Aviation Safety Regulation (DASR). Under the previous Technical Regulations, the ADF managed Aircraft Structural Integrity (ASI) via ASIP MIL-STD-1530, documented within an Authority approved Aircraft Structural Integrity Management Plan (ASIMP). Under the DASR, the ASIP construct was preserved for existing weapon systems and established as Acceptable Means of Compliance (AMC) for new acquisitions. Overall the safety record of the RAAF fleets is improving (Figure 9-1). One of best practices is presented using an Australia developed enhanced teardown technique to extend structural life while maintaining CAW.

The enhanced teardown technique was further demonstrated by NLR for extending the life Royal Netherlands Air Force (RNLAF) F-16 fleet in a cost-efficient and effective manner, as documented in Chapter 10. Some lessons learned on the application this technique are also documented in this Chapter, along with a future outlook on a proposal to jointly collect EIDS data for next generation fighter fleet F-35, which is one of the key inputs for fleet management and CAW. It is also notable that the AFIT developed some SHM and NDI techniques to efficiently support the ASIP program of their fleets (examples presented in Section VI (Annexes)).

The Polish AFIT also adopted the USAF ASIP MIL-STD-1530 principles, and applied the process for some Aircraft Structural Life extension Program (SLAP) for some fleets. The two chapters presented two examples using the typical OLM, FSFT, and IAT program to extend the structural life of PZL-130 "Orlik" trainer and Su-22 fighter-bomber.

Finnish Defence Forces (FDF) uses MIL-STD-1530 as a guideline for Aircraft Structural Integrity Program (ASIP) for Finnish Air Force's (FINAF) F/A-18 Hornet, BAE Hawk fleets, and the Finnish Army NH90 rotorcraft fleets. The FDF ASIP has evolved as a primary means to manage structural integrity in order to maintain safety and availability of aging systems and ensure economic service life of the fleets.

Although initiated during the sustainment phase, the FDF ASIP is intended to cover all the tasks defined in the MIL-STD-1530. Design and development (tasks I-III) information is to be identified as far as possible and incorporated into the program, to be assessed when the need arises during sustainment.

Increasing structural issues with the aging aircraft pose risks and challenges to meet requirements for operational availability and economic service life. Major concerns include crack findings on fracture critical structures for which there is no "full life" modification available and findings on structures that allow very small critical crack sizes. In addition, exceedance of certified safe life for some components may necessitate either significant re-certification activities or introduction of new structural inspections to further add to the increasing workload. These are examples of structural issues that justify the necessity to maintain a responsive and effective ASIP through the remaining service life.

24.3 PROPULSION INTEGRITY

The Propulsion System Integrity Program (PSIP) as described in the United States' MIL-STD-3024 offers a methodical systems engineering approach to the full life cycle management of propulsion systems and the key elements of sustainment and airworthiness based on many years of experience, research, and specific improvement efforts. PSIP applies to all engine components including rotating turbomachinery, static structures, externals, plumbing, and mechanical/electrical controls. Program activities are defined and scheduled to place an early emphasis on the definition of proper design criteria, to perform detailed structural analyses before hardware is fabricated, and to conduct component verification testing at realistic operational loads. In addition, to structural integrity, the PSIP also intends to address performance/operability and functional integrity disciplines. The overall objective of the mechanical integrity program is to enhance engine safety and reliability by improving component durability, damage tolerance, and quality. An important by-product of this program is the reduced cost of ownership that is realized when the production engine system is deployed for use.

The United States Army "Basis for Airworthiness" includes analysis and testing during product development. Many propulsion components are deemed 'on condition', whereas the component may remain in service an indefinite period of time as long as it meets inspection requirements. Some components have a prescribed retirement life (aka, life limit) due to a limitation in capability, such as Low Cycle Fatigue (LCF). These life limits are established to maintain safe operation of the component based on data and analyses available at that time. As the fleet matures into production and fielding, the basis for those life determinations must be reviewed periodically. Several potential changes that impact the life limit may have

occurred, including material processing, changes in design, and analysis tool revisions, as well as field experience and mission requirements. The US Army approach for continued airworthiness is established in Army Regulation 70-62, Airworthiness of Aircraft Systems.

The Royal Canadian Air Force (RCAF) established The Engine Structural Integrity Program (ESIP) and requires each Weapon System Manager to maintain defined program to, at regular intervals:

1) Reassess and document actual usage conditions;
2) Compare actual usage conditions against design usage conditions; and
3) Determine life consumption based on actual usage (of critical components, as a minimum) accordingly.

The ESIP also mandates issue tracking: safety-related issues are managed through the "Record of Airworthiness Risk Management" (RARM) process documented elsewhere in this report (Chapter 2, Sections 2.1 to 2.6), which is not a propulsion-specific process. At present, it is not yet possible to ascertain the effectiveness of the ESIP for the RCAF fleets, as compliance with the regulation is just started this year. One lesson learned: reassessment of the cyclic exchange rate (low cycle fatigue major cycles consumed per flying hour) of one RCAF fleet, performed shortly before the release of ESIP requirements, found that evolutionary changes in role and mission mix had resulted in significant increases in life consumption rate, on the order of 20 – 30 % per flying hour. This case is representative of the rationale for the ESIP. To support the RCAF airworthiness authority, NRC-Aerospace has been collecting failure mode data and developing damage tolerance methods, some of the recommendations have been implemented for the maintenance and operation of the military gas turbine engines.

Experimental research support from VTT Technical Research Centre of Finland (VTT) has enabled the FDF to increase the operational life (flight hours) of the high pressure turbine blades of the FINAF F/A-18 engines. The 10% increase in life yielded approx. 3 million USD savings to the taxpayers, with a nearly hundredfold return of the research investment (ROI).

24.4 MECHANICAL EQUIPMENT AND SUBSYSTEMS INTEGRITY

The United States Air Force established a structured systems engineering process as described in MIL-STD-1798 titled Mechanical Equipment and Subsystems Integrity Program (MECSIP). MECSIP is a cradle-to-grave task-based approach with the goal of achieving the desired level of safety and aircraft availability at the most economic cost across the life cycle of the weapon system. In addition to MECSIP, key elements of sustainment and airworthiness make up the current state of subsystems management practice in the USAF. MECSIP was derived from the successful Aircraft Structural Integrity Program (ASIP) and lessons learned from subsystems management before MECSIP was a requirement. The USAF class A and B combined mishap rate for manned aircraft due to mechanical equipment and subsystems causes has steadily declined for more than a decade. It should be noted that the USAF MECSIP includes the subsystem of electrical power generation and distribution (wiring, etc.).

The RCAF adopted Aircraft Mechanical Systems Integrity Program (MSIP) in 2015, with significant updates in 2019 in the form of a Technical Airworthiness Authority Advisory which provides further guidance on MSIP implementation. RCAF fully expects to revise preventive maintenance schedules and tasks based on operational experience in order to maintain the necessary level of safety. Canada's submission on Electrical Wiring Interconnect System (EWIS) monitoring focused on aircraft wiring issues. The regulatory authorities and industry groups have come to the realization that current maintenance practices may not be adequate to address aging non-structural systems. While age is not the sole cause of wire degradation, the probability that inadequate maintenance, contamination, improper repair, or mechanical damage causing degradation to a particular Electrical Wiring Interconnection System (EWIS) increases over time. Studies have shown a

tendency to be complacent about EWIS. Any efforts to combat aging wiring problems should be considered to be a best practice since this is an area that is often ignored but has the potential for catastrophic impacts to an aircraft.

The Finnish Defence Forces (FDF) is currently investigating implementation of a systematic, comprehensive approach for mechanical systems integrity management, with intention to avoid duplication of effort by examining MECSIP or other generally known standard practices. Many activities have been put into practice to manage integrity of mechanical systems of the F/A-18C/D, the BAE Hawk trainers, and NH90 helicopters. Some of interesting lessons learned are reported including, Invest on R&D related to data analysis methodologies as applied to analysis of increasing data on usage, health and environment of the aircraft and its systems; Make use of modelling and simulation to better understand of functioning and failures of the critical systems, aiming at the sufficient level of realism.

The German input is the only one in this report on life extension of fuel system and secondary power system of TORNADO aircraft. Overall the life extension program of TORNADO includes structures, propulsion, and subsystems, conducted by a tri-national consortium Panavia aircraft GmbH, for a number of NATO operators including German Air Force, British Royal Air Force, and Italian Air Force). The key safety parts of the fuel and power systems showed some similarity with structural integrity including mechanical fatigue and corrosion problems. A harmonized process was developed to implement the life extension program, with a good cooperation of government and industrial organizations. A lesson learned: for future developments, potential life extension requirements should be considered already in the design and qualification phase. Life demonstration for instance should be continued until equipment failure, but not stopped after having demonstrated the specified life.

24.5 SUMMARY

The best practices implemented by various nations include establishing and implementing integrity programs for the major aircraft systems: structures, propulsion, mechanical equipment, and subsystems. The United States developed military standards that provide general and detailed requirements for execution of each of these integrity programs (and others not addressed in this report) throughout the aircraft's life cycle. Many Nations have utilized ASIP MIL-STD-1530 as the basis for establishing structural integrity requirements for their specific aircraft applications. Due to lack of OEM support and access to design information, some nations may not be able to implement the Tasks I-III of MIL-STD-1530. Alternatively these nations often collaborate together to share data and experience, in order to maintain CAW. However, there appears to be much more diversity in approaches for other safety-critical aircraft systems; but this could simply be a reflection of the contributions made by each Nation to this report. Other systems integrity programs have been established using the similar Task structure as in MIL-STD-1530. Compared to structures, the failure modes of other systems may not be well understood.

In general, the common best practices described throughout this report (and the foundation for all integrity programs) follows:

1) Collect and evaluate operations and maintenance data.
2) Compare actual usage and maintenance actions with expectations during initial airworthiness certification through analysis, testing, or assessments.
3) Revise aircraft maintenance requirements based on results of above and continually reassess.
4) Determine when the maintenance program is no longer sufficient to maintain safety to approved levels.

24.6 REFERENCES

[1] Air Force Instruction 62-601, "USAF Airworthiness", June 2010.

Part 6: ANNEX OF COLLECTION OF CASE STUDIES ON BEST PRACTICE AND LESSONS LEARNED



Chapter 25 – FLOW CONTROL SYSTEM INTEGRATION INTO THE SUBSTITUTE MODELS FOR STRUCTURAL COMPONENTS LOADS ESTIMATION BASED ON FLIGHT PARAMETERS AND STATISTICAL INFERENCE METHODS – MIG-29 VERTICAL FIN USE CASE

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25.1 INTRODUCTION

Over 40 years have passed since damage tolerance philosophy was introduced into the design process of aircrafts [1]. One of the pillars of maintaining structural integrity of aircrafts is to control the loads spectrum of the structure. In particular, structural load determines the intervals between subsequent Non-Destructive Inspections (NDI) as well as the safety margins for further aircraft operation. The way that a particular aircraft is operated after its introduction into service does not necessarily fit its pre-assumed profile. Thus, it is necessary to monitor the loads of every aircraft in use. The modern approach to meeting this requirement is to implement OLM systems [2] as a necessary component of aircraft avionics. In the OLM case, aircraft loads related information could be available from a sensor network e.g., strain gauges or Fiber Bragg Gratings (FBG) permanently mounted in the aircraft structure and measuring its local strains (direct load monitoring). However this is not always possible, e.g., in the case of older aircraft, or economically efficient. In that case, some selected flight parameters, e.g., load factor, are used to determine aircraft load. Due to complexity and costs of OLM programs with direct load monitoring, indirect load monitoring, based on flight parameters analysis has lost nothing of its attractiveness. What is available instead of local strain distribution is a set of recorded flight parameters, which by the laws of inertia and aerodynamics should determine the dominant part of loads, acting on a given element.

For both approaches to load monitoring, different modes of element deflection need to be established (Figure 25-1). Depending on the mode, stress distribution at particular critical location can be different, therefore if different modes can occur, they need to be identified and corresponding fatigue cycles need to be counted accordingly. In the case of load monitoring based on flight parameters, an additional difficulty emerges. Beside identification of different stress distribution, functional relations between stress field and flight parameters also need to be established. One of the methods which can be applied for the task is Canonical Correlation Analysis (CCA) [3].

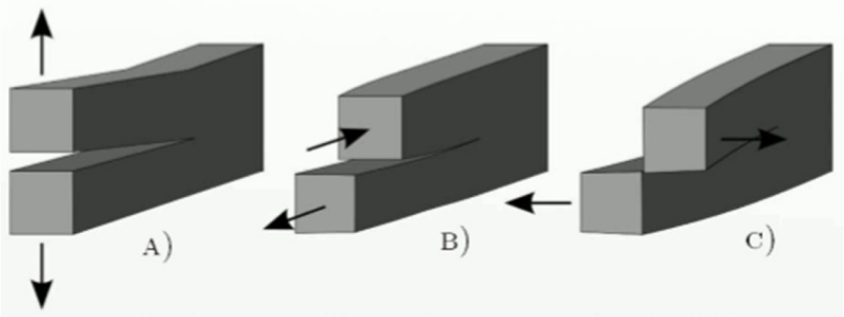


Figure 25-1: Examples of Load Modes of Failure: Opening (A), In-Plane Shear (B), Out-Of-Plane Shear (C).

The CCA method is defined as follows. Given two sets of variables, i.e., response variables, e.g., measured stresses or strains $\mathsf{E} = \{\sigma_1, \ldots, \sigma_M\}$ at critical locations and predictor variables, e.g., flight parameters $\mathsf{P} = \{p_1, \ldots, p_N\}$, one is looking for uncorrelated linear combinations of elements of E and P such that the correlation between them is subsequently maximized, i.e., the first two canonically conjugated combinations σ_1^c, p_1^c, satisfy:

$$\sigma_1^c = \sum_{j=1}^{N} \alpha_1^j \sigma_j, \qquad p_1^c = \sum_{j=1}^{M} a_1^j p_j,$$
$$cor(\sigma_1^c, p_1^c) = \max_{\tilde{\alpha}, \tilde{a}} cor(\sum_{j=1}^{N} \tilde{\alpha}^j \sigma_j, \sum_{j=1}^{M} \tilde{a}^j p_j), \tag{25-1}$$

whereas the next two combinations are uncorrelated with the first pair:

$$\sigma_2^c = \sum_{j=1}^{N} \alpha_2^j \sigma_j, \qquad p_1^c = \sum_{j=1}^{M} a_2^j p_j,$$
$$cor(\sigma_2^c, p_2^c) = \max_{\tilde{\alpha}, \tilde{a}} cor(\sum_{j=1}^{N} \tilde{\alpha}^j \sigma_j, \sum_{j=1}^{M} \tilde{a}^j p_j), \quad \text{and} \quad cor(\sigma_1^c, \sigma_2^c) = cor(p_1^c, p_2^c) = 0 \tag{25-2}$$

and analogously for every subsequent pair of canonical combinations.

The CCA method can be illustrated by the example of two modes of simple beam bending. For the two considered modes, forces are applied at the tip of the beam in its centre along the y-axis and z-axis respectively, resulting in a pure bending condition (Figure 25-2).

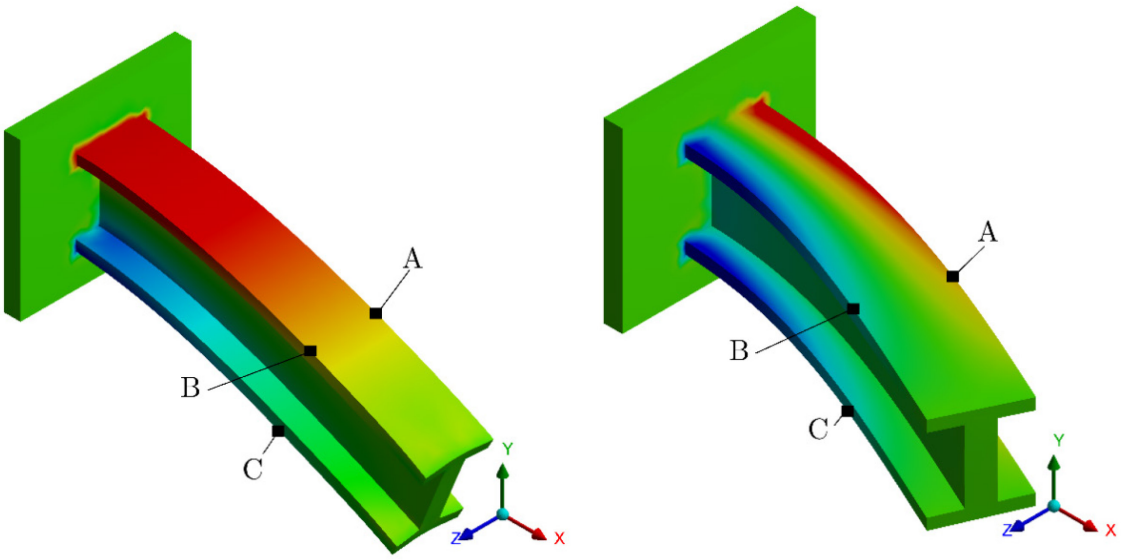


Figure 25-2: Two Modes of Beam Bending: Force in Y-Direction (Left) and Z-Direction (Right) Applied at the Tip.

Note: Strain gauges are mounted symmetrically, A and B on top, C and D on bottom side (D is not visible). Stress is visualized: red is tensile, blue- compressive and green- neutral.

Theoretical strains along the original x-direction of the beam at selected locations (Figure 25-2) are presented in Figure 25-3, assuming sinusoidal force-time relations:

- Loading in y-direction results in positive (tensile) strain for strain gauges A and B, and negative (compressive) for C and D (Figure 25-3(a)); and
- Loading in z-direction results in positive strain for strain gauges A and D, and negative for B and C (Figure 25-3(b)).

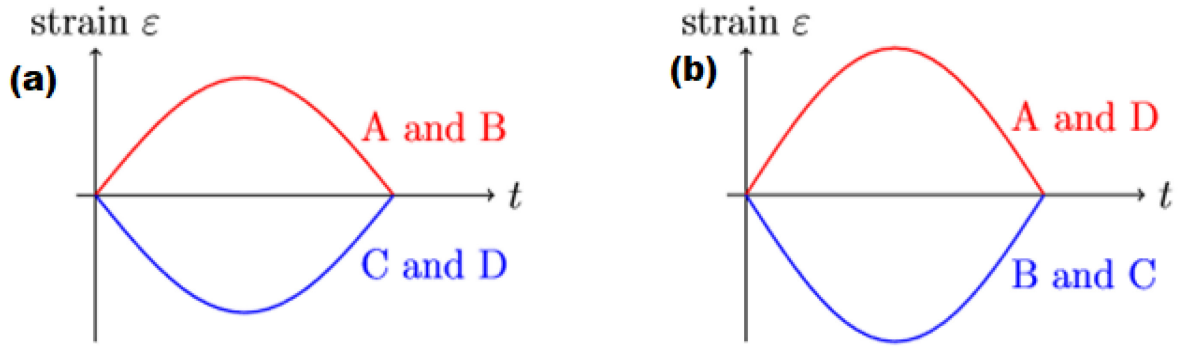


Figure 25-3: Strain Gauges Readings for Two Modes of Bending as Defined in Figure 25-2: (a) First Mode and (b) Second Mode. Sinusoidal force-time relations were assumed for clarity.

Denoting as F_1, F_2 load values of the first and the second modes respectively, the two sets of parameters upon which CCA method depends can be the following:

$$\mathrm{P} = \{F_1, F_2\} \qquad \mathrm{E} = \{\varepsilon_A, \varepsilon_B, \varepsilon_C, \varepsilon_D\} \tag{25-3}$$

For the first case (Figure 25-3(a)), the following condition is satisfied:

$$\varepsilon_1^c := \varepsilon_A + \varepsilon_B - \varepsilon_C - \varepsilon_D = a_1 F_1 \tag{25-4}$$

while for the second case (Figure 25-3(b)):

$$\varepsilon_2^c := \varepsilon_A - \varepsilon_B - \varepsilon_C + \varepsilon_D = a_2 F_2 \tag{25-5}$$

Also, for the first type of loads $\varepsilon_2^c = 0$ whereas for the second type $\varepsilon_1^c = 0$. Therefore the pairs describing both modes of loads:

$$(F_1, \varepsilon_1^c), \qquad (F_2, \varepsilon_2^c) \tag{25-6}$$

can be considered as canonical. The response of any strain gauge ε_I at the predefined locations (Figure 25-2) on any linear combination of the two considered forces F_1, F_2 can be represented as a linear combination of $\varepsilon_1^c, \varepsilon_2^c$. When two modes of bending are present in the beam consecutively, readings of strain gauges A and B are presented in Figure 25-4. The sequence of forces is presented in Figure 25-5 and corresponding canonical strains are shown in Figure 25-6. Canonical parameters show the mode of bending currently being present in the beam. Indeed:

$$cor(F_1, \varepsilon_1^c) = cor(F_2, \varepsilon_2^c) = 1$$
$$cor(F_1, F_2) = cor(\varepsilon_1^c, \varepsilon_2^c) = 0 \tag{25-7}$$

therefore canonically conjugated pairs Equation (25-6) would be obtained as a result of CCA method in that case. If there is any combination of bending modes present in the load spectrum, it can be captured by CCA, but in that case both of the canonical strains $\varepsilon_1^c, \varepsilon_2^c$ would be nonzero.

