TABLE OF CONTENTS

CHAPTER 1
AIRCRAFT MISSION REQUIREMENTS AND PRELIMINARY ENGINE DESIGN
Design Phases 1-1
Conceptual Design 1-1
Preliminary Design 1-1
Detailed Design 1-1
Aircraft Mission Requirements and Figures of Merit 1-5
Constraint Analysis 1-8
Mission Analysis 1-13
Engine Sizing and Cycle Selection 1-13
Cycle Modelling 1-26
Component Performance 1-28
Preliminary Component Design and Matching 1-30

CHAPTER 2
STATIC STRUCTURES
Introduction 2-1
Overall Engine Structure and Major Structural Components 2-1
Design Issues 2-6
Frames 2-7
Casings 2-18
Mounts 2-21
Containment 2-29
Structural Behavior and Analytical Methods 2-31
Maneuver Loads 2-33
Pressure Loads 2-33
Thermal Loads 2-33
Unbalanced Forces 2-34
Limit Conditions 2-35
Ultimate Loads 2-35
Fatigue 2-35
Damage Tolerance 2-36
Material Properties 2-36
Structural Testing 2-40
Summary 2-42

CHAPTER 3
FAN AND COMPRESSOR SYSTEMS
Introduction 3-1
Basic Aerodynamic principles, Components, and Definitions 3-1
Vector Diagrams 3-8
Blading 3-9
Basic Equations 3-10
Performance, Stall, Surge, and Stall Margin 3-11
Trends in Compressor and Fan Design 3-13
Design and Analysis Methods 3-15
Stall Margin Correlation 3-19
Efficiency Potential Correlation 3-20
Axisymmetric Analysis 3-23
Cascade Analysis and Blade Design 3-23
Fan and Prop Fan Configurations 3-28
Variable Geometry, Clearance, and Leakage 3-30
Multi-spool, Variable Geometry and Bleed 3-30
Leakage in Compressors 3-32

Clearance Control 3-33
Summary of Aerodynamic Design Considerations 3-33
Airfoil Physical and Functional Mechanical Design 3-33
Airfoil Mechanical Design Considerations 3-46
Airfoil Loading and Environment 3-46
Airfoil Failure Mechanisms 3-49
Ingestion 3-51
Airfoil Tradeoffs and Implications for Design 3-52
Rotor Physical and Functional Description 3-52
Rotor Design Considerations 3-56
Rotor Loading and Environment 3-56
Rotor Failure Mechanisms 3-60
Fatigue 3-60
Overspeed and Burst 3-60
Vibration 3-61
Rotor Tradeoffs and Implications for Design 3-61
Fan and Compressor Casings 3-62
Casing Design Considerations 3-63
Casing Failure Mechanisms 3-63
Buckling 3-63
Vibration 3-64
Other Failures 3-64
Casing Tradeoffs and Implications for Design 3-65
Fan and Compressor Variable Vane Actuation Systems 3-65
Actuation System Design Considerations 3-68
Actuation System Failure Mechanisms 3-68
Wear 3-68
Hammershock 3-68
Actuation System Tradeoffs and Implications for Design 3-68
Fan and Compressor System Design Considerations 3-68
Containment and Vibratory Weak Link Criteria 3-68
System Vibration and Balance 3-69
Stress Analysis of Rotor Disks 3-69
Numerical Example of Rotor Disk Stresses 3-70
Casing Containment Capability 3-73
Low Cycle Fatigue Life Analysis 3-74

CHAPTER 4
COMBUSTOR AND AUGMENTOR DESIGN
Combustor Aerodynamic Design 4-1
Introduction 4-1
Performance Requirements 4-1
Combustion Efficiency 4-1
Total Pressure Loss 4-1
Temperature Rise 4-1
Combustor Exit Pattern Factor 4-4
Combustor Exit Temperature Profile 4-4
Altitude Relight 4-4
Emmision Requirements 4-5
Critical Design Parameters 4-5
Space Rate and Aerodynamic Loading Parameters 4-5
Reference Velocity 4-6
Combustor Dome Height 4-6
Combustor Dome Velocity 4-6
Combustor Length to Dome Height Ratio 4-6
Combustor Passage Velocity 4-6

Number of Fuel Injectors 4-8
Pattern Factor Correlations 4-8
Combustor Flow Distribution 4-9
Fuel Injection System 4-9
Dilution Zone 4-9
Liner Coolong 4-11
Combustor Mechanical Design 4-11
Combustor Analysis 4-13
Fuel Nozzle Design 4-15
Ignition System 4-18

