Practical Methods for Aircraft and Rotorcraft Flight Control Design: An Optimization-Based Approach

Mark B. Tischler
Tom Berger
Christina M. Ivler
Mohammadreza H. Mansur
US Army Aviation Development Directorate
Aviation and Missile Research, Development, and Engineering Center
Ames Research Center
Moffett Field, California

Kenny K. Cheung
Jonathan Y. Soong
Universities Space Research Association
Ames Research Center
Moffett Field, California

AIAA EDUCATION SERIES
Joseph A. Schetz, Editor-in-Chief
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

American Institute of Aeronautics and Astronautics, Inc.
# Table of Contents

List of Figures ................................................................. xi  
List of Tables ................................................................. xxxxi  
Nomenclature ................................................................. xxxv  
Acronyms ................................................................. xlvi  
Preface ................................................................. li

Chapter 1. Introduction: The Flight Control Problem and Our Approach ................................................................. 1  
1.1 Roles of Flight Control System and the Development Process ......................................................... 2  
1.2 Flight Control System Design Challenges ......................................................... 13  
1.3 The Role of Integrated/Automated Tools in the Flight Control Design and Development Process ......................................................... 20  
1.4 Reference Material on Flight Control Design Experience—Seven Key Do’s......................................................... 23  
1.5 Flight Control System Design Using Multi-Objective Parametric Optimization ......................................................... 26  
1.6 Why Is This a Good Approach? ......................................................... 30  
1.7 Software Tools for Flight Control Design Using Multi-Objective Parametric Optimization ......................................................... 32  
1.8 Payoffs for Flight Control Performance and Development Cost ......................................................... 35  
1.9 Overall Objectives and Case Studies of This Book ......................................................... 36

Chapter 2. Fundamentals of Control System Design Methodology Based on Multi-Objective Parametric Optimization ......................................................... 39  
2.1 Roadmap of Multi-Objective Parametric Optimization Design Methodology ......................................................... 39  
2.2 Typical Results Based on XV-15 Hover Case Study ......................................................... 47  
2.3 Typical Results Based on XV-15 Forward Flight Case Study ......................................................... 53  
2.4 Summary ......................................................... 57

Chapter 3. Overview of CONDUIT® Software ......................................................... 59  
3.1 The CONDUIT® Interface ......................................................... 59  
3.2 Overview of CONDUIT® Workflow ......................................................... 61  
3.3 Key Components of CONDUIT® Problem Setup ......................................................... 62  
3.4 Modes of Operation ......................................................... 70  
3.5 Integration with Other Tools ......................................................... 84  
3.6 Summary ......................................................... 86
Chapter 4. Description of XV-15 Design Case Studies
4.1 XV-15 Hover Case Study
4.2 XV-15 Forward Flight Case Study
4.3 Summary

Chapter 5. Quantitative Design Requirements for Flight Control
5.1 Importance and Sources of Design Requirements
5.2 Definition of Handling Qualities and the Cooper-Harper Handling-Qualities Rating Scale
5.3 Generic Control System Specifications
5.4 Rotorcraft Specifications
5.5 Fixed-Wing Specifications
5.6 Proprietary/User-Defined Specifications
5.7 Performance Metrics
5.8 Criteria Sets for XV-15 Hover and Forward Flight Case Studies
5.9 Summary

Chapter 6. Simulation Requirements for Flight Control Design
6.1 Modeling Fidelity Requirements
6.2 Use of a Simplified Block Diagram
6.3 Linear Bare-Airframe Models
6.4 Additional Block Diagram Component Models
6.5 Nonlinearities
6.6 Analysis Validation
6.7 Summary

Chapter 7. Conceptual and Preliminary Design of Flight Control Systems
7.1 Partial- vs. Full-Authority Implementation
7.2 Control Law Architectures
7.3 Choice of Design Model and Estimating the Effects of Uncertainty
7.4 Preliminary Design of Feedback Compensation
7.5 Nested Outer Loops
7.6 Final Thoughts on Conceptual and Preliminary Design of the Flight Control System

Chapter 8. Design Optimization
8.1 Need and Challenge of Numerical Optimization of Flight Control Design
8.2 Numerical Scores for the Specifications
8.3 Numerical Optimization of the Design
8.4 Guidelines for Flight Control Optimization
8.5 Design Optimization and Analysis for the XV-15 Inner-Loop Hover Case Study
# TABLE OF CONTENTS

8.6 Design Optimization and Analysis for the XV-15 Inner-Loop Forward Flight Case Study .................................................. 331
8.7 Summary ............................................................................. 351

Chapter 9. Sensitivity and Robustness Analyses ......................... 353
9.1 Sensitivity Analysis of the Design Solution ............................. 355
9.2 Sensitivity Analysis for the XV-15 Hover Case Study ................. 370
9.3 Sensitivity Analysis for the XV-15 Hover Case Study With Poor Theoretical Accuracy .................................................. 380
9.4 Sensitivity Analysis for the XV-15 Forward Flight Case Study ..... 384
9.5 Assessing Robustness to Modeling Uncertainty ....................... 387
9.6 Non-parametric Uncertainty Analysis for the XV-15 Hover Case Study ............................................................. 395
9.7 Parametric Uncertainty Analysis for the XV-15 Hover Case Study ............................................................................. 398
9.8 Multivariable Stability Margin Analysis for XV-15 Hover Case Study ......................................................................... 399
9.9 Summary ............................................................................. 402

Chapter 10. Design Trade-Offs .................................................... 405
10.1 Design Margin Optimization (DMO) .................................... 405
10.2 Nested-Loop Design Margin Optimization Strategy for the XV-15 Hover Case Study ................................................... 418
10.3 Design Margin Optimization for the XV-15 Forward Flight Case Study ............................................................. 451
10.4 Summary ............................................................................. 465

Chapter 11. Optimization and Flight-Test Evaluation of Hover/Low-Speed Control Laws for a Conventional Helicopter: Comparison of Nested vs. Simultaneous Multi-Loop Strategies ............. 467
11.1 Two Optimization Strategies: Nested-Loop and Simultaneous Multi-Loop ............................................................. 468
11.2 Nested-Loop Optimization Strategy ...................................... 469
11.3 Description of the Model-Following Flight Control System .... 471
11.4 Design Specifications .......................................................... 475
11.5 Design Parameters .............................................................. 478
11.6 Effect of Optimization Strategy on Problem Size ................. 479
11.7 Inner-Loop Design Margin Optimization for the Nested DMO Design ............................................................. 480
11.8 Outer-Loop Design Margin Optimization ............................... 481
11.9 Validation of Analysis Model Stability Margins and Predicted Performance ............................................................. 482
11.10 Characteristics of the Final Designs ..................................... 488
11.11 Qualitative and Quantitative Evaluations ............................. 490
11.12 Discussion and Summary .................................................... 498