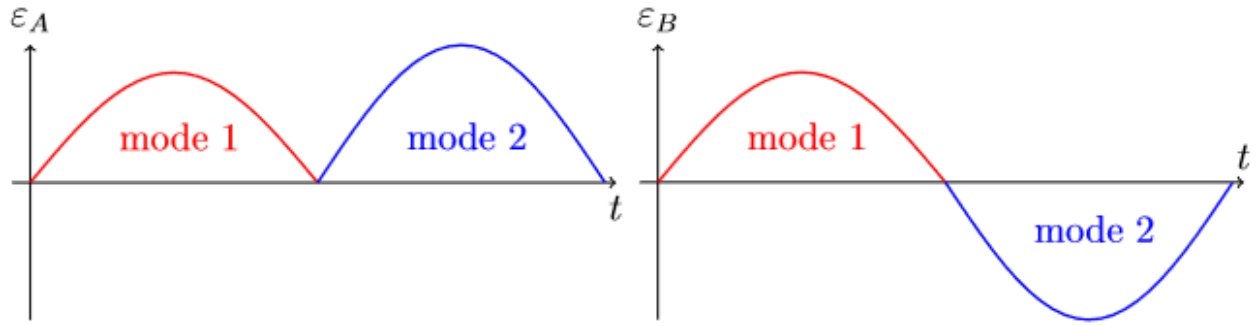


Figure 25-4: Strain Gauges Readings for Successive Bending in Mode 1 and Mode 2 for Strain Gauges A (Left) and B (Right).

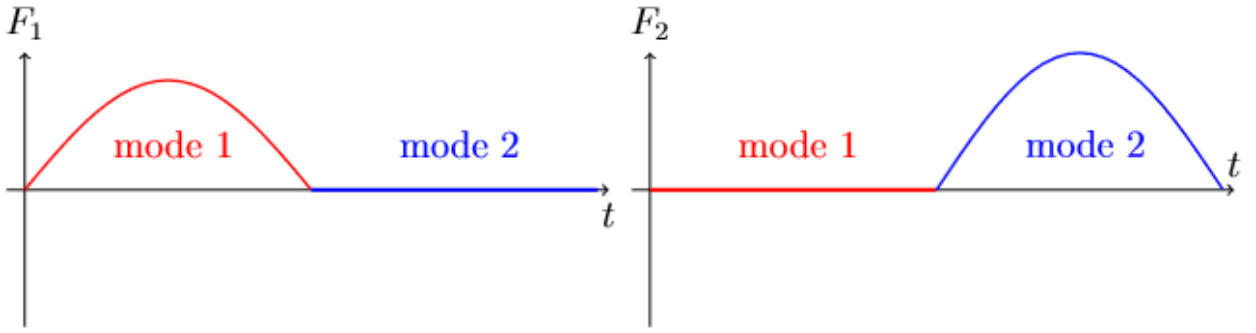


Figure 25-5: Load Values for Successive Bending: Force in Y-Direction (Left) and Z-Direction (Right).

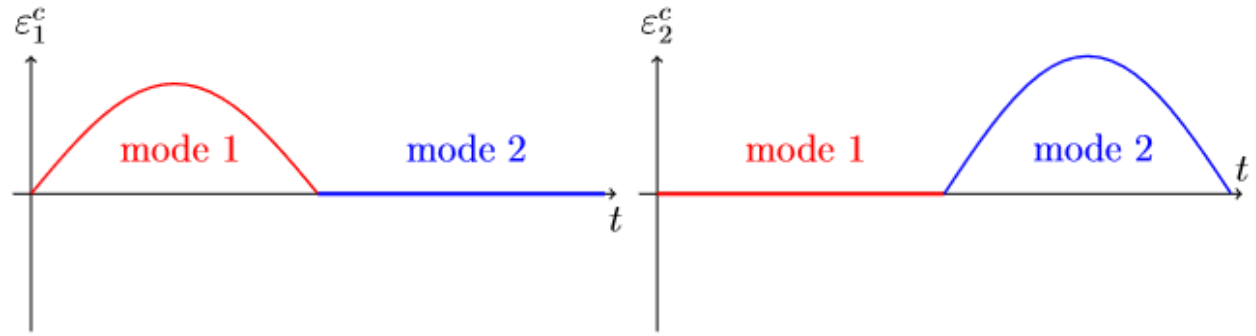


Figure 25-6: First (Left) and Second (Right) Canonical Parameters for Successive Bending in Mode 1 and Mode 2.

25.2 DETERMINING LOADS APPLIED TO A VERTICAL STABILIZER OF A TWIN TAILED AIRCRAFT

The CCA method was used for determining the stress distribution on a vertical stabilizer of MiG-29 aircraft. A scheme of the aircraft structure is presented in Figure 25-7.



Figure 25-7: A Scheme of MiG-29 Aircraft.

The stress distribution can be split into two terms: $\hat{\sigma}_{inert}$ coming from inertial forces and $\hat{\sigma}_{aero}$ resulted from aerodynamic forces:

$$\hat{\sigma}(\mathbf{r},t) = \hat{\sigma}_{inert}(\mathbf{r},t) + \hat{\sigma}_{aero}(\mathbf{r},t) \tag{25-8}$$

For vertical stabilizer, the second term was considered as the main contribution to stress distribution. The following flight parameters were initially considered for modelling of $\hat{\sigma}_{aero}$:

- V – The velocity of aircraft relative to the atmosphere;
- H – The altitude of aircraft;
- α – The attack angle;
- β – The sideslip angle;
- $\dot{\gamma}$ – The roll speed; and
- δ – The rudder inclination.

The function relating the dependence between flight parameters and stress was assumed to be of the following form:

$$\begin{aligned}\sigma &= \frac{\rho_0 V^2}{2}\left(1-\frac{H}{44300}\right)^{4.256}\left(\tilde{\sigma}_{nozzle}(V,\alpha)+\tilde{\sigma}_{slip}(\beta,V,\alpha)+\tilde{\sigma}_{roll}(\dot{\gamma},V,\alpha)+\tilde{\sigma}_{rudder}(\delta,V,\alpha)\right)= \\ &= p_{0870}\left(\tilde{\sigma}_{nozzle}(V,\alpha)+\tilde{\sigma}_{slip}(\beta,V,\alpha)+\tilde{\sigma}_{roll}(\dot{\gamma},V,\alpha)+\tilde{\sigma}_{rudder}(\delta,V,\alpha)\right)\end{aligned} \tag{25-9}$$

where ρ_0 is the air density at the ground level according to International Standard Atmosphere (ISA) model, $\tilde{\sigma}_{nozzle}, \tilde{\sigma}_{slip}, \tilde{\sigma}_{roll}, \tilde{\sigma}_{rudder}$ are dimensionless functions describing contribution to stress distribution due to:

- The Venturi effect, i.e., the aircraft is twin tailed (Figure 25-7) which can be considered as a nozzle;
- The sideslip angle;
- The rate of rotation; and
- The position of the rudder.

Thus the first factor in the Equation (25-9) describes the aerodynamic pressure at the altitude H, and functions $\tilde{\sigma}_{nozzle}, \tilde{\sigma}_{slip}, \tilde{\sigma}_{roll}, \tilde{\sigma}_{rudder}$ should return the stress distribution for different manoeuvres of the aircraft. The exact form of $\tilde{\sigma}_{nozzle}, \tilde{\sigma}_{slip}, \tilde{\sigma}_{roll}, \tilde{\sigma}_{rudder}$ functions was not known, therefore for CCA application Taylor expansion was used, e.g.,:

$$\tilde{\sigma}_{nozzle} = c_V V + c_{VV} V^2 + c_\alpha \alpha + c_{\alpha\alpha} \alpha^2 + c_{V\alpha} V \alpha \tag{25-10}$$

with unknown constants c_V, c_{VV}, c_α, $c_{\alpha\alpha}$, $c_{V\alpha}$, etc. All the variables resulting from that expansion, e.g., $p_{aero}V$, $p_{aero}V^2$, $p_{aero}\alpha$, $p_{aero}\alpha^2$, were considered as independent input variables to CCA model, i.e., a new set of flight parameters was considered in comparison to the set of initially selected variables.

The CCA model was applied on the data obtained during flight test campaign of two MiG-29 aircrafts. Thus, in total there were four independent installations of OLM systems (Figure 25-8, Figure 25-9):

- OLM1 – Mounted on the left stabilizer of the first aircraft;
- OLM2 – Mounted on the right stabilizer of the first aircraft;
- OLM3 – Mounted on the left stabilizer of the second aircraft; and
- OLM4 – Mounted on the right stabilizer of the second aircraft.

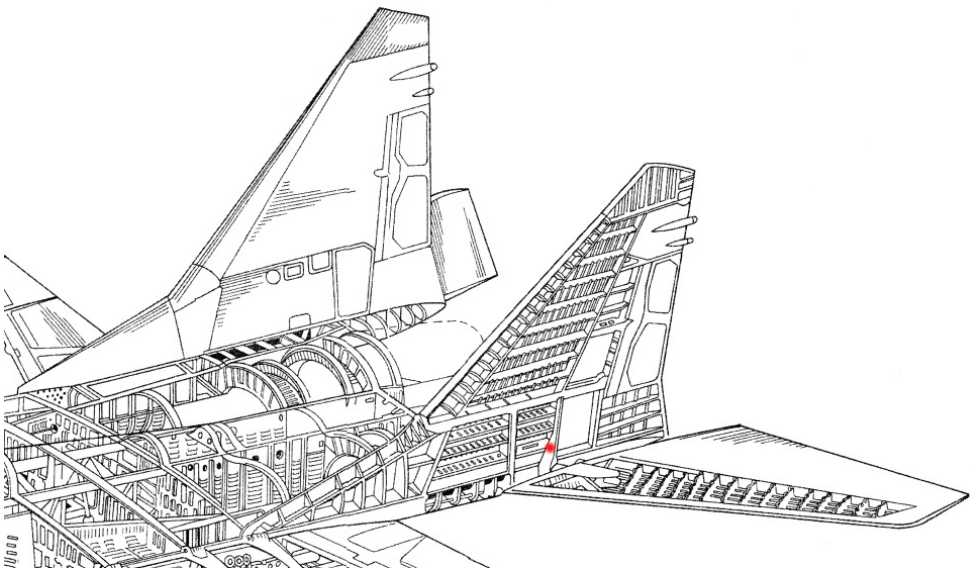


Figure 25-8: Location of a Selected Strain Gauge (Red) Used for Loads Monitoring of MiG-29 Vertical Stabilizer.



Figure 25-9: Example of Strain Gauge of OLM System.

The CCA model was trained using only the data obtained by the OLM1 installation and tested on the other data from strain gauges corresponding to OLM2, OLM3 and OLM4.

A single mode of stress distribution was noticed as a result of CCA. The first canonical flight parameter was in good correspondence with about 70% of the data obtained from strain gauges in OLM2, OLM3, OLM4 and they had the highest amplitude of the records. The remaining data from the strain gauges had small variations during flights and were too noisy to be predicted. Examples of the correspondence between normalized canonical parameter and normalized records of a strain gauge obtained during steady and high manoeuvre flights are presented in Figure 25-10.

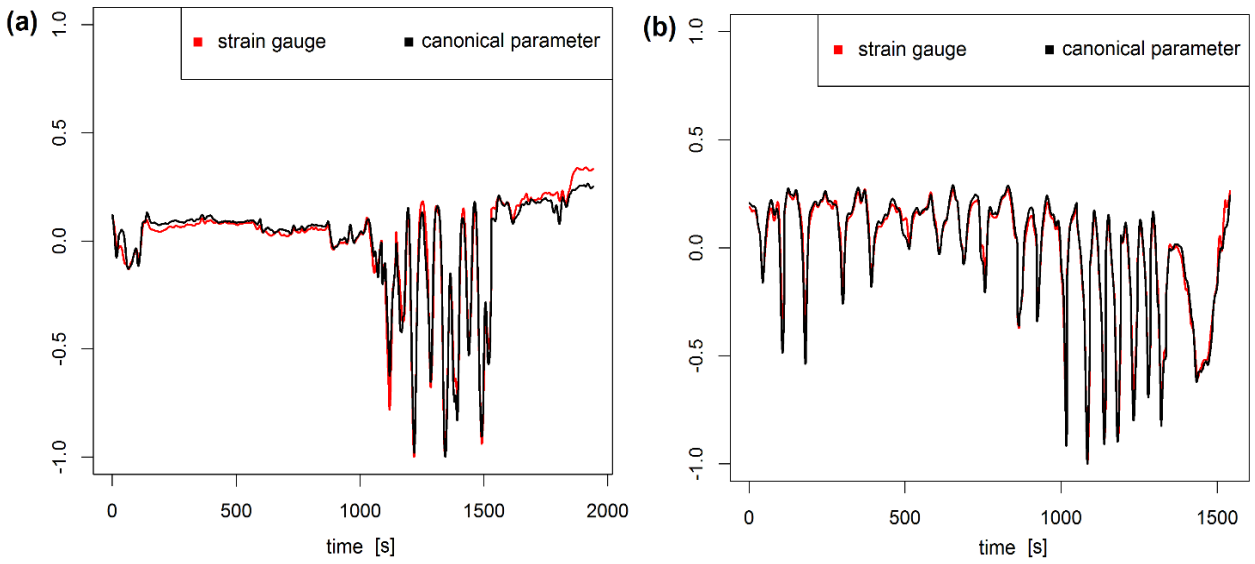


Figure 25-10: Examples of Normalized Strain Records from Strain Gauge (Red) and Canonical Flight Parameter (Black) for: (a) Steady and (b) High Manoeuvre Flights.

The leading contribution to stress distribution conjugated to the canonical parameter ε_1^c was due to the $\tilde{\sigma}_{nozzle}$ term. The nozzle characteristics are dependent on the parameters Equation (25-10):

- V – The velocity of aircraft relative to the atmosphere; and
- α – The attack angle.

Based on that data, several scenarios of flight configurations for Computational Fluid Dynamics (CFD) computation were prepared. In table below, distribution of occurrences of peaks and valleys of $\tilde{\sigma}_{nozzle}$ term with respect to parameters V , α are presented for a certain number of flights. Parameter V ranged between V_1 to V_9 and parameter α took values in the range α_1 το α_{31} (true values of V and α are hidden intentionally). Colours of cells separates between different geometric configurations of the aircraft, e.g., for high angles of attack, the geometry of the wing changes). Flight configurations Values marked in red in Table 25-1 were selected for CFD computations. The selected cases were supposed to span subspace of the $V-\alpha$ space sufficiently broad to capture different distributions of aerodynamic loads and whose occurrence is not rare at the same time.

Figure 25-11 gives an example of CFD computation for a particular flight configuration and Figure 25-12 gives an example of aerodynamic force distribution on the surface of the stabilizer based on CFD computations.

Table 25-1: Frequency of Occurrences of Peaks and Valleys of the Nozzle Term.

$\alpha \backslash V$	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9
α_1	0	2	1	13	6	4	5	0	0
α_2	214	20	66	152	113	48	26	37	5
α_3	318	82	232	732	734	1202	3059	2240	205
α_4	793	181	1255	4432	13752	24227	27488	15057	911
α_5	448	1295	9198	62916	146908	259183	250014	**70120**	2661
α_6	220	9088	147983	576181	1145989	1266522	636115	91436	2986
α_7	1295	59789	**956659**	2956306	3010393	1624642	469213	36944	4092
α_8	4511	314354	3527864	4534276	2514661	**951120**	234361	18216	2712
α_9	12784	1076472	3779997	2613920	1150829	429741	110004	7703	1514
α_{10}	30178	1302743	1842749	1050538	463809	202810	52845	3965	727
α_{11}	65712	807516	**765251**	495699	253180	**120762**	24739	**1771**	400
α_{12}	74316	386490	392761	286264	157597	73329	12160	865	157
α_{13}	72827	223026	269199	208723	116088	42178	6274	541	73
α_{14}	50370	128424	**190580**	154871	79449	**22045**	3127	280	64
α_{15}	31037	89725	144010	118497	52089	12288	1888	145	13
α_{16}	18421	66638	113588	89235	30763	6718	921	73	2

$\alpha \setminus V$	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9
α_{17}	11683	53869	98927	63059	17741	3735	442	24	0
α_{18}	8761	48944	86673	43162	11430	2400	240	8	0
α_{19}	6326	36340	**56983**	23422	6382	**1320**	117	2	0
α_{20}	4189	25274	32298	12281	3435	751	47	0	0
α_{21}	2852	16523	19248	7376	1964	384	15	0	0
α_{22}	2062	12336	13370	5214	1485	242	1	0	0
α_{23}	1729	11366	11324	4557	1173	161	6	0	0
α_{24}	1636	10605	8959	3591	969	109	6	0	0
α_{25}	1595	9372	7234	2737	786	91	0	0	0
α_{26}	1566	8543	5866	2163	608	58	4	0	0
α_{27}	1226	6777	**4737**	1454	353	33	0	0	0
α_{28}	966	5211	3455	1010	194	15	1	0	0
α_{29}	629	3190	1908	549	66	7	0	0	0
α_{30}	229	1144	651	112	26	1	0	0	0
α_{31}	59	256	138	45	4	1	0	0	0

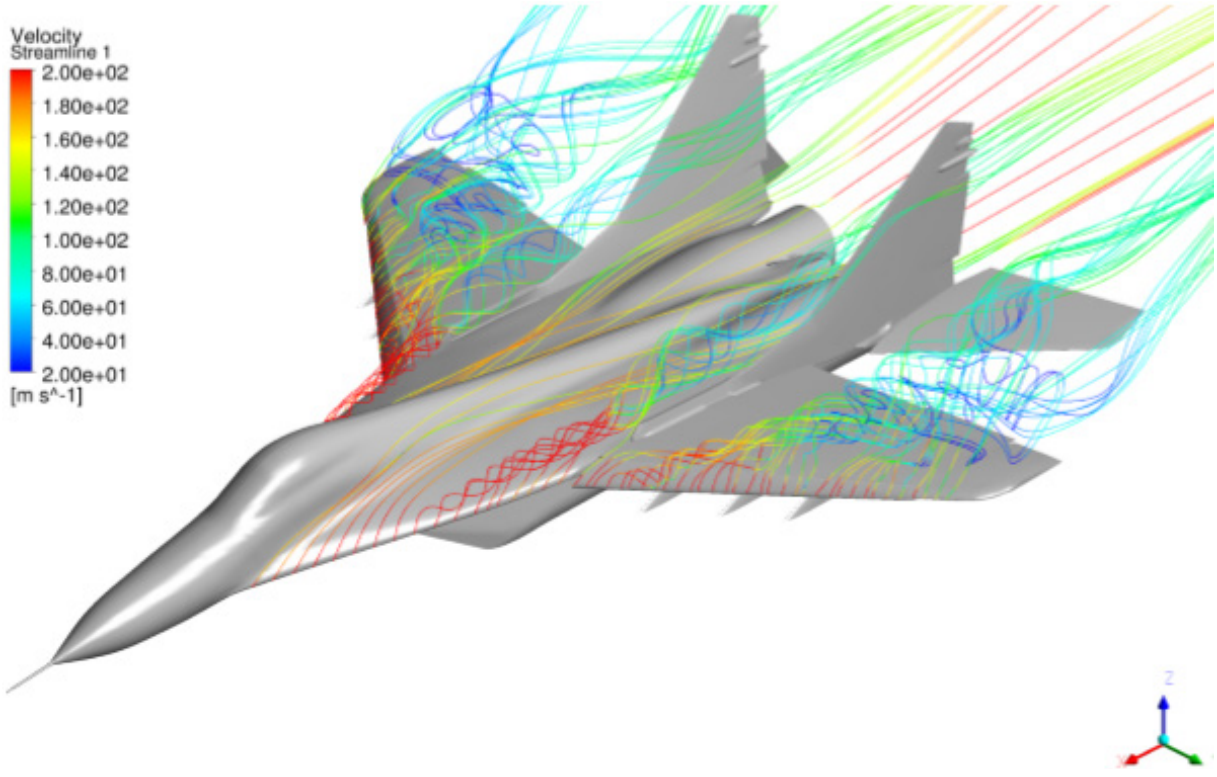


Figure 25-11: Example of CFD Computation for a Particular Flight Configuration.