CHAPTER 5
TURBINES
Turbine Aerodynamic Design 5-1
Introduction 5-1
Principles of Operation 5-6
Cycle (or Thermodynamic) Point of View 5-6
Turbine Aero Point of View 5-8
Radial Equilibrium 5-10
Performance Considerations 5-10
Basic Performance Parameters 5-10
Stage Flow Coefficient 5-11
Reaction 5-13
The Turbine Map 5-15
Turbine Loss Sources 5-15
Design considerations 5-24
Cooling Considerations 5-24
Turbine Testing 5-28
Turbine Mechanical Design 5-30
High Pressure Turbine Function 5-30
Design Considerations and Goals 5-30
Turbine Operating Conditions 5-31
High Pressure Stator Component Parts 5-33
HPT Combustor Casing 5-33
Inner Nozzle Support and Inducer 5-33
HP Nozzle 5-34
HP Turbine Shroud 5-34
Static Seals 5-36
HP Rotor Component Parts 5-36
Compressor Discharge Seal (CDP) Disk 5-37
Forward Shaft 5-37
Forward Outer Seal (FOS) Disk and Retainer 5-37
HP Disk 5-38
Aft Retainer 5-38
Aft Shaft 5-38
HP Blade 5-39
The Mechanical Design Process 5-39
The Basic Design 5-41
Preliminary Design 5-41
Engineering Drawings 5-42
Working The Details 5-42
Component and Factor Testing 5-47
Final Certification Analysis 5-47
Low Pressure Turbine Design 5-50
Low Pressure Turbine Rotor Components 5-50
Blades 5-50

LPT Disks 5-50
Interstage Seals 5-50
Blade Retainers 5-52
Shafting 5-52
Low Pressure Turbine Stator Components 5-53
LPT Nozzles 5-53
Shrouds 5-53
Interstage Seals 5-53
Pressure Balance Seal 5-53

CHAPTER 6
ENGINE QUALIFICATION AND CERTIFICATION
Engine Qualification 6-1
Master Test Plan 6-1
Program Master Plan 6-1
Engine Spec and Program Master Plan 6-1
Qualification for Production Release 6-1
Engineering Program Plan 6-1
Design Reviews 6-7
Component Qualification 6-7
Corrosion Qualification 6-13
Altitude Qualification 6-14
Endurance Testing 6-14
Operability Evaluation 6-14

CHAPTER 7
BEARINGS AND SEALS
Introduction 7-1
Mainshaft Bearing Types 7-1
Fatigue Life Considerations 7-4
Ball Dynamic Analysis 7-8
Heat Generation and Cooling 7-10
Clearance Control 7-13
Cage Slip 7-14
Preloading of Roller Bearings 7-15
Roller Skewing and End Wear 7-15
Static Capacity/Secondary Damage 7-16
Elastohydrodynamic Lubrication 7-16
Materials 7-18
Dynamic Seal Types 7-20
Labrinth Seals 7-20
Clearance Control 7-20
Stick Slip Instability 7-22
Out of Round Instability 7-22
Campbell's Criterion 7-23
1/Rev Excitation 7-23
Aeroelastic Instability 7-23
Rotor-Stator Interaction 7-23
Acoustic Coupling 7-23
Damping 7-25
Configuration and Materials Consideration 7-25
Carbon Seal Design 7-25
Circumferential Seals 7-25
Face Seals 7-27
Pressure Balanced Split Ring Intershaft Seal 7-27
Split Ring Unbalanced Intershaft Seal 7-27
Materials 7-27

Sump Design 7-30
Oil Scavenging 7-30
Fire Safety 7-30
Coking 7-30
Interference Fitting of Bearing Rings 7-30
Bearing Support Stiffness 7-31
Thermal Out of Round 7-31
False Bearings 7-31
Titanium Fires 7-31

CHAPTER 8
SECONDARY SYSTEMS
Introduction 8-1
Air Systems 8-1
HPT Cooling System 8-1
LPT Cavity Purge System 8-5
Parasitic Leakage Purge System 8-5
Heating Systems 8-9
Anti-Icing/De-Icing 8-9
CDP Seal Bore Heating 8-9
TRF Hub Heating 8-9
Clearance Control Systems 8-9
Flange Cooling 8-10
LPT Case Cooling 8-10
HPC Bore Cooling 8-10
Seal Pressurization 8-10
Labyrinth Seals 8-14
Customer Bleed 8-16
Oil Systems 8-16
Lube Supply System 8-16
Lube Tank 8-17
Lube Pump 8-17
Lube Pipe Lines and Jets 8-17
Lube Scavenge System 8-19
Lube Scavenge Pump 8-19
Fuel Iol Cooler 8-19
Chip Detectors 8-19
Supm Vent System 8-21
Air-Oil Separators 8-21
Oil Consumption 8-23
Oil Filtration 8-23
Lube Heat Rejection 8-23
Fire Safety Analysis 8-23
Sump/Support Heat Transfer Analysis 8-23
Axial Bearing Thrust Control 8-26
HP Rotor Thrust 8-26
Interfaces 8-26

CHAPTER 8
INLETS AND EXHAUST SYSTEMS
Aerodynamic Aspects of Inlets and Exhaust Systems 9-1
Introduction 9-1
Inlet Design 9-1
Elements of the Subsonic Inlet 9-1
Inlet Performance 9-1
Low Speed Design Considerations 9-4