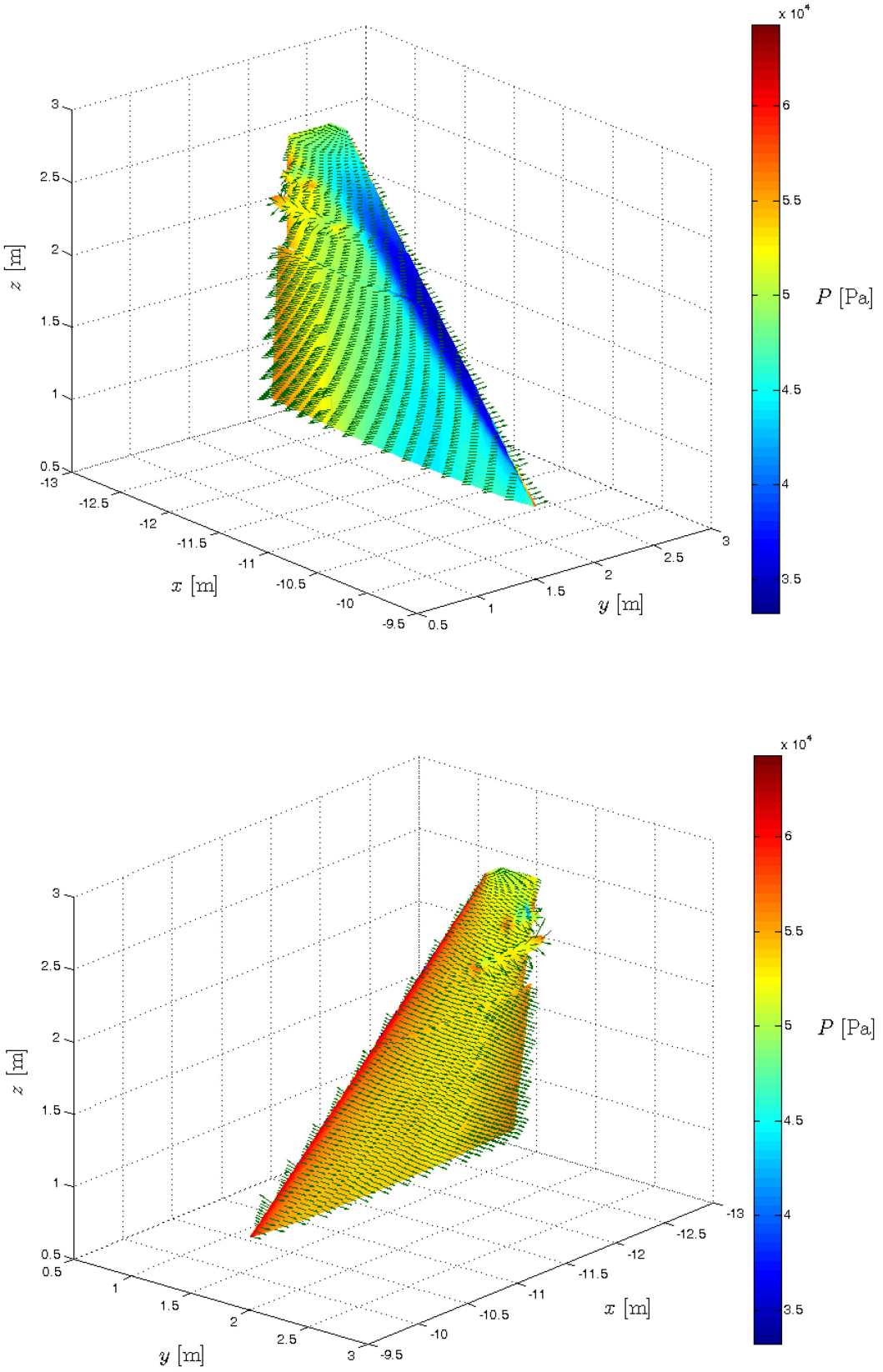


Figure 25-12: Example of the Aerodynamic Force Distribution on the Surface of the Stabilizer Based on CFD Computations.

For comparison using CCA analysis, a single value needs to be estimated, which characterizes the pressure distribution. Since the mode selected by means of CCA analysis is dominated by the nozzle contribution $\tilde{\sigma}_{nozzle}$, a proper parameter to be compared with the obtained canonical parameter ε_1^c (Figure 25-10) is the bending momentum of the stabilizer, i.e., the momentum of aerodynamic forces distribution computed with respect to the axis of the stabilizer attachment to the frame (Figure 25-13).

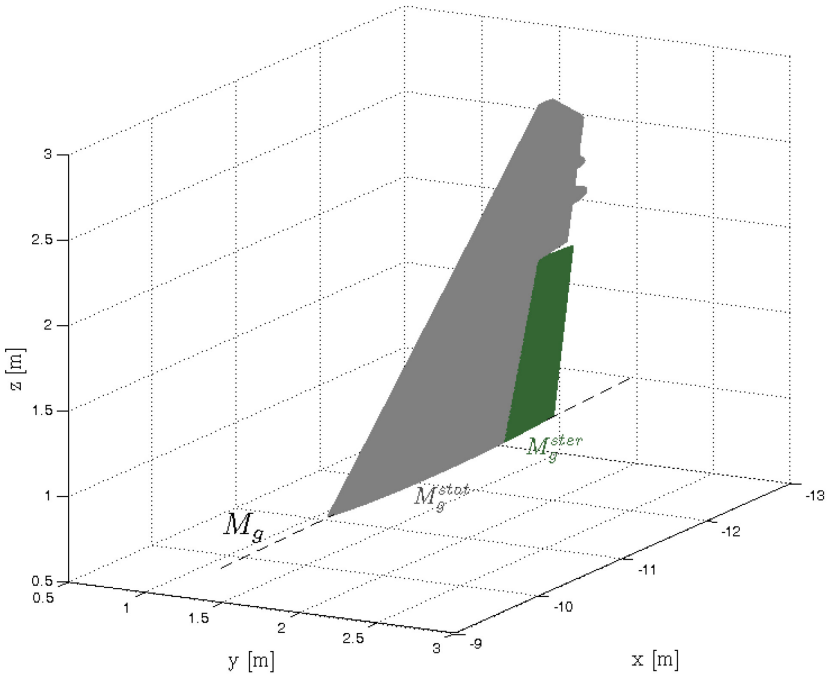


Figure 25-13: Vertical Stabilizer of the Aircraft with Indication of the Axis with Respect to which Bending Momentum is Computed.

In the coordinates frame presented in Figure 25-13, the bending momentum of the stabilizer M_g is given by the formula:

$$M_g = \iint_U \mathbf{e}_x \bullet \left((\mathbf{r} - \mathbf{r}_0) \times (-p(\mathbf{r})\mathbf{n}(\mathbf{r})) \right) d^2\mathbf{r} \tag{25-11}$$

where:

- U denotes the surface of the stabilizer (including rudder surface);
- $\mathbf{r}_0$ is a point on the bending axis of the stabilizer (Figure 25-13);
- $\mathbf{e}_x$ denotes unit vector along the x-axis;
- $\times$ denotes cross product of vectors;
- $\bullet$ denotes the scalar product of vectors;
- $p(\mathbf{r})$ is aerodynamic pressure acting on a given point $\mathbf{r}$ at the stabilizer surface; and
- $\mathbf{n}(\mathbf{r})$ is unit vector normal to the stabilizer surface.

Given the momentum M_g calculated for every CFD case (Table 25-1), a model of dependence of M_g in the form similar as in Equation (25-9) was considered:

$$M_g = \frac{\rho_0 V^2}{2}\left(1-\frac{H}{44300}\right)^{4.256}\tilde{M}_{normle}(V,\alpha),$$
$$\tilde{M}_{normle}(V,\alpha) = d_V V + d_{VV}V^2 + d_\alpha \alpha + d_{\alpha\alpha}\alpha^2 + d_{V\alpha}V\alpha. \tag{25-12}$$

The unknown constants were estimated by fitting it to values of M_g calculated by the formula Equation (25-11). This allowed the interpolation of the obtained CFD results to the entire $V-\alpha$ space under consideration (Table 25-1) and also to predict values of bending momentum during flight. Examples of the correspondence between normalized canonical parameter ε_1^c, normalized records of a strain gauge and normalized values of bending momentum M_g obtained during steady and high manoeuvre flights are presented in Figure 25-14 There exists a very good correspondence between calculated bending momentum and the canonical parameter, which confirms the applicability of the CCA method for the determination and prediction of loads on aircraft structures.

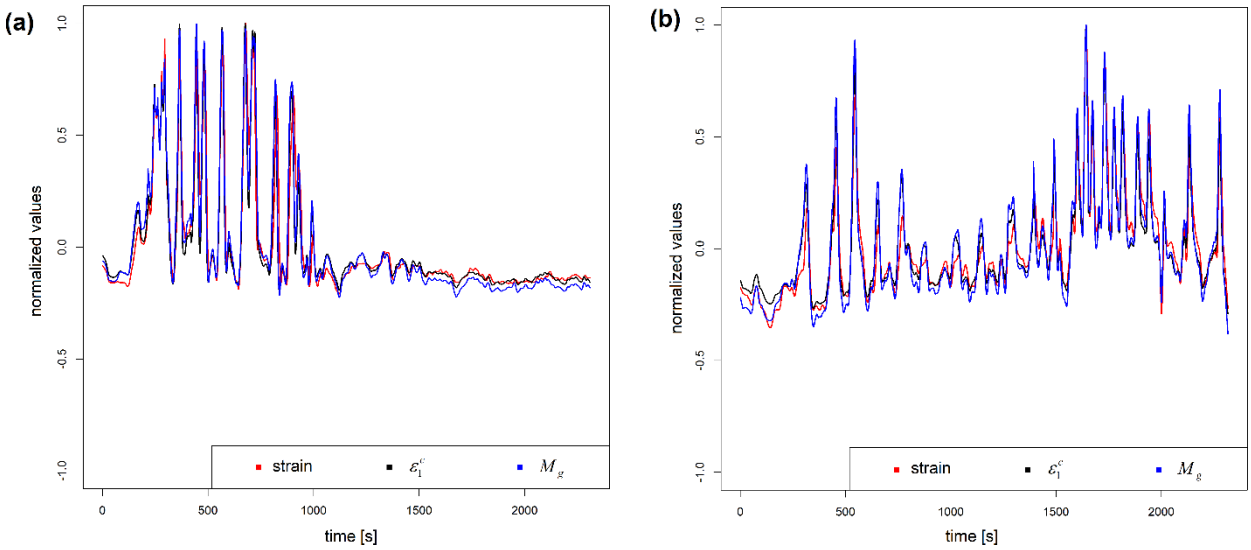


Figure 25-14: Examples of Normalized Records of Strain Gauge (Red), Canonical Flight Parameter (Black) and Bending Momentum (Blue) for: (a) Steady and (b) High Manoeuvre Flights.

25.3 SUMMARY

This chapter presented Canonical Correlation Analysis (CCA) as a proper method for selection of flight parameters well suited to predict loads of the aircraft structure. CCA allows both for identification of different modes of stress distribution as well as identification of flight parameters which are the best suited for their prediction. This chapter also presented the results of the application of this method to identifying loads acting on the vertical stabilizer of twin tailed aircraft. The determined canonical predictors were in very good correspondence with loads values acting on vertical stabilizer which were calculated using Computational Fluid Dynamics simulations (CFD).

25.4 REFERENCES

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Chapter 26 – SU-22 FSFT STUDY CASE AND MI-8 HARD LANDING TEST STUDY CASE

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26.1 SWEPT-WING JET AIRCRAFT FSFT

26.1.1 Introduction

Poland is one of the last countries in the world that still operates Sukhoi Su-22 Fitter aircraft (Figure 26-1). Nowadays the Su-22 is a rather obsolete construction and has limited combat value. The Polish Air Force has decided to extend their service live and keep them operating. The reason for such a decision lies in the lack of an available fleet that could fulfil auxiliary tasks e.g., anti-aircraft defence training or cooperation with the Army at the test range.

In 2014, the decision was made to extend the service life of Su-22 aircraft for another 10 years. The Original Equipment Manufacturer (OEM) had also set the limitation of the total number of landings allowed to accumulate by each structure during its service life. Operated aircraft, especially the two-seaters version, have approached the limitation. Taking into account the actual status and planned needs, there was a need to increase the limit in number of landings as well as a total number of allowed flight hours. It was decided to implement a research program, whose task was to confirm the possibility of further operation of Su-22 aircraft and to establish a new limitation.



Figure 26-1: Test Object Sukhoi Su-22 UM3K Fitter.

26.2 SERVICE LIFE EXTENSION PROGRAM

The research program took advantage of specific conditions in which Poland used Su-22. Strong points were:

- Experienced overhaul capacity (WZL-2 S.A. Bydgoszcz);
- Air Force Institute of Technology – scientific support;

- 30-years of Su-22 operation experience; and
- Full record of operational usage for each aircraft.

The weak point was a lack of OEM involvement in the program.

The essential element of the program was the implementation of a Full-Scale Fatigue Test (FSFT) [1]. In order to determine the adequate loads acting on the aircraft structure during the fatigue test, the spectrum of operating loads of aircraft used by the Polish Air Force was determined and load measurements were performed at selected phases of the flight during dedicated research flights.

Based on collected data from on-board recorders, different statistics were calculated. As a result of those analyses, an average operational profile was obtained. An appropriate load spectrum for FSFT was developed based on vertical acceleration statistics (Nz values) [2], [3].

A lack of design data had to be overcome by means of extensive reverse engineering activity. The geometry of the structure had been previously digitalized. Based on this data, computer models were developed, one series for Finite Element (FE) calculations and second for Computational Fluid Dynamics (CFD) simulation.

The flight tests were carried out to collect data for validation of computer calculations. One aircraft was equipped with a dedicated flight recorder (ACRA KAM-500) and instrumented with strain gauge sensors. Before flight tests the measuring system was calibrated. During the calibration, known forces were applied to the structure and the outputs of the sensors were recorded. Different methods for force application were adopted, e.g., dedicated sequences of refuelling, adding masses (bombs), and acting forces (wing clamps). Forces and moments were measured in different sections of the structure during several test flights. Special attention was paid to landings. Available historical data from recorders could not be used for determination of loads during landings because of low recording frequency / sampling rates. The numbers of landings with different gross mass and vertical speed were carried out.

The test article for Full-Scale Fatigue Testing (FSFT) was taken from a monument (Figure 26-2). One of the withdrawn two-seaters had served as a monument at an Air Base. The operational history of that aircraft was known. After some preparations performed by Military Aviation Works No. 2 JSC (WZL-2), the aircraft was delivered to VZLU Prague (Czech Aerospace Research Centre) for FSFT.

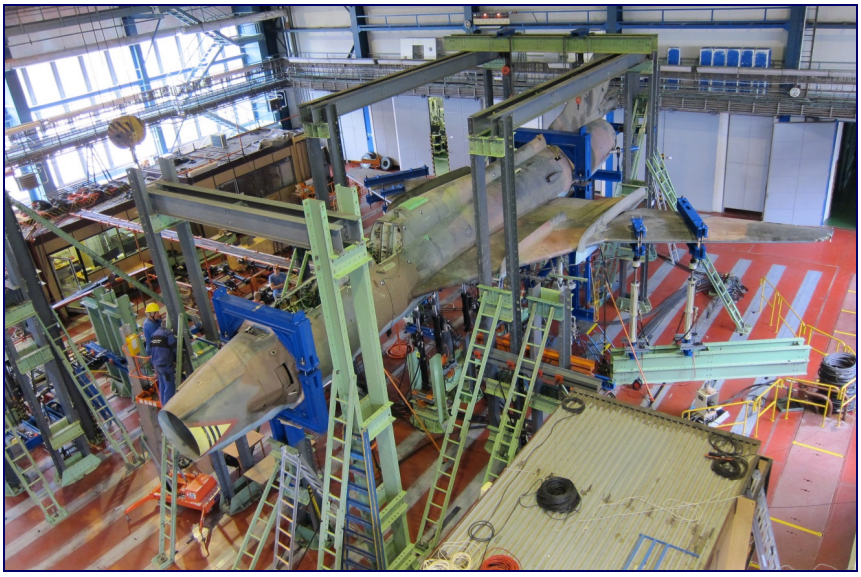


Figure 26-2: The Test Rig of the Su-22 UM3K Full-Scale Fatigue Test.

The FSFT initially was to consist of three stages:

- Stage 1: landings;
- Stage 2: flights; and
- Stage 3: flaps.

The aim of Stage 1 was to prove that the structure can withstand an increased number of landings. The landing gear itself was not the aim of the test because the Polish Air Forces (PLAF) has a satisfactory number of spare landing gears at their disposal to ensure that the desired number of landings for the whole fleet can be achieved.

A mix of different landing scenarios were simulated, followed by NDI checks. The structure passed the exam.

The aim of Stage 2 was to prove that the structure can withstand more flight hours. Flight hours are a subsidiary measurement unit. The procedure was based on applying cyclic loading. The Su-22 aircraft structure has swept wings. This could significantly increase the level of complexity of FSFT. Based on developed statistics, it turned out that most of missions were performed with a constant wing swept angle, 45 degrees. A 30 degree angle was used during the landing phase and a 63 degree angle for supersonic flights. The number of supersonic flights was very low and these flight categories could be neglected in total fatigue life considerations. Thus the FSFT test rig had to be adjusted for wing angle configuration changes between Stage 1 and 2. A dedicated NDI program was developed and executed while Stage 2 of the FSFT was being performed. There were no serious damages or cracks discovered in Stage 2.

The Stage 3 dealt with the flaps. Forces acting upon the flaps during take-off and landing were calculated analytically and using a CFD model. Flaps were released and blocked. After the test, no damages were found by NDT inspectors.

26.2.1 Summary of the Su-22 FSFT

The Su-22 had successfully completed the whole FSFT. It was decided to add an additional stage (Stage 4). The intention of Stage 4 was to introduce serious damage to the structure that would really limit the service life of the structure. The configuration from Stage 2 was reset. The load spectrum consisted of the maximum load cycles only.

After repeating numerous cycles, the main wing spar broke. This automatically terminated the Su-22 FSFT. The test article was delivered back to Poland (WZL-2) where the Teardown Inspections (TI) were started. Teardown Inspections provided the opportunity to inspect areas that were not accessible during FSFT. Though some new inspection findings appeared, they were not significant enough to change the general opinion about the durability of the Su-22 structure under the FSFT.

26.3 MILITARY TRANSPORT HELICOPTER HARSH LANDING TEST

26.3.1 Introduction to Transport the Helicopter Harsh Landing Case

In this chapter, a vertical drop test of a military transport helicopter is presented along with a sample of its results. The experiment has been one of the tasks of the European Defence Agency's (EDA) ASTYANAX research project. The project was carried out by a consortium of Italian, Spanish and Polish companies and research organizations.

The main aim of the project was to further develop the methodologies researched in the preceding EDA project HECTOR which dealt with devising of a predictive expert system used for detection of cracks and defects in the airframe [4], [5], [6], [7]. The expert system parameters were devised based on a series of finite element simulations. In the ASTYANAX project this approach has been extended from a helicopter panel to the full structure of the Mil Mi-8 Hip helicopter. One of the damage modes for which the predictive network had to be calibrated was the harsh landing event. An experiment was devised to provide data for this calibration [8].

26.3.2 Problem of Harsh Landings

The problem of harsh landings is an important issue in the operation of the Mi-8 helicopters in the Polish Air Force, and also an important factor that determines the design of the sensor and prediction network that is the goal of the ASTYANAX project. Harsh (high-velocity) landing is a frequent occurrence in the PLAF, as can be seen from the analysis of recorded flight data, which is especially true for the battlefield environments (missions in Afghanistan and Iraq). Because preliminary analyses lead to the conclusion that the Mi-8 airframe is relatively resistant to fatigue cracking, the harsh landing impact may be the most important factor causing deterioration of the helicopter structure. The manufacturer of the helicopter has not established a recommended limit for a “harsh landing” event. Authors therefore used a 3,05 m/s velocity as a guideline limit [8].

26.3.3 Test Setup

Although most of the mentioned full-scale drop/crash tests utilized a dedicated test rig, because of the relatively uncomplicated test requirements (i.e., a simple vertical drop), in the present activity an existing gantry crane of the ArcellorMittal steel mill in Warsaw was used (Figure 26-3). The crane was certified for a load of 50 tonnes, which was well in excess of the planned helicopter weight of 11 tonnes. The crane had a maximum hook height of 8,5 m, which gave an operating range of 2 m for the test (the height of the helicopter-release mechanism system was 6,5 m). The test was planned as a basic vertical drop. For each drop attempt, the helicopter was successively raised to a higher level, so that the touchdown velocity increased.



Figure 26-3: Mi-8 Hip Helicopter – Gantry Rail Test Set Up with Release Mechanism.

26.3.4 Instrumentation

The helicopter was instrumented with an elaborate sensor suite to capture the movement, rotation as well as structural response of the airframe. The ACRA KAM-500 data recorder has been used for recording of the main test signals. The measurement was performed with a 15 kHz sampling rate. The sensors used include:

- 54 strain gauge channels in various bridge configurations;
- 4 accelerometers;
- 4 laser distance meters;
- 2 shock absorber length sensors;
- 25 wireless polymer strain gauges;
- 6 MicroStrain® nodes (strain gauges and Micro-Electro-Mechanical-System (MEMS) accelerometers);
- 4 lines of 190 Fibre Bragg Grating (FBG) sensors; and
- 12 Piezoelectric Transducer (PZT) sensors in three network groups.

Location of the sensors is presented in Figure 26-4. PZTs, MicroStrain® no Nodes, and FBGs used a separate acquisition system [8].

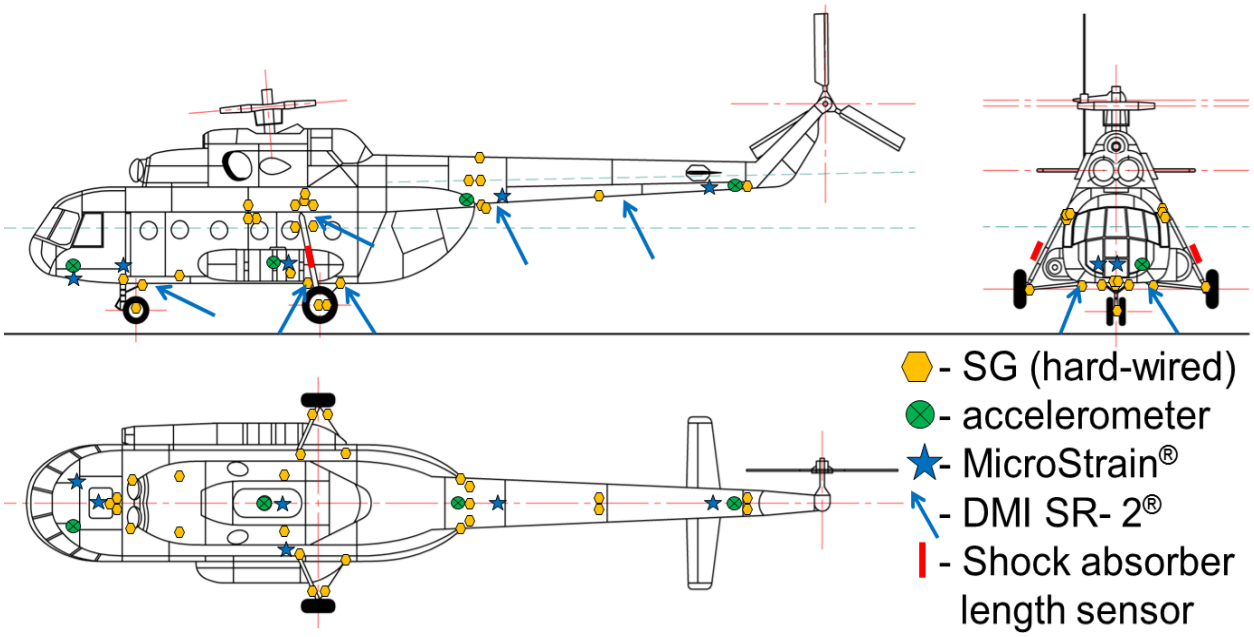


Figure 26-4: Mi-8 Hip Helicopter – Instrumentation Location.

The FBG sensors were placed in the main areas of concern for the ASTYANAX project, and are crucial in calibrating the designed sensor system that will be the result of the project. The strain gauge locations were established based on the operator experience as well as on a preliminary finite element simulation. The findings from the test will be used to validate a finite element model of the Mi-8 helicopter.

In addition to the on-specimen measurement systems described above, additional external systems were used to measure geometry before and after each of the drop attempts. Also a fast camera system (1000 frames per second) were used in the experiment.

Two acceleration sensor types were used in the experiment – the piezoelectric, triaxial ENDEVCO 65R-10 accelerometer as well as the classic, soviet produced, uniaxial MP-95 spring-mass g-meter. The MP-95 was placed in the centre of mass and oriented along the vertical axis of the helicopter, the 65R-10s were installed in the centre of mass as well as in the front and back sections of the fuselage. The soviet MP-95 is the same type of sensor that is used in routine service of the Mi-8 – this enables a comparison of flight test data and the drop experiment signals.

26.3.5 Release Mechanism

The SeaCatch quick release mechanism (Figure 26-3), produced by McMillan Design was used for the release of the helicopter. Release occurred by opening of the system's grips, which is done with the use of pneumatics. The release mechanism was attached to the gantry crane hook via a wire rope sling and a high strength shackle. The helicopter was attached to the SeaCatch via a special lug used by the maintenance depots to move the helicopter. The special lug was connected to the main rotor shaft. The hanging point was located on the vertical axis of helicopter centre of mass.

26.3.6 Drop Test Assumptions

Test heights that result in touchdown velocities below 3,05 m/s were initially chosen for the experiment. The drop attempt velocity incrementally approached the harsh landing regime. The landing regime limits are presented in Table 26-1 [9]. Based on the balance of potential and kinetic energy, 47,4 cm was calculated as the regime transition drop height.

Table 26-1: Suggested Landing Regimes.

Regime	Sink-rate-at-ground contact (SRAGC) [m/s]	Type of landing	Fuselage-earth contact expected
A	> 8,53 m/s	CRASH	YES
B	3,05 m/s < SRAGC < 8,53 m/s)	HARD	NO
C	< 3,05 m/s	NORMAL	NO

Because of the relatively low structural impact of the 48 cm drop, an additional drop height of 75 cm was employed. The 0 cm level was defined as the height at which the main gear wheels barely touch the ground. The fast camera markers used for the velocity measurement are presented in Figure 26-5.

26.3.7 Drop Test Execution

Before the drop test, the Centre of Gravity (CG) location was adjusted with the use of 3,25 tonnes of sandbag ballast. The CG was located in a position that reflects normal operating conditions. This was done by appropriate distribution of ballast in the freight area. The top fuel tank (on the fuselage) was filled with water. After the weight distribution adjustment, the helicopter was hung at a 4°10' pitch angle, which was representative of typical in-flight orientation. Figure 26-6 shows the sequence of events during the drop.

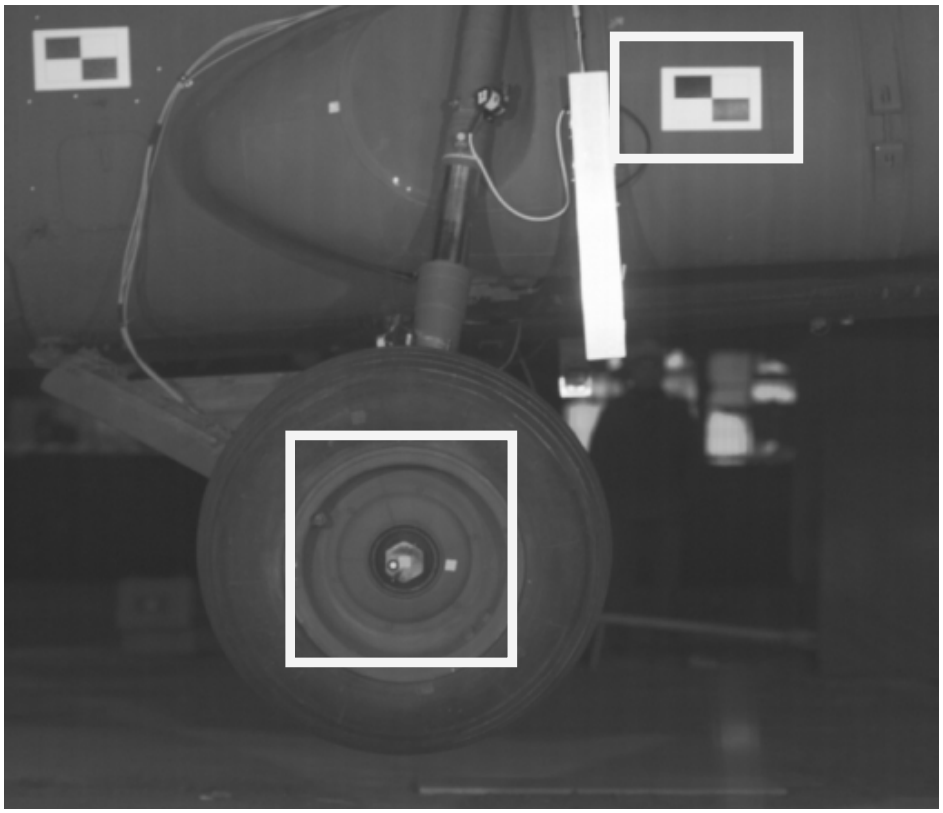


Figure 26-5: Fast Camera Markers.

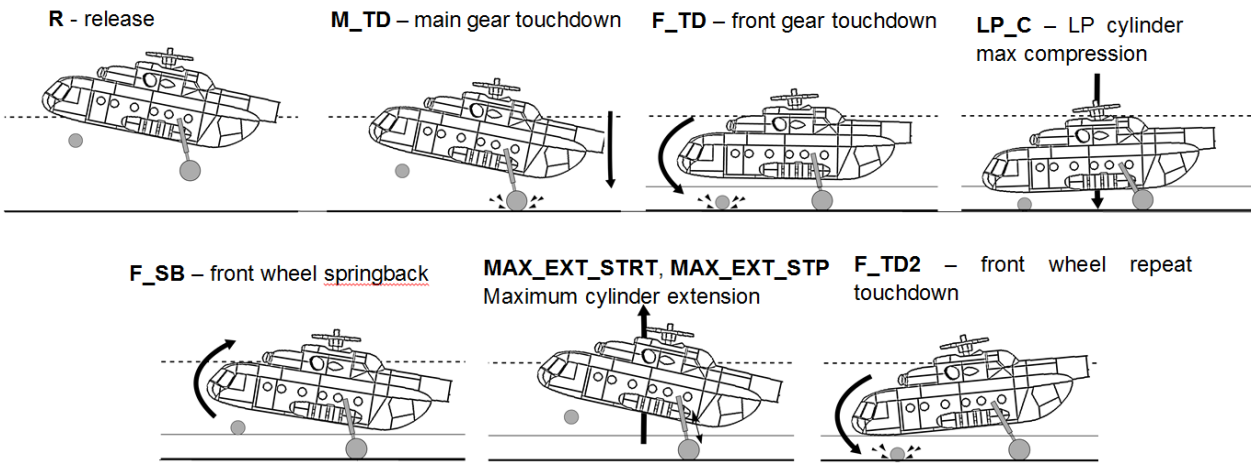


Figure 26-6: Sequence of Events During Drop.

Some difficulties arose during the experiment. Firstly, the fluid pressure in the cylinder was low for the 0 cm level, because the absorber fluid chamber was not fully refilled. Because of that, the vertical displacement was excessive for the first (0 cm level) drop attempt. For the subsequent drops the fluid was replenished before each attempt. This resulted in disproportionately higher loads and strains for the 0 cm drop. The influence of this low cylinder load is clearly seen in the presented signals. Also a problem with the release mechanism was encountered – for some of the drop attempts the helicopter got stuck in the grips of an opened release mechanism (due to friction), and the specimen didn't drop. This was remedied by applying lubrication to the grip area of the release mechanism, so the helicopter could slide off the grips.

26.3.8 Test Summary

A series of events and interactions take place in the course of a single vertical drop (see Figure 26-7 and Figure 26-8). Firstly, after the quick release system is opened, a characteristic structural response is seen during the free-fall phase. This response is identical for all of the drop heights and is a result of removal of the hanging reaction force. After the free-flight phase, the main gear tires touch down and the front tire touches down shortly after. After touchdown, the process of shock absorber contraction starts in the main gear, which results in striking of the contraction limiter by the Low Pressure (LP) cylinder, with the High Pressure (HP) absorber still moving. The high pressure absorber reaches its maximum contraction afterwards (in which moment the gas chamber of the absorber reaches maximum pressure). In this phase the deceleration of the helicopter reaches the highest amplitude, and the highest strain gauge signals are recorded.

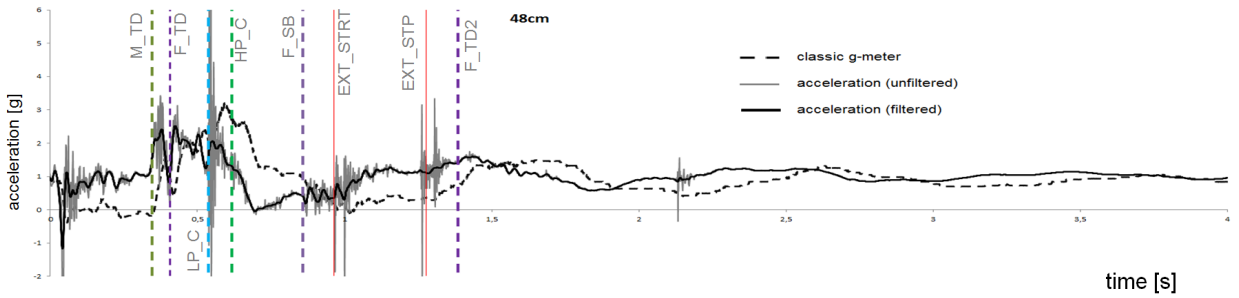


Figure 26-7: Sample of Accelerations Overview for ~0.5 m Drop Test.



Figure 26-8: Helicopter Before Release and at Maximum Strut Compression.

The experiment provided an extensive amount of data, enabling a detailed insight into the dynamics of a harsh landing event [10]. Analysis of the recorded data (strain gauge readings in particular) suggests that the Mi-8 airframe is resistant to ground impacts for impact velocities below 3.05 m/s – i.e., the assumed harsh landing threshold. For the highest drop level, only an onset of plastic deformation is observable. The geometry measurement methods used routinely in Mi-8 helicopter geometry assessment did not record any significant deformation. This finding is confirmed by the strain gauge readings – the highest recorded strains were below the yield limit of the material.

More results and deeper analysis of the harsh landing test is accessible in conference proceedings and Refs. [6], [10], [11].

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Chapter 27 – MIG-29 AND F-16 STUDY CASES

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27.1 INTRODUCTION

The MiG-29 is the basic fighter jet used in Polish Air Force. Two main criteria in the maintenance approach of MiG-29 are based on Hour Service Life consumption (called HSL) and service life based on aircraft age (so-called Calendar Service Life – CSL). AFIT played a role in the introduction of new maintenance approach named On Condition Maintenance (OCM) in connection with the possibility of extending service life of some airplanes. One of the primary tasks was NDT (Non-Destructive Testing) work for critical components, as well as a corrosion inspection program for MiG-29 aircraft. Activities connected with the NDT and corrosion inspection program are also delivered for other aging aircraft of Polish Armed Forces. In this review, only part of the NDT work will be presented and related to the composite skin of vertical tail of MiG-29. The MiG-29 is an aircraft with double vertical tail construction. The vertical tail consists of aluminum substructure and composite skin made of CFRP (Carbon Fiber Reinforced Plastic). The skin is monolithic, with a thickness range of 1.8 mm – 3.8 mm and it is joined to the substructure using rivets and adhesive [1].

27.2 MIG-29 STUDY CASE

Non-destructive testing of the MiG's-29 vertical stabilizers is focused on CFRP skin and damages classified as [2]:

- Delaminations – description and monitoring of damage area;
- Disbonds – description and monitoring of damage area;
- Porosity – identification of damage presence; and
- Foreign object inclusions – identification of damage presence.

Techniques which are used for the inspection of MiG-29 vertical stabilizers are also used for F-16 horizontal and vertical stabilizers are presented in Table 27-1. In Figure 27-1, an automated C-Scan system used for the inspection is shown.

Table 27-1: Information about NDT Techniques Used and Their Capabilities.

	Low Frequency Acoustics	**Shearography**	**Ultrasonic Testing (UT)**
Delamination	-	-	+
Disbond	+	+ **(core-skin disbond)**	+
Porosity	-	-	+
Foreign Object Inclusion	-	-	+

As can be observed from Table 27-1, only multimode NDT damage detection is efficient enough to cover possible damage detection [2], [3]. Due to the different failure mode occurrence in the inspected structure, such an approach covers the possibility of damage detection and proper description. For implemented OCM program, detailed NDT with the use of ultrasonic and low frequency acoustics is being under used at present.

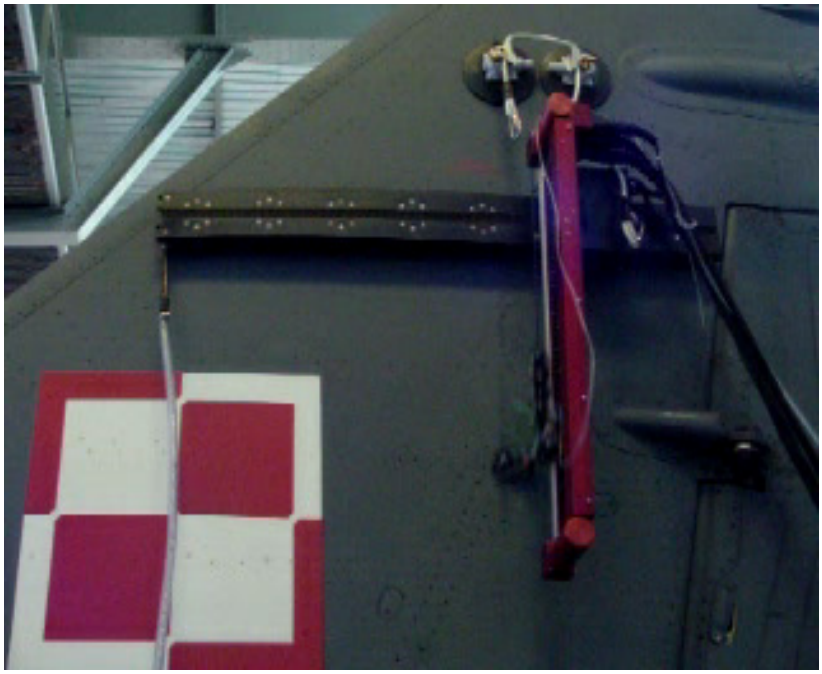


Figure 27-1: MiG-29 Vertical Stabilizer Automated NDT Inspection.

To perform structural integrity testing of the composite vertical stabilizer of a MiG-29 jet, ultrasonic testing is applied. The total surface area for inspection is approximately 11 sq. meters per aircraft. The aircraft population, which is currently being tested, is more than 30. Thus the total area for inspection is more than 600 sq. m for the whole monitored aircraft population. Classical NDT tests using manual hand scanning are very difficult or impossible, because the work has to be done on a very large area. An automated scanning procedure was therefore applied. The MAUS®V system (Mobile AUtomated System) that was used is a hybrid construction and makes possible inspections with such techniques as:

- Ultrasound, eddy current;
- Eddy current;
- Mechanical Impedance Analysis (MIA);
- Pitch-catch;
- Resonance; and
- Phased Array.

The system is fully portable and enables inspection on horizontal and vertical inverted surfaces due to flexible track system equipped with special fixturing. Figure 27-2 shows a MAUS®V system installed for an inspection of the vertical stabilizer composite skin of a MiG-29. Low frequency acoustics and ultrasonic inspection with MAUS system are quantitative methods. The results are presented in so-called C-scan mode, which makes damage location and sizing possible. The system's embedded interface enables amplitude and TOF (Time Of Flight) C-Scan data presentation. In Figure 27-2, the Time of Flight C-scan of a MiG-29 vertical stabilizer is presented.

The colour range in the TOF data provided gives information about different composite skin thicknesses as well as the depth of the damage location. This type of data presentation is very helpful for damage description, as well as for fast determination of the damage location.

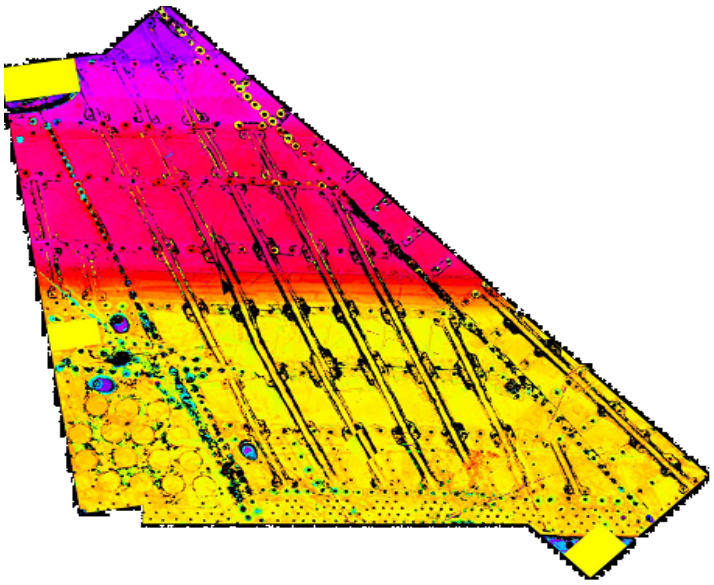
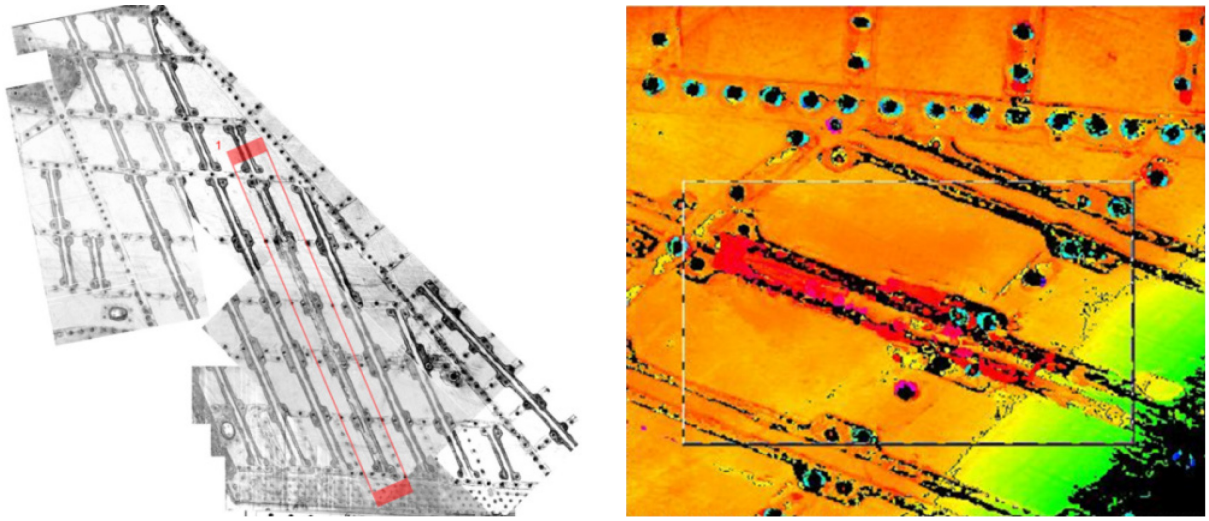


Figure 27-2: TOF C-Scan of a MiG-29 Vertical Stabilizer.