Exhaust Nozzles 9-6
Elements of the Exhaust System 9-6
Flowpath Design Considerations 9-7
Exhaust System Performance 9-8
Thrust Reverser 9-8
Elements of the Thrust Reverser System 9-8
Reverser Flowpath Considerations 9-8
Reverser Performance 9-9
Nacelle Design 9-9
Elements of the Nacelle 9-9
Nacelle Performance 9-9
Installed Performance 9-10
Acoustic Considerations 9-10
Mechanical Aspects of Inlets and Exhaust Systems 9-11
Mechanical Design of Inlet 9-11
Lightening Zones 9-16
Commercial High By-Pass Fan Nozzle/Reverser 9-19
Fan Reverser 9-19
Fixed Structure Component System 9-22
Bulkhead Sidewalls 9-22
Inner Cowl 9-22
Outer Support Assembly 9-22
Vane Deflectors 9-22
Translating Cowl 9-22
Fan Reverser Opening System 9-22
Blocker Doors 9-22
Fan Reverser Control Actuation System 9-22
Supply Manifold 9-25
Deploy Operation 9-25
Stow 9-25
Commercial High By-Pass Primary Exhaust System Design 9-26
Lightening strikes 9-26
Abnormal Condition Requirements 9-26
Structural Property Variables 9-27
Weight and Producibility 9-27
Military Afterburning Variable Nozzle System 9-27
Components and Operation 9-29

CHAPTER 10
INSTALLATION AND CONFIGURATION
Commercial Propulsion System Installation 10-1
Commercial Nacelle Systems 10-1
Inlet 10-4
Engine Buildup (EBU) Hardware 10-5
Exhaust System 10-10
Military Engine Installations 10-10
Engine Installation Design Considerations 10-10
Installation Considerations Affecting Engine Maintainability 10-10
Engine Envelope 10-16
Engine-Airframe Interfaces 10-16
Configuration 10-25
Design Philosophy 10-25
Design Approach 10-25
Technical Requirements 10-33
Design Practices 10-33
Design Reviews 10-34

Design Tools, Assembly Aids, and Customer Mockups 10-36
Engineering Design Tool 10-36
Assembly Aid 10-37
Mockup 10-37
Production Engine Assemblies 10-37

CHAPTER 11
CONTROLS ENGINEERING
Introduction 11-1
Applications 11-1
Control System Requirements 11-1
Control Philosophy 11-5
Controls Terminology 11-5
Control Strategy 11-5
Developing Requirements 11-5
Control System Design 11-8
Stability and response 11-9
Definitions and Nomenclature 11-9
Design Requirements 11-14
Design Tools and Methods 11-16
Basic Engine Control Functions 11-17
Core and Fan Speed Control 11-17
Acceleration and Deceleration Control 11-19
Variable Stator Vane control 11-21
Speed and CDP Min and Max Limiting 11-23
Commercial Controls Objectives 11-26
Power Management Control 11-26
Idle Speed Control and Scheduling 11-35
Variable Bleed Valves (VBV's) 11-37
Turbine Clearance Control and Rotor Active Clearance Control 11-39
Reverse Thrust Scheduling 11-44
Military Control Objectives 11-45
Fan Inlet Guide Vane Control 11-45
Turbine Temperature Control 11-45
Fan Operating Line Control 11-46
Augmentor Fuel Scheduling 11-50
Special Functions 11-54
Component Design 11-55
Hydromechanical Control 11-57
Main Engine Controls (MEC's) 11-59
Hydromechanical Units (HMU's) 11-62
Augmentor Fuel Control 11-62
Other Control Components 11-66
Pumps 11-66
Actuators 11-69
Valves 11-71
Sensors 11-74
Electronic Controls 11-78
History 11-78
Environmental Design Factors 11-81
Temperature 11-81
Vibration 11-81
Lightening 11-81
Electromagnetic Interference 11-82
Nuclear Radiation 11-82

Digital Controls 11-82
Definition 11-82
Comparison to Analog 11-87
Redundancy Management 11-91
Adjustment Capability 11-92
Maintainability Features 11-93
Aircraft Bus Interfaces 11-94
Throughput 11-94
Resolution 11-96
Sampling and Digital-to-Analog Conversion 11-97
Software 11-99
Real-Time Software 11-99
Development Process 11-99
Functional Allocation 11-100

CHAPTER 12
LIFE ANALYSIS
Qualification/Certification, Life Analysis 12-1
Commercial Life Analysis 12-1
Thermal Analysis 12-1
Stress Analysis 12-2
Flight Cycle 12-6
Materials Data 12-7
Military Approach 12-11
Life Analysis Summary 12-12

CHAPTER 13
PRODUCT SUPPORT
Product Support 13-1
Maintenance 13-3
Field Related Problems 13-5
Engine Aging 13-6
Condition Monitoring 13-8
End User Assessment 13-9