In the amplitude data presented in Figure 27-3(a), a different grey scale intensity is indicative of different signal attenuation. The amplitude mode is useful for determining damage location. The distribution of the damage locations relative to the side of the vertical tail (internal and external) as well as left or right tail has been found to have an approximately normal distribution. Some interesting inspection results are presented in the Figure 27-4 and Figure 27-5.



(a) PE-Amplitude Mode C-Scan. **(b) PE-TOF Mode C-Scan.**

Figure 27-3: Large Delamination Along Longeron of MiG-29 Vertical Fin.

If more information about damage characterization is required, additional full waveform capturing is performed, based on B-scan visualization (presented on the Figure 27-4). These results are used for the detection of delaminations and foreign object inclusions. A typical distribution of damages is in the form of disbonds, located at the bottom of the stabilizer, shown in Figure 27-5. As previously mentioned, monitoring of all operating aircraft contained in AFIT designed service bulletins has been implemented.

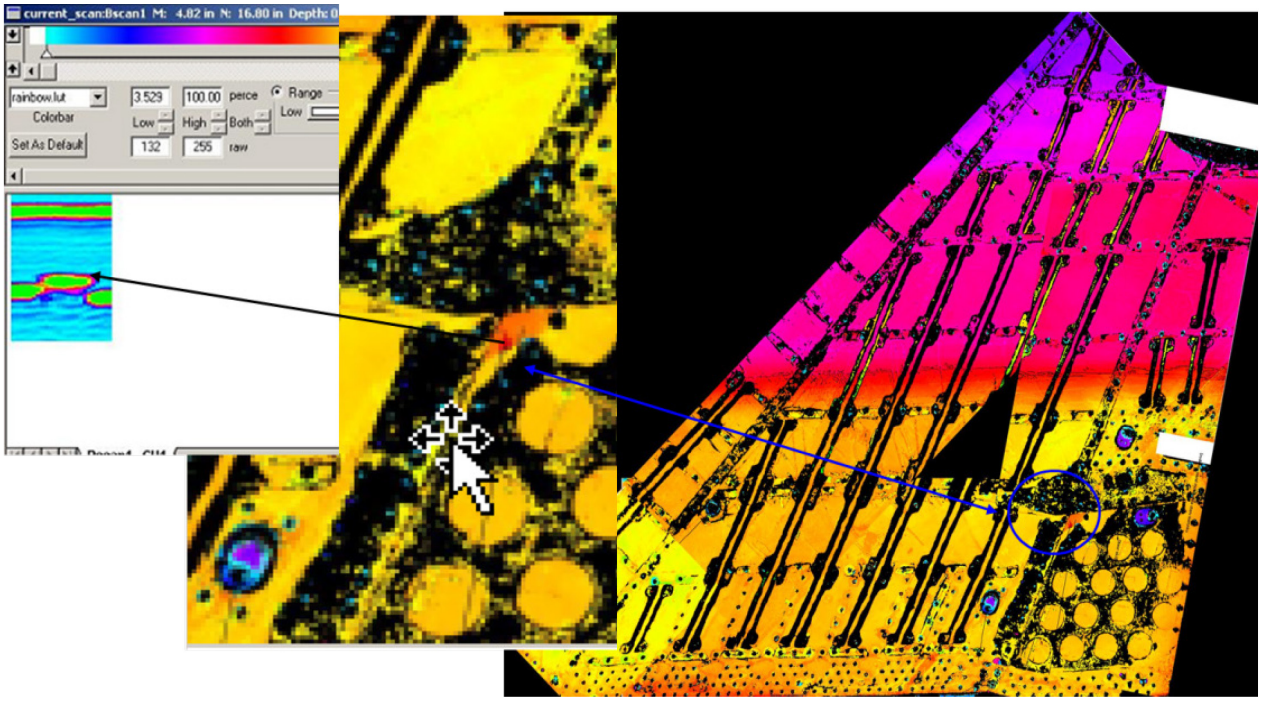


Figure 27-4: Foreign Object Inclusion (Embedded) in MiG-29 Vertical Fin.

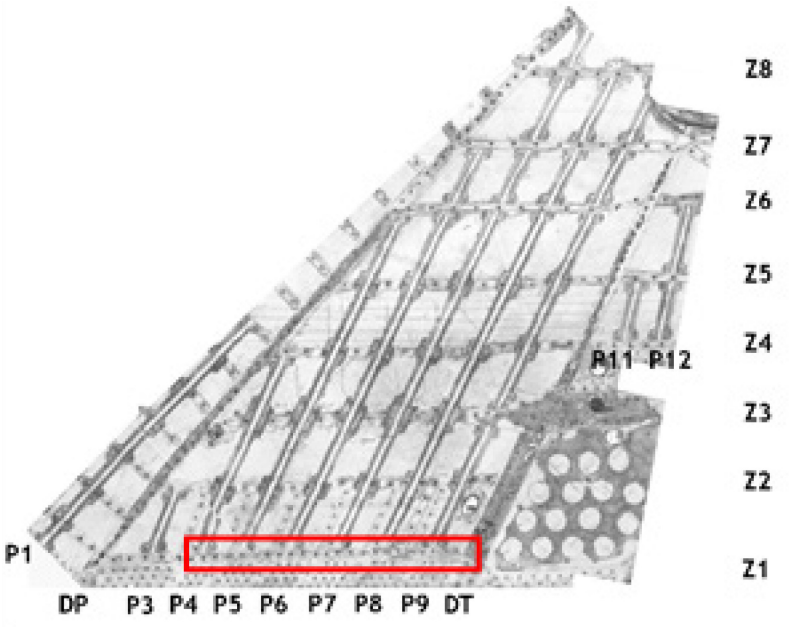


Figure 27-5: Distribution of Disbonds in the MiG-29 Vertical Stabilizer.

27.3 F-16 STUDY CASE

In connection with the introduction to service of the F-16 fleet of aircraft in 2008, AFIT designed and implemented into service the first NDT inspection service bulletin to collect data about composite structure. For that purpose, ultrasonic and shearography inspections on a single aircraft were delivered, as shown in Figure 27-6.



Figure 27-6: F-16 Horizontal Fin Ultrasonic Inspection (Left) and Shearography Inspection (Right).

Figure 27-7 presents data from the ultrasonic inspection of the horizontal stabilizer (top side). Based on detailed information of structure design and thickness changes, failure mode occurrence can be analyzed.

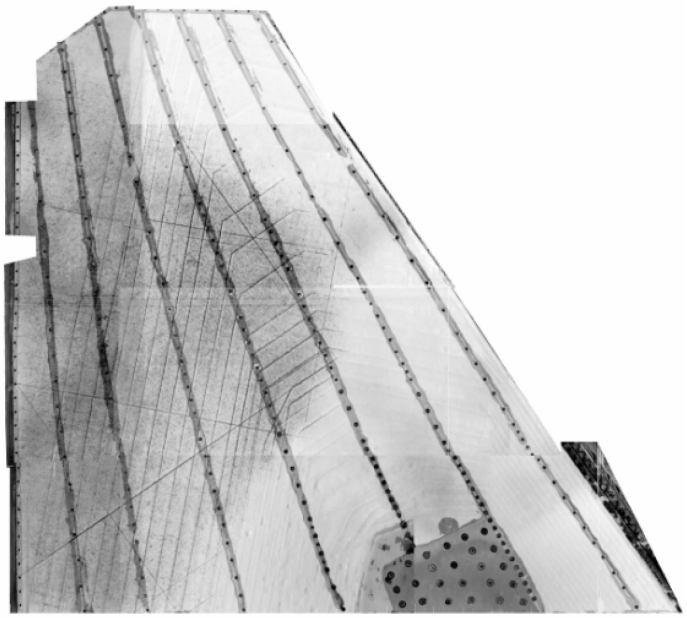


Figure 27-7: Amplitude C-Scan F-16 Horizontal Stabilizer.

This approach to the first inspection of the composite elements provides holistic information about the initial structure condition. From the manufacturing and maintenance point-of-view, various failure modes may occur, thus profound knowledge about structural integrity starting from aircraft manufacture and aircraft delivery is important. Figure 27-8 presents an example of a delamination around a rivet, which occurred during original structure manufacturing. From the whole aircraft fleet population, damage distribution information was collected and stored in a database.

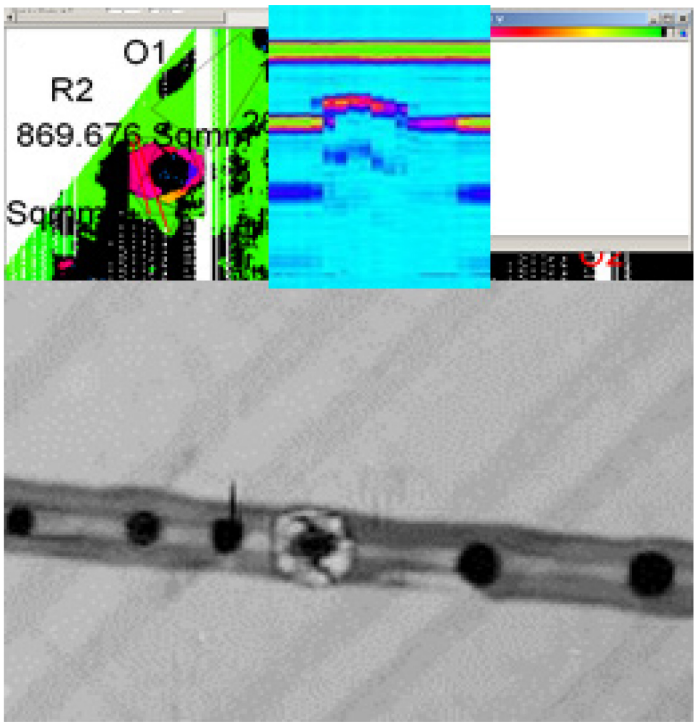


Figure 27-8: Amplitude and TOF C-Scan F-16 Horizontal Stabilizer with Damage Presence.

27.4 CONCLUSIONS

All the information presented here is related to the automated and advanced NDI of composite aerospace structures. All these activities are connected with NDI procedures and service bulletins accepted by the appropriate Technical Airworthiness Authority in the Polish Air Force. MiG-29s are inspected as part of scheduled maintenance for the purpose of structural integrity monitoring, which is part of on condition maintenance. Structures on F-16s were inspected for collecting data related the initial structure integrity of composite structures which will be used for further perspective support of aircraft maintenance.

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Chapter 28 – NDT ACTIVITIES DURING COMPOSITE BONDED REPAIR OF PL C-130E WING BOTTOM SKIN

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28.1 BACKGROUND

28.1.1 General

Continued airworthiness is required to accomplish aviation safety regulations. Non-destructive inspections, according to regulations (CS 23.573.a) are mandatory to ensure structural integrity and safety for composite structures. Such inspections also concern composite bonded repair. During the realization of Programmed Depot Maintenance (PDM) on C-130 owned by Polish Air Force, Military Aviation Works No. 2 identified composite bonded repair on the bottom side of wing. Based on the documented requirements, a composite patch should be inspected using infrared thermography. The available documentation consists of a procedure for thermography inspection and technical documentation for manufacturing of specimens. Documentation of the repair itself was not available.

28.1.2 Bonded Repair

The composite bonded repair resulted from the need to reinforce an area of wing skin weakened by the presence of corrosion. The load carrying capacity was to be ensured by a repair package made of Boron prepreg. This is a widely-used solution to repair corrosion grind-outs [1], [2]. The repair technology applied to the aircraft used a prefabricated Boron Fiber Reinforced Plastic (BFRP) patch bonded to the wing skin using adhesive film. This solution has been commonly used in military aviation for more than 20 years [2], [3]. Due to the stiffness of the patch, the gap between the patch and the place where corrosion damage is removed in the wing skin should be filled with an adhesive film. Figure 28-1 shows schematically a corroded wing skin, after grinding and with repair patch.

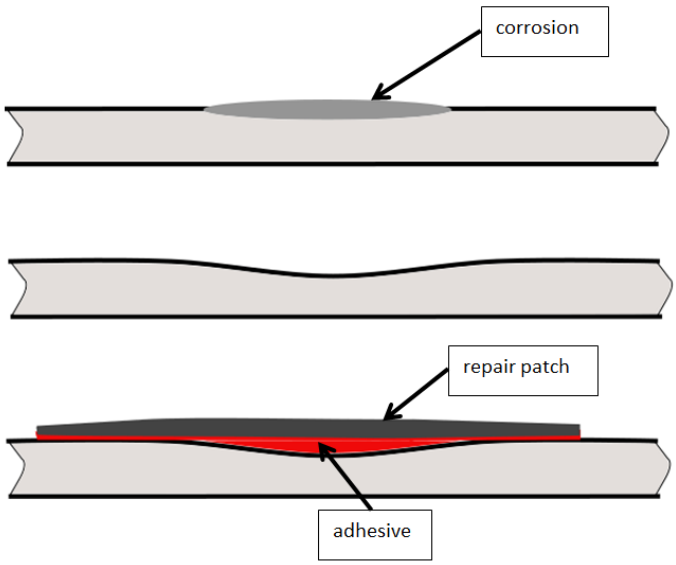


Figure 28-1: Bonded Repair Corrosion Grind-Outs.

28.2 WORKFLOW

28.2.1 Order of Work

Figure 28-2 shows the order of work, including non-destructive testing using Eddy current (ET) and Infrared Thermography (IRT) techniques.

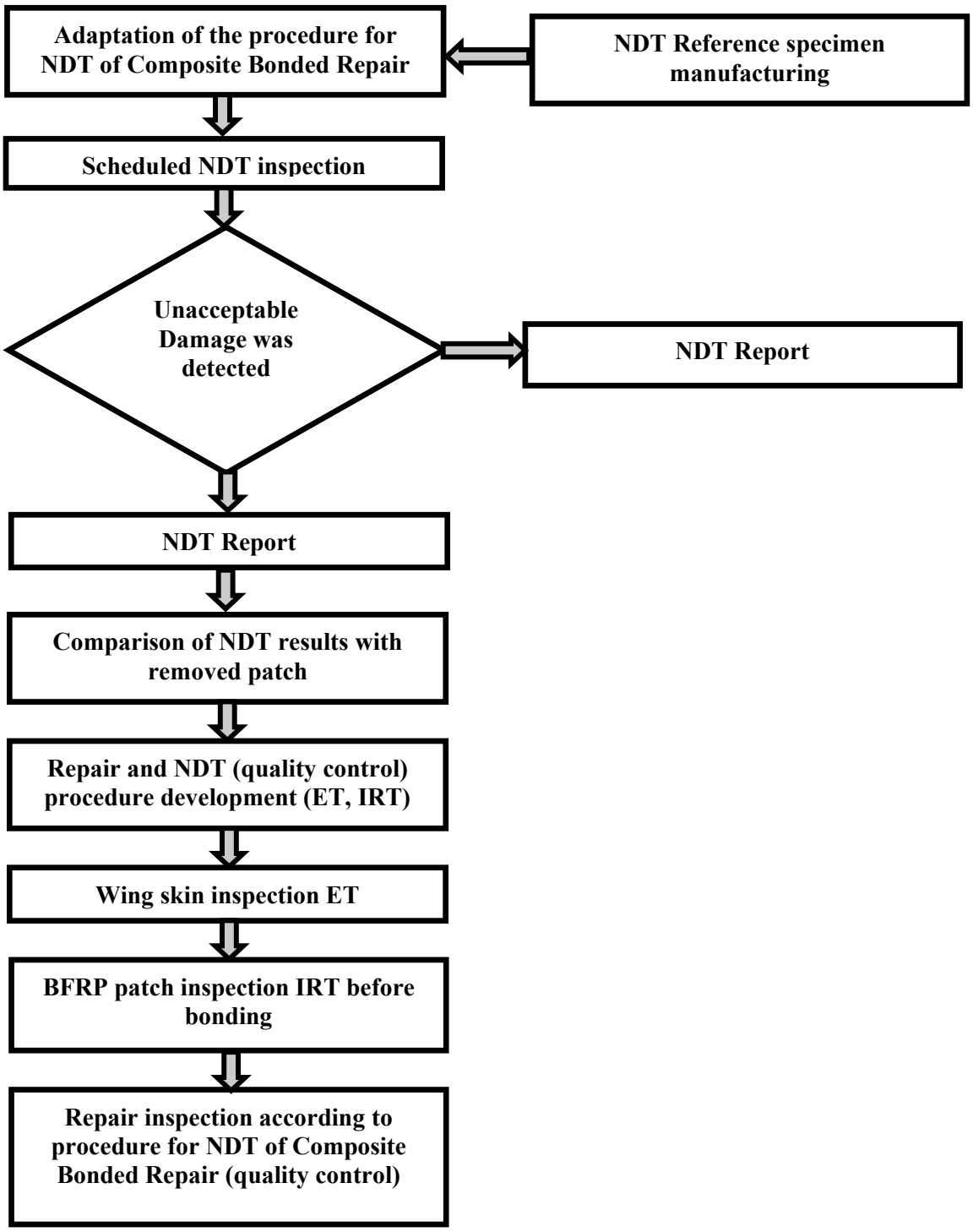


Figure 28-2: Order of Work.

28.2.2 Adaptation of the Procedure for NDT of Composite Bonded Repair

Based on the available documentation, a reference specimen was prepared and the procedure for non-destructive testing of the Composite Bonded Repair was developed using the thermography method. The specimen contained artificial disbonds in the form of pillows made of paper and adhesive tape in various sizes, distributed between the aluminum plate (Figure 28-3) and the repair patch (Figure 28-4), and inside the repair patch between layers. The specimen also contained grind-outs filled with adhesive film. Hollows in the specimen enabled assessment of whether there was air trapped between the patch and the ground skin (Figure 28-5) or whether it was filled with adhesive. This issue is very important in case the applied repair package is pre-heated in an autoclave, because its stiffness does not allow it to fit into the surface hollows [4].

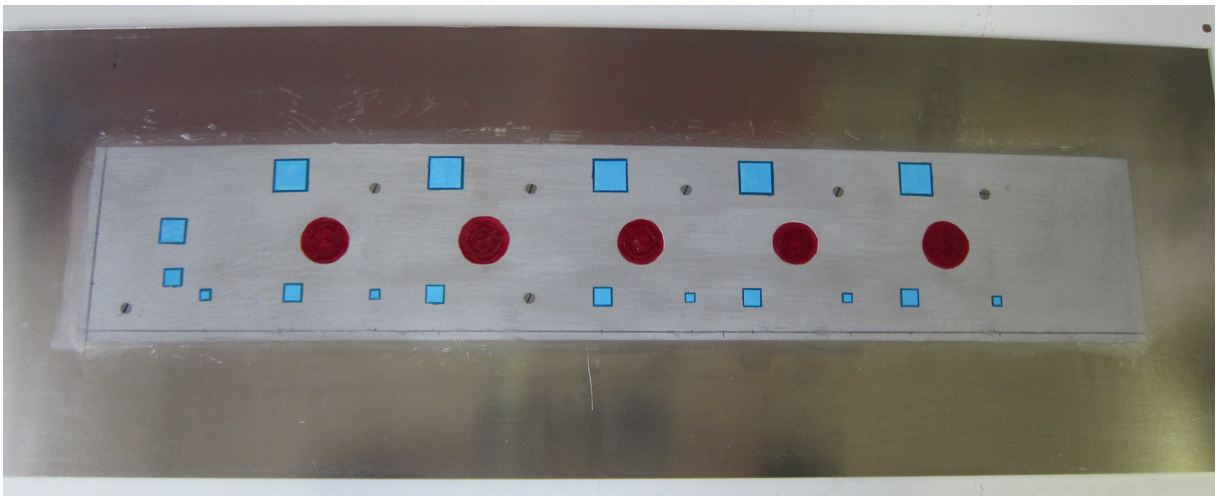


Figure 28-3: Reference Specimen Prepared for Apply BFRP Patch.

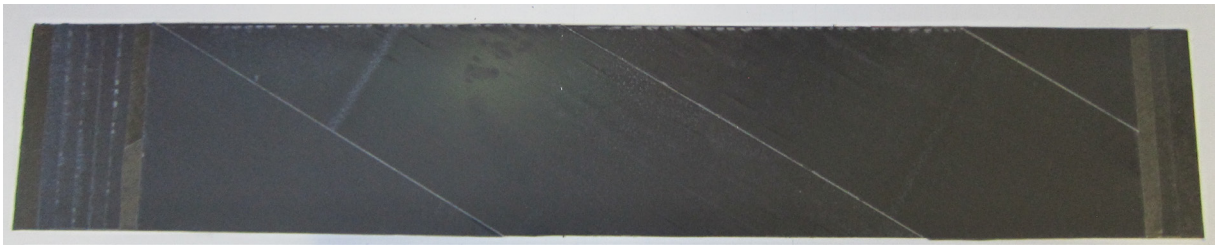


Figure 28-4: BFRP Patch Prepared for Apply.

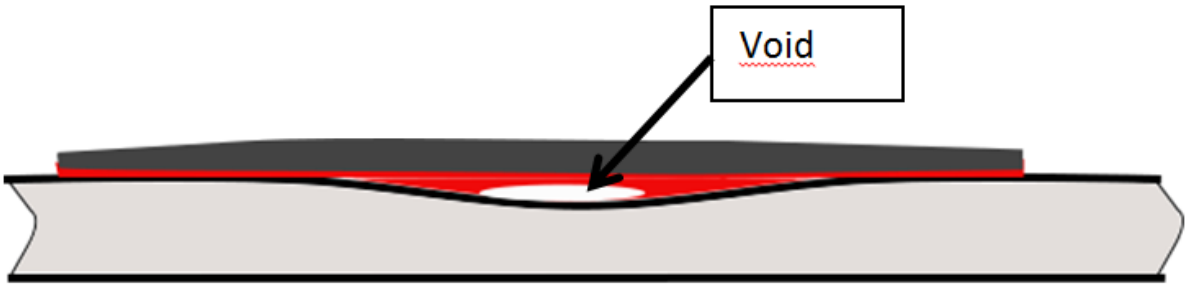


Figure 28-5: Void Trapped Between Patch and Wing Skin.

28.2.3 NDT Inspection

Bonded repair damage was detected during the scheduled inspection using the IRT thermography method. A “snowflake” shaped damage was detected, indicating the presence of a defect, likely incurred during bonding of the repair patch. As mentioned in literature [1], [3], for composite bonded repair, an allowable bond defect size should be determined. The damage found exceeded the criteria set out in the documentation, and therefore it was decided to replace the repair. Figure 28-6 shows the flaw indication.

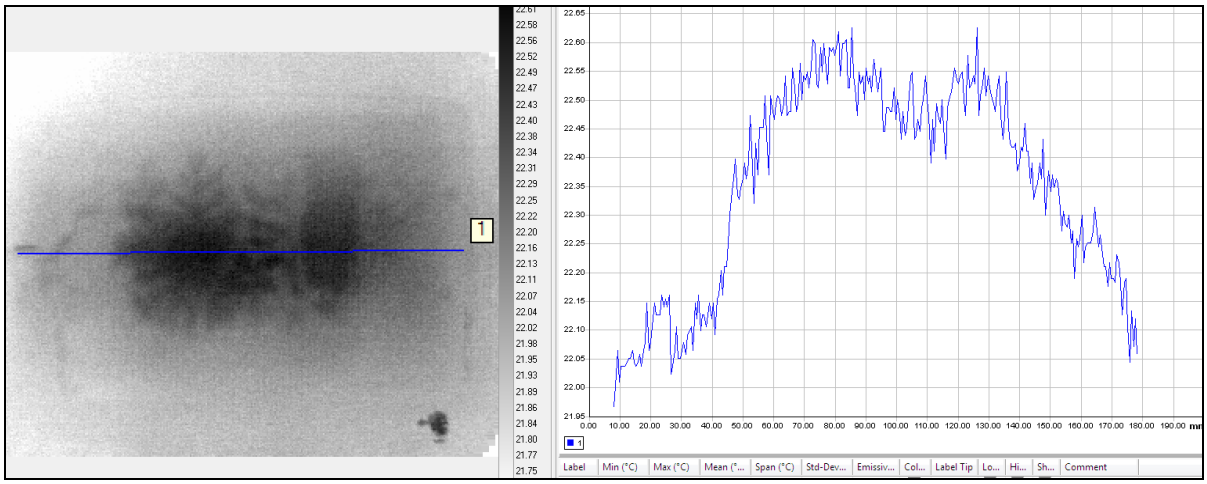


Figure 28-6: Flaw Indication (Left) and Temperature Profile (Right) Plotted for Blue Line.

28.2.4 Comparison of NDT Results with Removed Patch

During the removal of the repair patch, no damage in BFRP patch was found. After grinding, patch damages inside the adhesive layer were found (Figure 28-7).

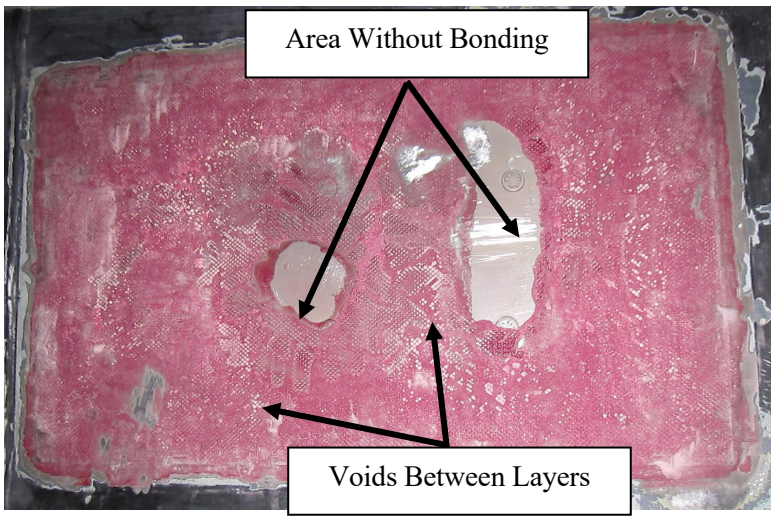


Figure 28-7: Adhesive Layer After Patch Removing, with Evidence of Voids and Areas Without Bonding.

The damage found corresponded to the thermography indications. There was evidence of lack of bonding on two fragments of the wing skin, and voids between layers of the adhesive film.

28.2.5 NDT Quality Control Procedure Development and Application

Due to the need to replace the repair patch, a repair procedure was developed. An important part of the preparation of repair documentation was the development of NDT procedures. A Magneto Optic Imager (MOI) 308TDF eddy current procedure for crack detection in the wing skin was added to a previously developed thermography procedure, shown in Figure 28-8. The thermography procedure was used also to inspect the BFRP patch before bonding. After bonding of the patch, the thermography procedure was used to assess the bond quality. Thermography results are shown on Figure 28-9.



Figure 28-8: Inspection Using MOI 308 TDF.

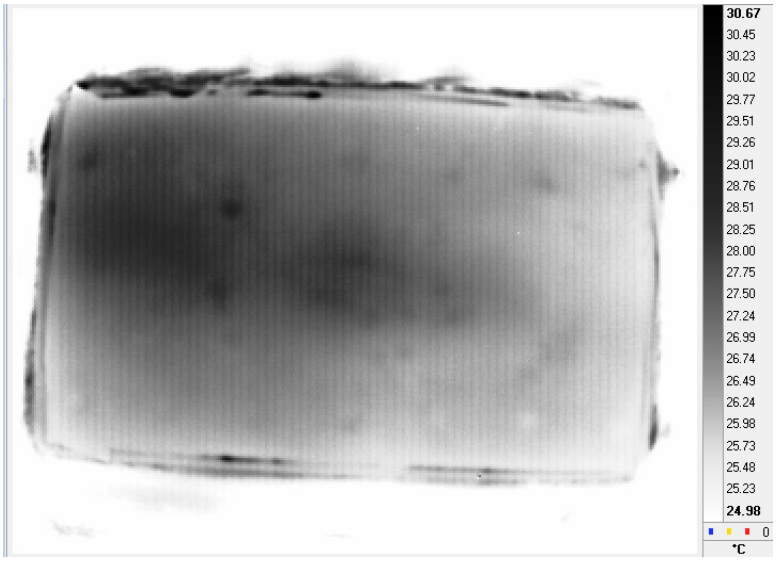


Figure 28-9: Thermography Result.

28.3 SUMMARY

This study identified significant manufacturing defects in repair packages, indicative of the poor quality of previously developed or implemented repair technology. Based upon these inspections results, AFIT developed their own procedure for repair as well as for NDT.

In this work, the authors used the FLIR SC7000 camera, which was demonstrated to have sufficient sensitivity to determine the integrity of the repair patch. This procedure was used primarily to determine the quality of the repair patch after prefabrication, prior to bonding of the repair patch to the structure.

In the AFIT developed repair procedure, attention was paid to the bonding of the repair patch to the wing skin structure. The NDT inspection procedure has been extended to include the MOI procedure for wing skin cracks detection.

28.4 REFERENCES

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Chapter 30 – HELICOPTER BLADES FAILURES MODES

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30.1 HELICOPTER BLADES FAILURES MODES

The Polish Military Fleet of Helicopters mainly consists of Russian made helicopters, such as the Mi-2, Mi-8, Mi-17, Mi-14, and Mi-24. The approach to the maintenance of Main Rotor Blades (MRB) of these helicopters is based on service life. There are two criteria for the maintenance of helicopter MRB:

- Service life based on hours – so-called Hour Service Life – HSL (measured in hours); and
- Service life based on time interval – so-called Calendar Service Life – CSL (measured in years).

The above mentioned criteria are also used to determine the MRB service life. The contribution to MRB life from actual operations (HSL) is in the range of 30 – 40 % of the service life. This means that theoretically MRB even in a good condition must be replaced because of aging (CSL). The introduction of Cost Benefit Analysis was necessary for the AFIT/ITWL (Air Force Institute of Technology) to realize an MRB service life extension program.

There are types of MRB blade constructions used in the Polish Air Force, Navy, Army: one with single spar and multi-section honeycomb, the other with single spar and non-section honeycomb structure. Table 30-1 presents information about the main rotor blades used in Polish Armed Forces helicopters. Most of the blades used in the Polish Armed Forces are metal with multi-section structure. Their differences consist of size, spar manufacturer and number of blades (Qty), as well as HSL and CSL [1], [2].

Table 30-1: Information about MRB Used in Polish Air Force.

No	Type	Construction	Qty	HSL [h]	CSL [y]
1	Mi-2	Metal, single spar, multi-section	3	1000	6
				1500	6
				1000	8[1]
				1500	
2	W-3, W-3WA	Composite, single spar, non-section	4	1500	10
				1500	13[2]
3	Mi-8	Metal, single spar, multi-section	5	2000	7
4	Mi-14PS Mi-14PL	Metal, single spar, multi-section	5	750	6
5	Mi-17	Metal,single spar, multi-section	5	2000	7 6[3]
6	Mi-24D Mi-24W	Metal,single spar, multi-section	5	1200	9 6[3]

Note: [1]Spar manufactured in Poland; [2]After detailed servicing; [3]Operating in sea environment.

Detailed analysis of the operating intensity of the helicopters proved that the percentage use of HSL of helicopters is negligible comparing to assumed level. Figure 30-1 presents the percentage share of the use of HSL of selected helicopters used in the Polish Armed Forces [2].

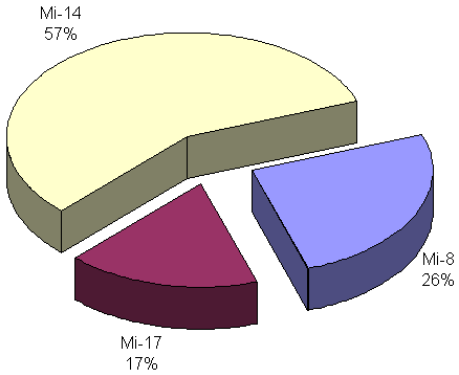


Figure 30-1: Percentage Use of HSL.

The percentage share of HSL use is taken into consideration at the end of the CSL. It means that it is not economical to replace MRB with new sets when the HSL percentage use is only 17% – 57%. However, the existing maintenance procedures are not able to take into account the technical condition of aged main rotor blades. For this, it was necessary to perform exact statistical data analysis which should include such points (amongst others) as:

- Percentage share of failure mode;
- Percentage share of failure effect;
- Percentage share of MRB elements;
- Number of failures caused by selected mode;
- Percentage share of failures caused by aging process;
- Safety and reliability analysis; and
- Possibility of using cluster analysis.

These analyses give necessary information for further work. In the AFIT there is a database system (SAN) which stores the data about failures, providing the possibility of various analyses. Figure 30-2 presents information about percentage share of various failure modes expected during the service life of MRB.

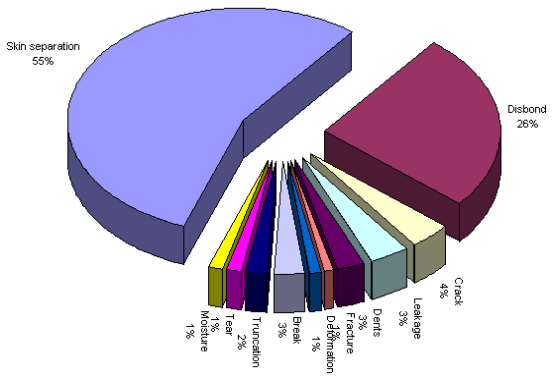


Figure 30-2: Percentage Share of Various Failure Modes.

The most frequent failure was skin separation, as well as disbond. A much lower contribution was due to other failures. Failure was determined by several factors. The most important factors were aging and manufacturer fault. The next one was in-service damage with only 11% share of failure effect (caused by low level of HSL). During further analysis, the most critical elements were determined, as well as the number of events, and cluster analyses were performed. These analyses provided a good base for determining what method should be used and which MRB should be inspected.

Maintenance procedures used so far, not only in the Polish Armed Forces, were based on visual inspection, with the additional support of hammer (coin) tap testing. Those techniques are fast and fairly simple to use but are not reliable and are operator dependent. The next important issue is the fact that these procedures are also very dependent on the so-called “human factor”. Taking that into consideration, as well as analyzed data from failure analysis, appropriate NDE work was performed. Selected enhanced NDI techniques, such as: Shearography; MIA; Pitch-Catch; Ultrasonic; Ultrasonic Phased Array; Eddy Current; and X-Ray, were applied [2], [3]. These techniques were supported with a PC interface, which made post process data analysis on site. The other advantages of having a PC based interface were: data storing and data comparison; automation of arm scanning procedures; and enhanced visualization. The first step in the NDE work was to prepare special specimens using out of service MRB, as well as those still used in service. Using these, it was possible to create damages similar to the those found in service for comparison and to determine detectability limits. The next issue was to compare these with serviceable MRB in a different condition, and different CSL or HSL. One of the tasks was also to perform low energy impact tests on selected MRB from W-3 helicopters and establish damage detection. Some of the results of these inspections are presented below.

Based on extensive R&D programs, special test plans were stablished. A specialized specimen was designed, and a test scenario for damage detection was implemented.

The first step of that work was to determine damages which could be detected and which happen during the service life of MRB of helicopters used in the Polish Armed Forces. Those damages could be described as follows:

- Disbonds (skin to honeycomb, skin to spar);
- Cracks (in the spar);
- Corrosion; and
- Water ingress (honeycomb cells).

One of the important issues connected with the maintenance of the metal MRB is crack growth in the spar structure of the blade. Detailed analysis of the failure modes made it possible to determine so-called “hot spots”, i.e., spar areas where the cracks occur the most often.

It is possible to divide the spar structure into three areas – Figure 30-3 A, B, C. Areas A (leading edge) and B consist of Top Wall (TW) and Bottom Wall (BW). Area C is a location where all the sections are bonded to the spar, and where the Rear Wall (RW) is located. Detection of the cracks in Areas A and B is easier because of the geometry. Inspection is difficult on the blade leading edge, where an anti-erosion layer is installed.

In the several specimens made from MRB blades, cracks were created by fatigue cycling in a load frame, which provided an opportunity to determine which inspection techniques were most efficient at crack detection. As a result, eddy current and ultrasonic inspections were chosen for the study.

Eddy currents are a useful tool for the inspection of aluminium alloys. The major limitation of this technique is the so-called depth of penetration, which depends on conductivity and the frequency of excitation of eddy currents in the material being inspected.

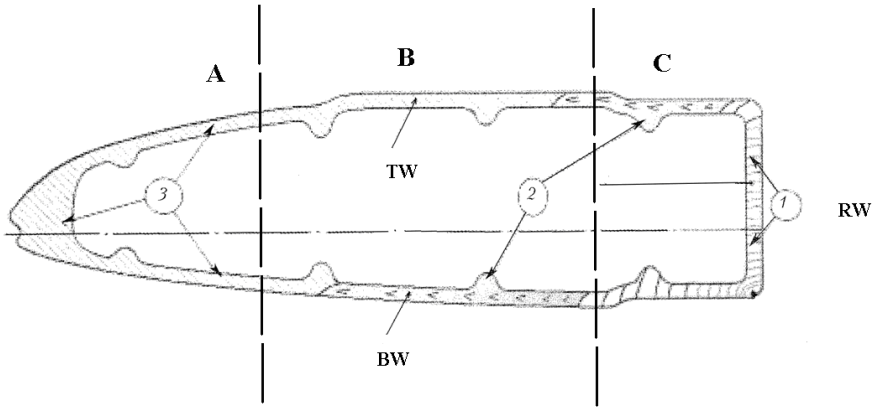


Figure 30-3: Spar Cross-Section.

The thickness of the spar in most locations is in the range of 3.3 mm. At the airscrew, the thickness increases to 5.6 mm. Based on conductivity measurements, the estimated depth of penetration was determined to be equal to 3 mm. This means that most of the TW and BW is inspectable. Figure 30-5 presents a C-scan result with a visible crack, which was grown by fatigue from the notch shown in Figure 30-4.

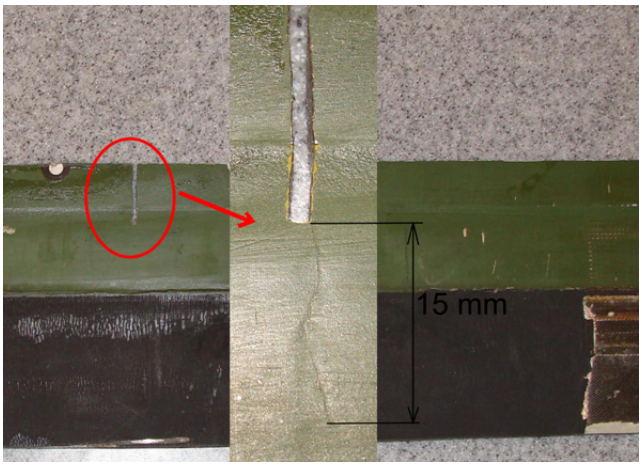


Figure 30-4: Crack in the Spar.

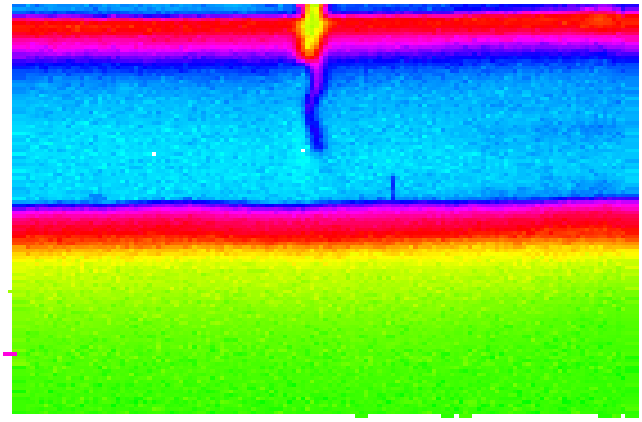


Figure 30-5: Crack in the Spar.

Another issue, which is important for eddy current inspection, is density. The density of eddy currents decreases with increasing depth of penetration. Such phenomena should be considered as the inspection is performed on deeper crack locations.

Because of the large inspection area, some applications should be used to increase inspection speed, while maintaining reliability. For that reason, automated data collection with the use of eddy currents as well as Magneto Optic Eddy Current Imager (MOI) were selected. Such inspections enable fast and reliable data collection and data storing. The MOI inspection is easy and fast because the use of visualization is based on the "Faraday effect" to polarized light beam. Figure 30-6 shows an example an MOI inspection.

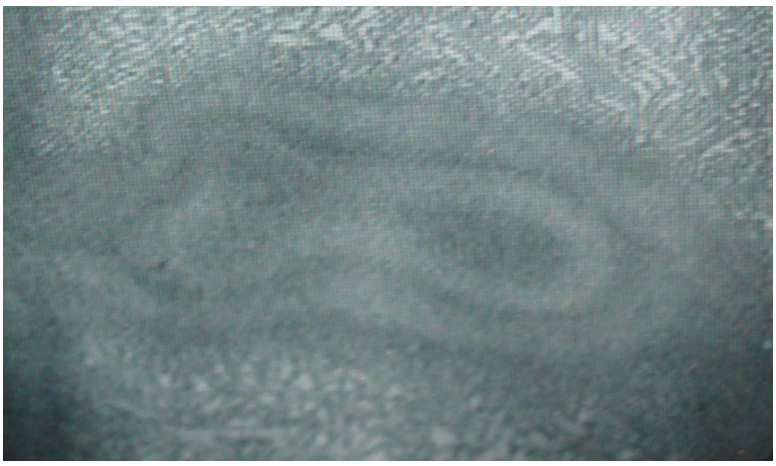


Figure 30-6: MOI Crack Visualization.

It is necessary to mention that a large area of the MRB leading edge is protected with a non-conductive layer, which makes crack inspection using conventional eddy current difficult. Moreover, the use of the ultrasonics in that area is not possible because of large signal attenuation caused by the rubber layer. For that application, some tests will be conducted using Remote Field Eddy Current, which enables deeper penetration, especially through the non-conductive layer.

For the further evaluation of the spar structure, ultrasonic and X-Ray tests were carried out. Ultrasonics is a relevant inspection technique, which enables detailed defect characterization. However, because of extreme sensitivity for some selected failure modes, strict conditions should be fulfilled, such as: signal to noise ratio, frequency selection, and coupling assurance. For the blade inspection, shear waves for crack detection were considered to be the appropriate technique. Other tests were made using X-Ray. The X-Ray technique enables inspection of difficult to access areas, and data can be stored and compared as images. Tests were made to assess crack detectability in the spar structure, especially under the leading edge protection layer.

Figure 30-7 presents data from X-Ray inspection made with the energy range 60 – 80 kV according to EN 584-1. On that figure, there is a visible crack going from the hole in the BW. Results were not as expected (especially on the leading edge). Cracks were not clearly visible and data interpretation strongly depended on the experience of the data analyzer. For that particular application, eddy currents and ultrasonic are more efficient. Another application is pitting corrosion detection. For that application, ultrasonic is efficient. Tests were made with appropriate specimens which had drilled holes with different sizes and depths.

Another important issue is the detection of disbonds leading to skin separation (and section separation) between the section to spar, and skin to honeycomb disbonds. Taking into the consideration that some of the damages are not allowed (or size is specifically limited), determination of detection possibility is required.

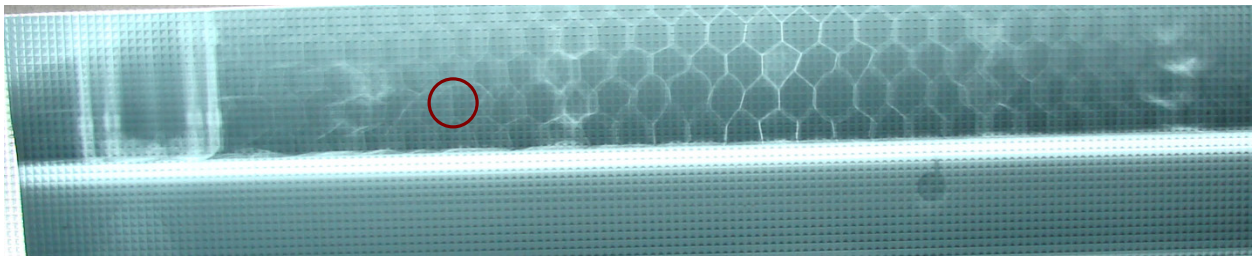


Figure 30-7: X-Ray Results.

For that reason, special specimens were designed and made from the blade elements. Figure 30-8 presents disbonds which were made for the different types of blades. For that specimen, shearography, Mechanical Impedance Analysis (MIA) and resonance testing were applied.

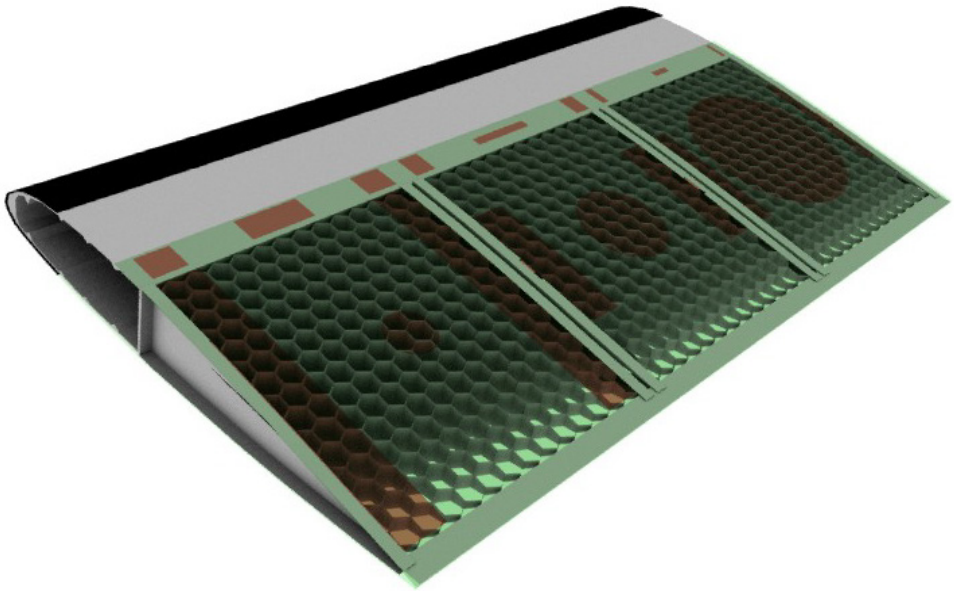


Figure 30-8: Specimen with Disbonds.

Figure 30-9 presents results of blade inspection with the use of MIA. For that damage, it is possible to detect skin to honeycomb disbonds and section separation both with the use of MIA and shearography. Low resolution results were obtained using resonance testing.

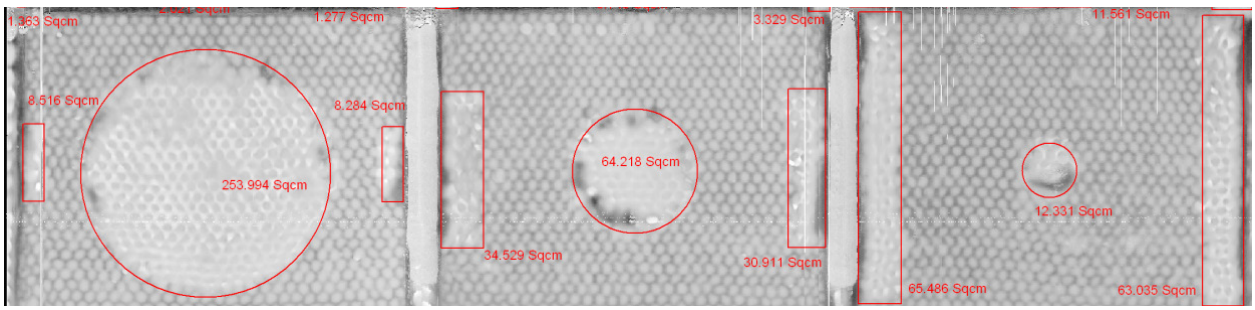


Figure 30-9: MIA Testing Results.

For most of the highlighted scenarios, several tests successfully detected and described the damage. Based on the results of this three year program, several service inspection bulletins have been elaborated and introduced to service life extension programs.

Figure 30-10 presents the approach used for in-service NDI inspection of the Mi-8 helicopter main rotor blades.

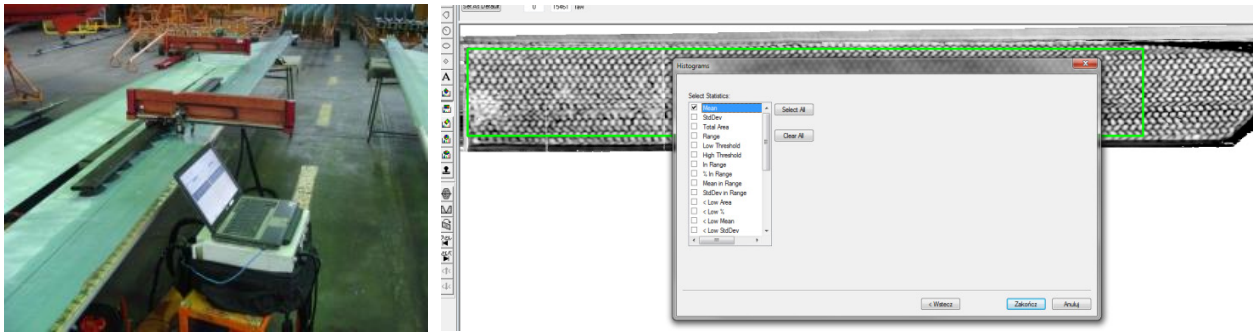


Figure 30-10: MRB In-Service Inspection.

30.2 CONCLUSIONS

Based on developed NDI bulletins, service life extension programs have been delivered on the selected main and tail blades for different types of helicopters, which have enabled further helicopter operation. Moreover all the NDI technologies elaborated on here are currently used as part of on condition based maintenance procedures. Such procedures are also part of airworthiness policy which is in accordance with planned implementation of European Military Airworthiness Regulation to Polish MOD.

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Chapter 31 – METALLIC HELICOPTER BLADES COMPOSITE REPAIRS STUDY CASE

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31.1 INTRODUCTION

The Polish Armed Forces are currently operating hundreds of the Mi family of helicopters. The helicopter metal fuselage is usually resistant to battle and the human factor conditions. Unfortunately, the metal rotor blades of Mi helicopters are sensitive to operating conditions. Each blade is made with a monolithic aluminium spar and mutually separated trailing sections, which are bonded to the spar. The sections are constructed of metal sandwich panels.

During aggressive military operating conditions, blades sections are often damaged by: debonding from the spar, fatigue cracks forming in sections of the skin, dents and perforations, as well as erosion. The manufacturer assumed that structurally damaged sections should be replaced, provided that repair technologies are applicable only to cosmetic damages. Unfortunately, there is a limit to the number of repairs, which prevents replacement of two neighboring sections due to the high temperature curing cycle experienced during the section replacement. Additionally, the old technology repairs are expensive and time-consuming. Therefore, it has been necessary to develop new repair technologies to enable the repair of rotor blade structural damages. This chapter focuses on discussing important issues in the field of repair technology.

31.2 CONSTRUCTION AND GENERAL CHARACTERISTICS OF ROTOR BLADE LOADS IN THE MI FAMILY OF HELICOPTERS

The general construction of metal rotor blades for various helicopter types in the Mi family is the same. The details differ only in the dimensions (Figure 31-1).

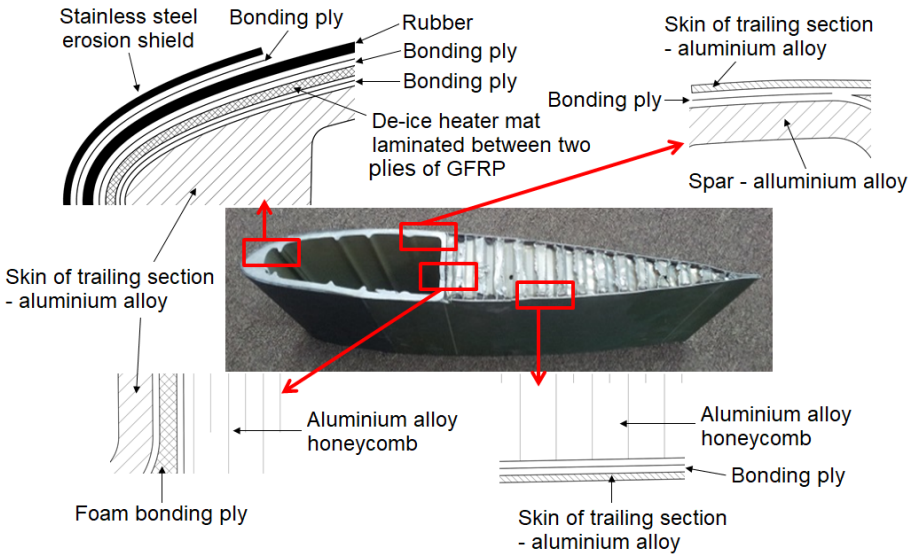


Figure 31-1: Cross-Section of the Mi-2's Metal Rotor Blade.

Rotor blades are elements that belong to Category 1 – primary structures because their integrity determines helicopter integrity and therefore crew safety [1]. The rotor blades are the most loaded aircraft elements, because they are operated in complex load conditions (Figure 31-2).

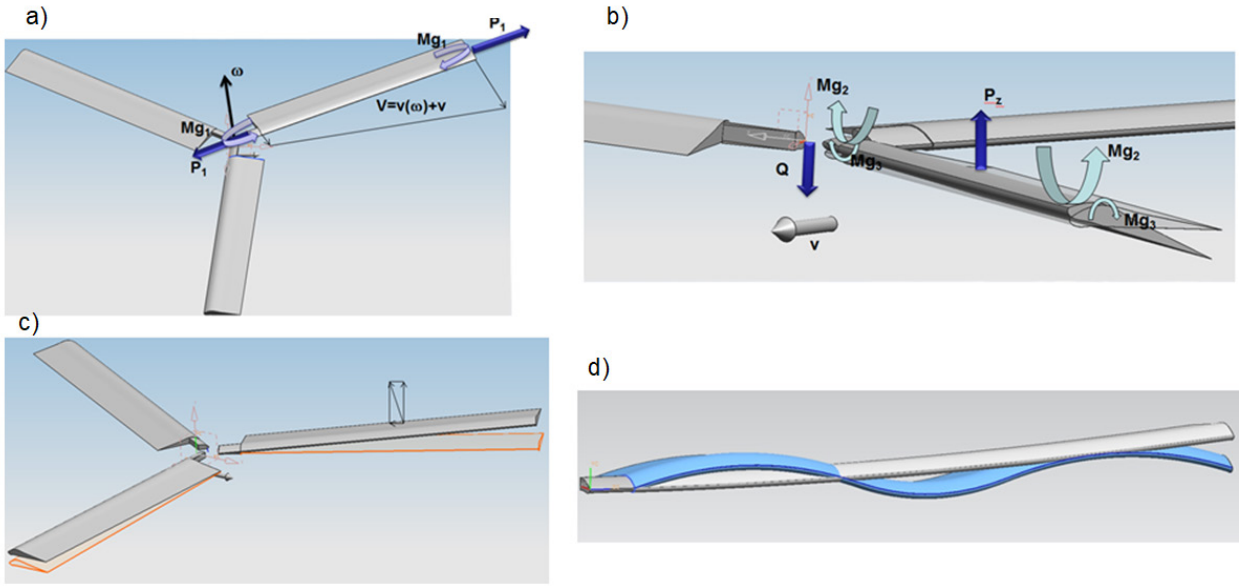


Figure 31-2: Scheme of Helicopter Rotor Blade Loads: (a) Tensile Force – Centrifugal P_1, Bending Momentum of the Blade in the Direction of Flow M_{g1}; (b) Carrier Force P_z; Aerodynamic Momentum M_{g3}; (c) Loads Related to the Change of Blade Position During the Flight; (d) Vibrations.

The blades are loaded during operation and during maintenance as well. It should be underlined that the sections are made in a sandwich structure, so they have a very low resistance to point loads, such as those that occur from impact. This situation can occur during take-off and landing, where elements are picked up from the ground or during maintenance, i.e., when tools are mistakenly dropped on the blade.

Rotating elements are exposed to erosion. It can be assumed that a helicopter is on the ground with running engines for about 20% of its service life. This time is related the start-up and periodic operations. The average contamination of solid particles in air at standstill is 40 mg/m^3 – this is the value of air density during the strongest sandstorms (for example in Afghanistan) experienced during desert take-off. The rest of the operating time with running engines takes place in the air, where the average contamination in air with solid particles is 0.3mg / m^3 [2]. The rotor blade safe life of the Mi-2 helicopter is 2000 hours. During service operations, the components on the leading edge and on the trailing sections can be thinned or even completely eroded through.

Each helicopter flight can experience variable atmospheric conditions. The variable atmospheric conditions may be result of changes in flight altitude or type of mission. In addition, helicopters in the Mi family are intended for inland and sea operations. The adhesive joints and other polymeric materials, rubber, sealants and others present on the blade are exposed to variable temperature and high humidity.

The aviation regulations for the certification of heavy helicopters [3] do not explicitly define the maximum operating temperature of rotor blade. Subsection CS29.1043 indicates the minimum temperature of lubricant tests, which is -55.5 °C. The data contained in [4] regarding the Mi-38 heavy helicopter, indicates that the helicopter meets the European requirements of JAR-29 in terms of operating conditions. According to the

authors of Ref. [4], the regulations require that the operating temperature should be within the range of 60 ÷ 50 °C. The aviation regulations regarding the certification of heavy helicopters [3] in subsection CS29.45 indicate that the maximum operating humidity is 80%. Unfortunately, in sea conditions, humidity reaches 100%, and in addition, the atmosphere contains a mist of saltwater, which is an electrolyte conducive to galvanic corrosion.

All the above factors cause the rotor blades to be subject to emergency failures before the end of service life resulting from the safe life. The repair technologies provided by the manufacturer, unfortunately, do not allow the restoration of the properties to pre-damage levels. Therefore, AFIT as an institution supporting the Polish Air Force took up the development of new modern technology in the repair rotor blades.

Figure 31-3 shows typical emergency damage to blades in the Mi family of helicopters.

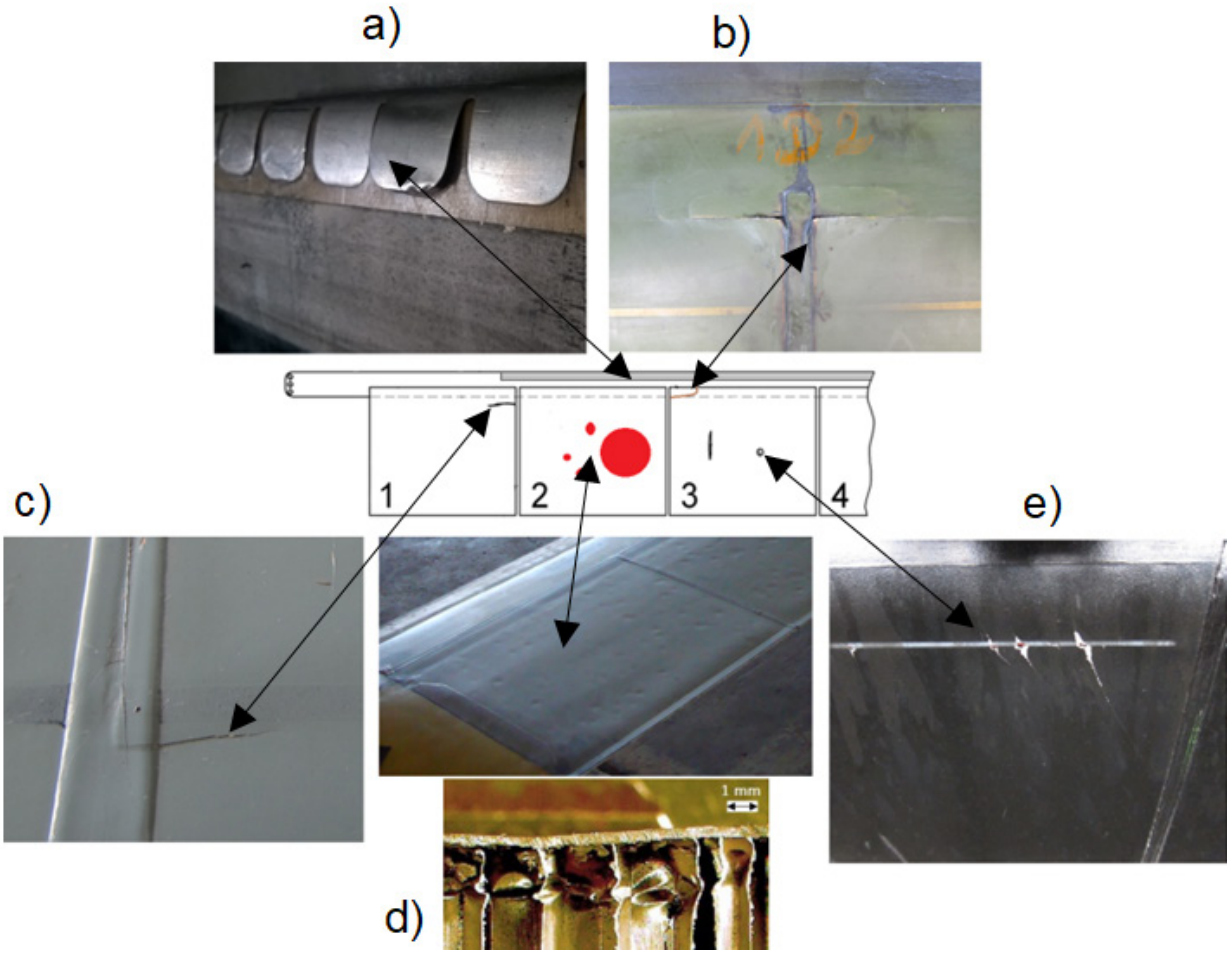


Figure 31-3: Damage Types in Mi Metal Rotor Blades: (a) Disbonding a Piece of Stainless Shield on the Leading Edge; (b) Disbonding Between Skin Trailing Section and Spar; (c) Cracks a Skin's Section; (d) Dent; (e) Puncture in a Skin's Sections.

In accordance with the applicable regulations in the Polish Air Force [5], it is unacceptable to operate rotor blade with punctured a skin's sections, cracks a skin's section and disbonding a piece of stainless shield on the leading edge. However, depending on the damage location and damage size it can be to use blades with the dent damage and disbonding between skin trailing section and spar.

31.3 LEADING EDGE REPAIR TECHNOLOGY

Strength tests were made, with the purpose of determining the causes of disbonding between the stainless shield and the rubber on the leading edge. During tests, the force of disbonding was measured. Based on the recorded force during test and failure type of samples, after tests it was assumed that this type of damage sustained in the rotor blade during operation may result from high stiffness of the rubber and high stiffness of the stainless shield. Beside the results mentioned above, the results of tests also indicated that the surface of shield was not prepared properly before bonding (Figure 31-4).

The repair consists in removing the original stainless shield and rubber in the area of the leading edge fittings and replacing the removed components with new ones with better properties (Figure 31-5).

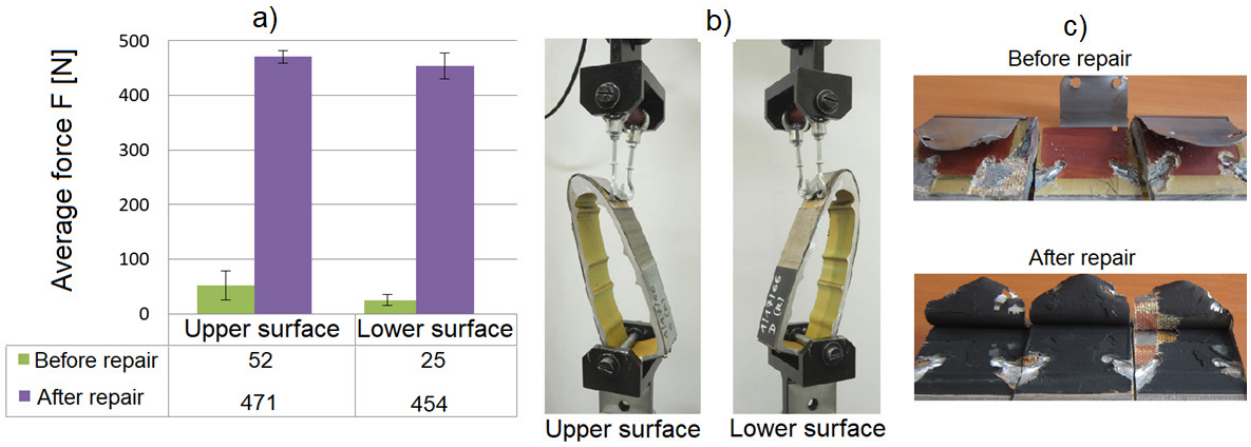


Figure 31-4: Strength Testing of the Bonding Join on the Leading Edge: a) Test Results Before and After Repair; b) Character of Loading; c) the Failure Type of Samples after Tests.

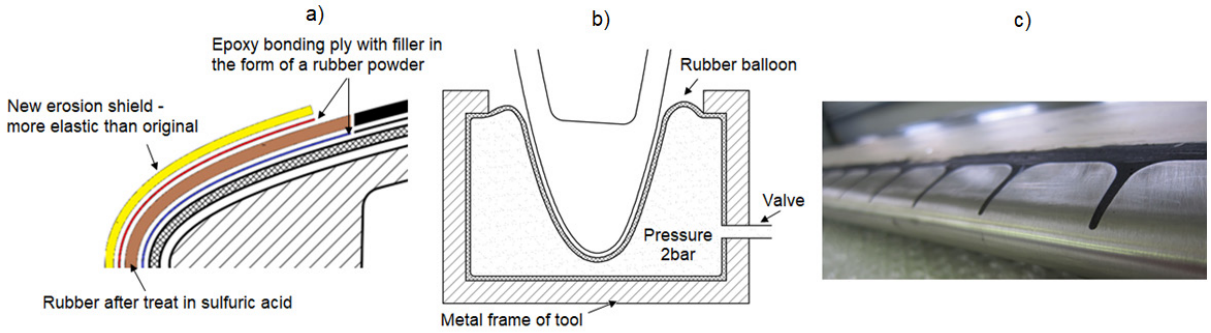


Figure 31-5: Repair of the Leading Edge: (a) Scheme of the Repair, (b) Scheme of Assembly Station, (c) the Leading Edge After Repair.

For repair, a rubber with lower stiffness was selected and additionally subjected to etching with sulfuric acid. Etching with sulfuric acid increases the adhesion properties of the rubber and also makes it more elastic. The metal hardware was replaced with a thinner stainless-steel sheet than the original one. A thinner metal sheet is used for a shield because it is more flexible, which allows it to be adapted to the variable geometry of the blade during operation. Before being bonded, the shield surface was prepared by chemical treatment and the use of primer hardened at 400 °C. High temperature causes adequate primer hardening and allows diffusion across the metal. The use of a suitable adhesive paste mix allows for a durable and flexible connection.

Although the repair seems relatively simple, the technological process is composed of many complicated stages. These include etching with sulfuric acid, preparation of the metal surface for bonding and bonding rubber for the heating package and shield for rubber.

31.4 THE REPAIR TECHNOLOGY OF THE TRAILING SECTION

The repair of the trailing sections concerns four types of damage shown in Figure 31-3:

- Disbonding between skin trailing section and spar;
- Cracks in a skin's section;
- Puncture in a skin's sections; and
- Dent.

The repair technology of disbonding between skin trailing section and spar provided by the manufacturer consists in re-bonding the skin to spar by injecting a liquid epoxy resin into the gap between skin and spar. This method is in fact not effective, because it is not possible to properly clean the surfaces between bonding. To properly prepare the surface would be to bend out the skin. Unfortunately it is unacceptable, because it would cause permanent plastic deformation of the skin at the bending point.

During the research at AFIT a method of repair was developed consisting in removing the debonding skin and reconstructing the structure from the equivalent material (Figure 31-6). This method enabled proper cleaning of the bonding surfaces, preparation of the surfaces for bonding and protection against corrosion.

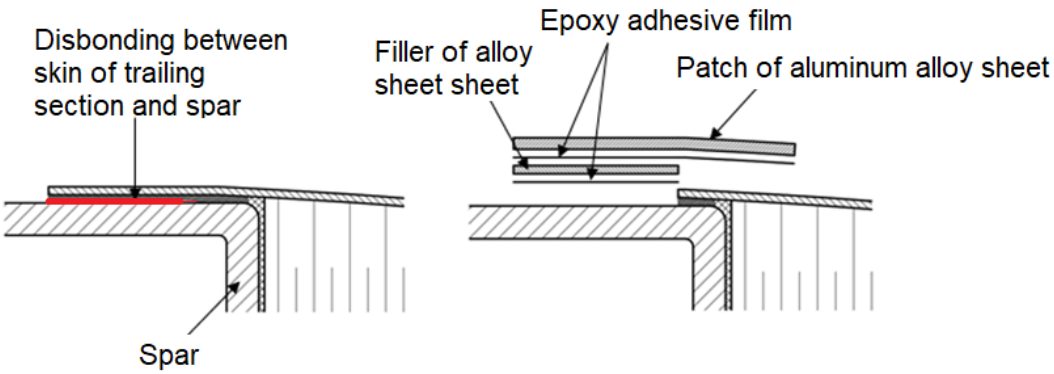


Figure 31-6: Repair Technology of Disbonding Between Skin Trailing Section and Spar.

The calculations and tests have shown that the patch carried the load no worse than the original skin [6].

The technology repair is the same for cracks in a skin's section as well as for punctures in a skin's sections. The repair consists in removing the paint coat in the area of bonding, drying the structure (Figure 31-10) and then bonding the patch (Figure 31-7).

The most difficult process from among those presented is the dent repair. The repair consists in removing damaged components of section and reconstruction it using new ones with equivalent properties (Figure 31-8).

Restoring a structure is a two-step process. First, the replacement core with the technological excess protruding above the surface of the skin is bonded. After hardening of the adhesive films, the core is mashed even with the skin surface. Then an aluminium alloy patch is bonded.

The section with repairs is presented in (Figure 31-9).

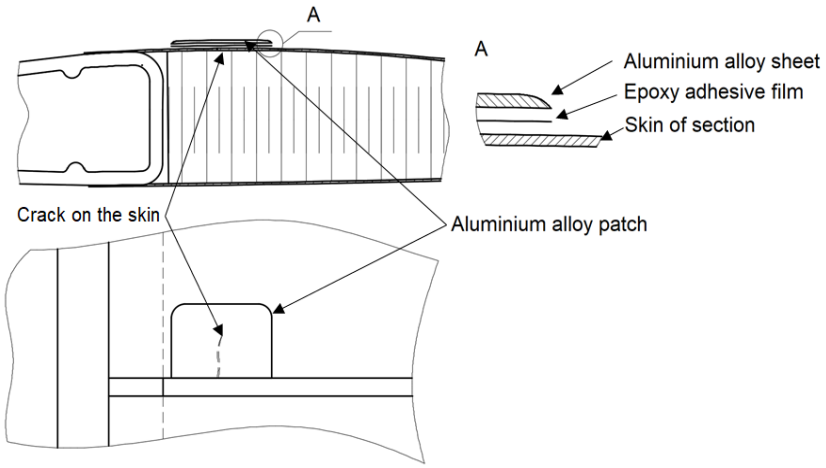


Figure 31-7: Repair Technology of Cracks in a Skin's Section and Puncture of a Skin's Sections.

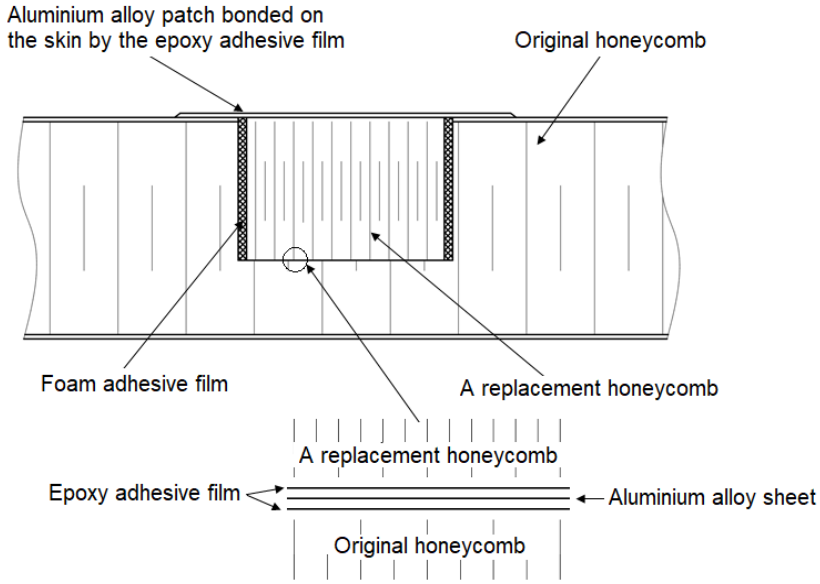


Figure 31-8: Repair Technology of Dented Trailing Section.

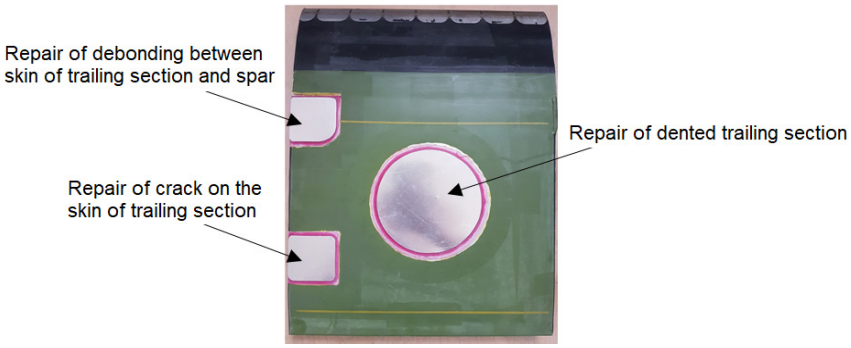


Figure 31-9: The Section with Repairs.

31.5 TECHNOLOGICAL DETAILS OF REPAIR

31.5.1 Drying Process

As a result of damage to the skin of the section and weather changing conditions, water condenses in the core cells. The water then penetrates into the porous binding line and thereby causes disbonding the skin from the core. Therefore, the structure should be dried before bonding. The draining equipment of the structure is shown in Figure 31-10.

The vacuum bag film should have a few small holes so that air circulates in the vacuum bag to allow the suction of moisture. Therefore, it is important that the process was carried out in a room where the air is clean and dry.

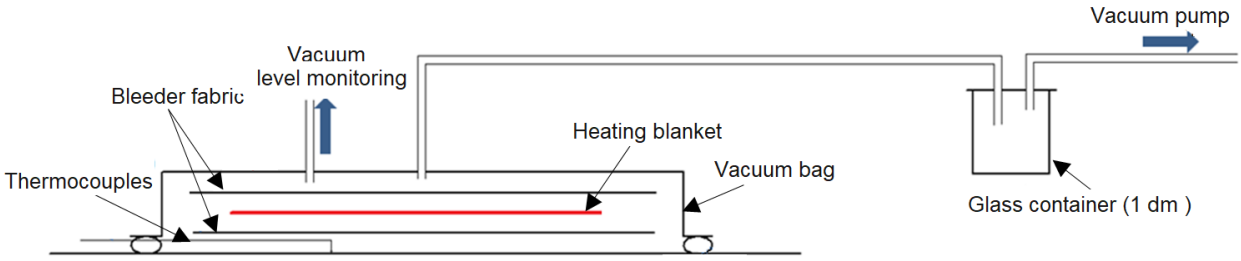


Figure 31-10: The Drying Equipment of the Structure.

The boiling point of the liquid depends on its pressure. The diagram in Figure 31-11 can be useful to set the temperature of the heating blanket depending on the value of the vacuum existing in the vacuum bag.

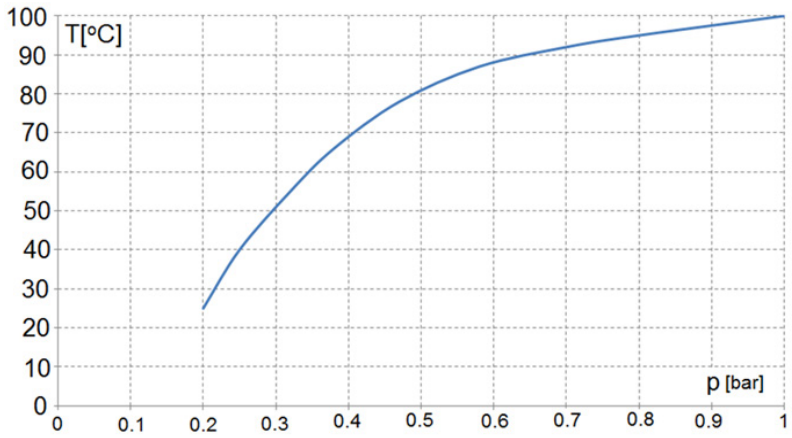


Figure 31-11: Water – Boiling Points at Vacuum Pressure.

31.5.2 Preparation of Metal Surfaces Before Bonding

A prerequisite for obtaining a durable bond between two metals is proper surface preparation. The traditional method of metal surface preparation is to degrease it and grind to increase the contact with resin. This method allows adhesive joints to be obtained. Unfortunately, this joint is not durable in a moisture environment. The moisture penetrates between the hardened resin and metal so causes separation these components (Figure 31-12a)).

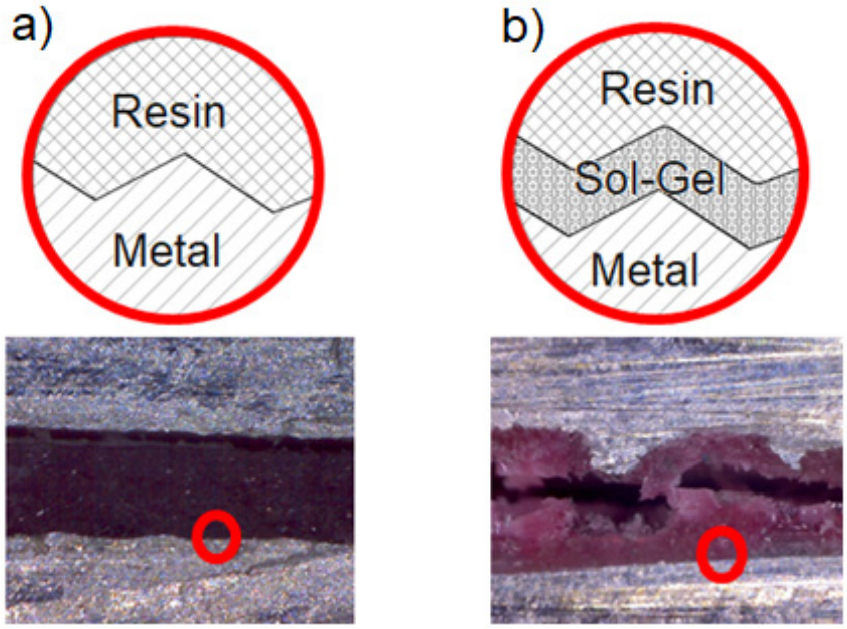


Figure 31-12: Surface Preparation for Bonding and Type of Failure During Wedge Test (ASTM D3762) of the Joint Subjected to 100% Humidity Exposure: a) Mechanical Treatment – Adhesive Damage, b) Mechanical Treatment and the Use of Sol-Gel Treatment – Cohesive Damage.

The chemical treatment of the surface before bonding with the use of Sol-Gel allows a chemical joint at the metal-resin interface. The chemical joint limits the destructive effect of water (Figure 31-12b).

31.5.3 The Cure Cycle

For the repairs presented here, a thermosetting epoxy adhesive film was used. The properties and porosity of composite and bonding line depend on the cure cycle. Therefore, a proper cure cycle was developed based on the research (Figure 31-13).

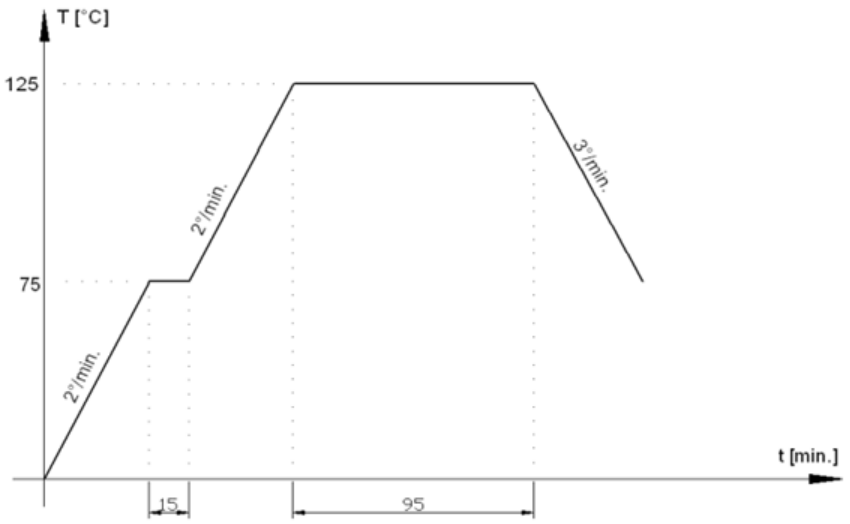


Figure 31-13: Example of the Cure Cycle Curve.

During composites production, stationary devices such as an oven or autoclave are used to realize the thermal cycle, but for repairs, a mobile device is used (Figure 31-14).

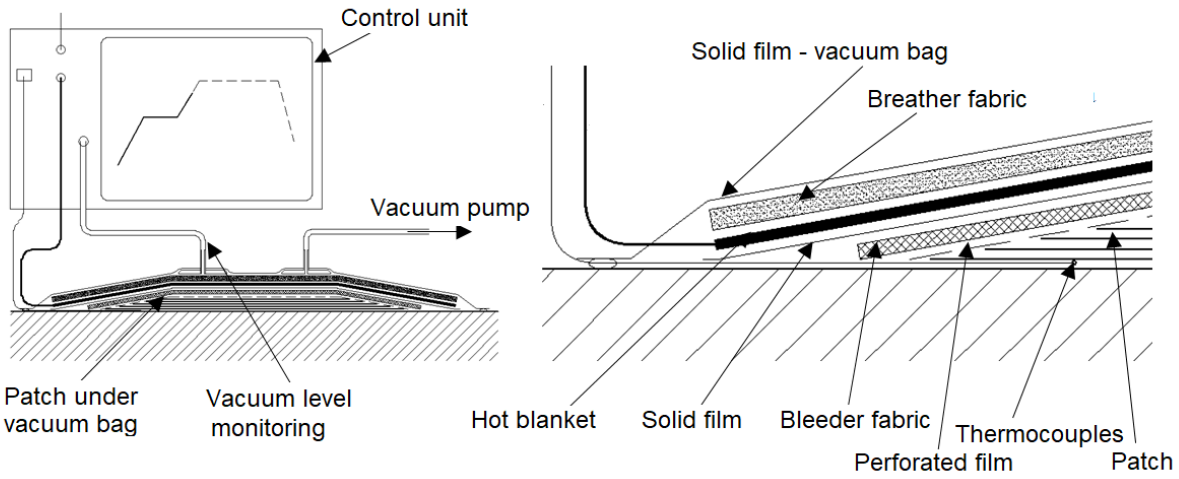


Figure 31-14: Schema of Device and Vacuum Bag During Cure Cycle of Patch.

31.6 SUMMARY

This paper presents a method for carrying out repairs on metal rotor blades in the Mi family of helicopters. Some of the repairs presented have already been put into operation in the Polish Air Force. Some repairs will be implemented in the near future. For all repair methods, necessary tests on the ground in accordance with the developed test program have been carried out. Preparations are underway for the last stage of the research – experimental flights.

Details of the research program, calculations and the manner of carrying out ground-based tests together with the results are described in Ref. [6].

The most important benefit of the new technologies developed is the financial saving. No less important is the way that the developed technology allows us to become less dependent on materials from the Russian market. Materials that can be used for the new technology are available primarily in the EU and the USA. In addition, repairs may be carried out by a trained staff of the Polish Air Force. Some repairs are possible both in the Military Works and in field bases during the implementation of military missions.

In summary, the developed new technologies significantly increase the possibility of maintaining a continuous airworthiness of the blades.

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14. Abstract

Due to high procurement costs associated with replacing aging aircraft fleets, NATO Nations are frequently required to operate their aircraft for longer than the original design life. The objective of this Task Group was to develop a technical report containing the best practices and lessons learned that exist in NATO nations for aircraft structural, propulsion, and mechanical systems. The documented best practices on continuing airworthiness of aging aircraft systems aim at capturing the unique aptitudes that have developed in each participating nation. With these documented practices, the different NATO nations will be able to adopt them as they see appropriate.

Aircraft structural systems have the most developed integrity program, with Propulsion systems well-defined and becoming matured. Mechanical systems are progressing, but many lessons from structural and propulsion integrity programs could be used to further mechanical systems integrity program efforts. Employing aircraft structures-like methods may improve the overall aircraft continued airworthiness, especially at or beyond the original service life limit.



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