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Editors

Modeling and Control for a Blended Wing Body Aircraft

A Case Study

Springer

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Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline (new theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies,...—new challenges). Much of this development work resides in industrial reports, feasibility study papers, and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

Aerospace has always been a fertile field for testing the techniques of advanced modern control. New control methods that have a multivariable framework and promise ways of computing controllers able to withstand quantifiable levels of uncertainty are always going to be of interest in applications where the models are large-scale, high-order, resonant, and conceptually complex. When the methods of H_∞ and robust control first appeared in the literature, the *Advances in Industrial Control* series saw several entries applying these techniques to airframe dynamics, including:

- *Robust Multivariable Flight Control* by Richard J. Adams, James M. Buffington, Andrew G. Sparks, and Siva S. Banda (ISBN 978-3-540-19906-9, 1994);
- H_∞ *Aerospace Control Design* by Richard A. Hyde (ISBN 978-3-540-19960-1, 1995); and
- *Robust Aeroservoelastic Stability Analysis* by Rick Lind and Marty Brenner (ISBN 978-1-85233-096-5, 1999).

The trend of new control methods finding application in the aerospace field continues and we can cite the recent *Advances in Industrial Control* monograph *Fault Detection and Fault-Tolerant Control Using Sliding Modes* by Halim Alwi, Christopher Edwards and Chee Pin Tan (ISBN 978-1-85729-649-8, 2011) as one example where the control scheme was tested on a professional civil aircraft flight simulator. And then there is the *Advanced Textbooks in Control and Signal Processing* volume: *Robust and Adaptive Control with Aerospace Applications* written

by two highly respected aerospace control engineers, Eugene Lavretsky and Kevin Wise (ISBN 978-1-4471-4395-6, 2013).

A development of the last few years is a spate of monographs in the series reporting control developments for autonomous mini-aircraft, commonly called “drones”. This is a development driven by the emergence of a new technological aerospace vehicle. With the theme of emerging technologies for the aerospace field, there have been several European research programs funding some projects to investigate the interface between such technologies and the capabilities of advanced control techniques. One example was the recent *Advances in Industrial Control* monograph: *Fault Diagnosis and Fault-Tolerant Control and Guidance for Aerospace Vehicles: From Theory to Application* by Ali Zolghadri, David Henry, Jérôme Cieslak, Denis Efimov and Philippe Goupil (ISBN 978-1-4471-5312-2, 2013).

The present monograph *Modeling and Control for a Blended Wing Body Aircraft: A Case Study* with Editors Martin Kozek and Alexander Schirrer is another example of the outcomes of recent European aerospace research. This time the objective was to investigate the “greening” of air travel through the use of a “blended wing body” (BWB) aircraft to reduce fuel consumption and CO₂ production and the capabilities of today’s advanced control methodologies. Thus, the monograph reports a modeling and design study with several advanced robust control methods applied to a conceptual BWB aircraft. The research project was titled “Active Control for Flexible 2020 Aircraft” and the craft itself was dubbed the “ACFA 2020”; an interesting artist’s impression of the futuristic-looking aircraft appears on page 12 of the monograph. The proposed aircraft was designed for civil applications with control design performance requirements of robust stabilization of the aircraft and structural design goals of aero-structural dynamic shaping, vibration and load alleviation. These design goals are also linked to passenger ride comfort.

The monograph’s content comprises eight chapters divided into an opening overview chapter, followed by Part I (three chapters) reporting the aircraft modeling, the technical and conceptual design and the models necessary for the control studies (namely, the application of model reduction techniques). Part II (three chapters) focuses on the control design starting with a review of control techniques, followed by feedback control and finishing with feed-forward control designs. The eighth chapter (Part III) concludes the monograph with a discussion of the results and presents ideas for future research directions.

Far from being purely academic research, the work reported in this monograph was guided by leading aerospace companies, including EADS Innovation Works, Airbus France, Hellenic Aerospace Industry (HAI) S.A., and the Israel Aerospace Industries (IAI). Interested readers will include the aerospace and control academic communities and engineers from a wide range of aerospace, modeling, and control disciplines.

Glasgow, Scotland, UK

Michael J. Grimble
Michael A. Johnson

Foreword

The need for improved performance, reduced operating costs, and reduced effect of aircraft emissions on climate change is driving aircraft designers to adopt lightweight, high-aspect ratio flexible wings. Reducing weight decreases aerodynamic drag, leading to less fuel consumption. High-aspect ratio wings minimize drag over lift, improving the aircraft performance on aspects such as long range and endurance. These modifications are being applied to modern commercial airplanes, mainly by using composite materials for both fuselage and wings. On the other hand, lightweight, high-altitude vehicles with large wing span exhibit high flexibility and significant deformation in flight increasing the interaction between the rigid body and structural dynamics modes.

The Active Control of Flexible 2020 Aircraft program (ACFA 2020) concentrated on reductions in fuel consumption, CO₂ and NO_x emissions reduction and reduction in external noise by 50 %. A blended wing body (BWB) aircraft configuration was selected as an innovative approach to future commercial aircraft. The ACFA 2020 project embraced the two challenges (emissions and noise), and the following main deliverables were formulated:

- Design of multi-objective active multi-input/multi-output (MIMO) control concepts for BWB-type aircraft.
- Predesign of an ultra-efficient ACFA 2020 aircraft configuration.

This book describes the modeling and design of the BWB aircraft, the application of several MIMO flight control techniques for rigid body and aeroelastic control of the BWB aircraft, and validation of the model combined with the flight control techniques.

This book is perfectly timed to provide insight to researchers and engineers working on future aircraft systems. I had the pleasure of following the ACFA 2020 progress during the program. It is exciting to see this manuscript documenting ACFA 2020 come to fruition.

Minnesota, USA, July 2014

Gary Balas
Distinguished McKnight University Professor
Aerospace Engineering and Mechanics
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Preface

This book is based on the outcome of the European Commission (EC)-funded research project “Active Control of a Flexible 2020 Aircraft” (ACFA 2020), which was conducted from 2008 to 2011. It succeeded the EC-funded research projects “Very Efficient Large Aircraft” (VELA) and “New Aircraft Concepts Research” (NACRE), which investigated concepts for a large blended wing body (BWB) commercial aircraft. The ACFA 2020 project worked out multi-objective control concepts as well as an ultra-efficient BWB predesign aircraft model for 450 passengers.

This book collects several major results from the ACFA 2020 project covering key developments in structural and dynamic modeling as well as multi-variable, multi-objective control design methods. The scope of the book covers the conceptual design as well as the modeling process to obtain a numerical simulation model and model reduction methods to obtain the basis for controller design. The second part is dedicated to control design, covering various advanced feedback and feed-forward design methods to address the multitude of arising control goals: stabilization, load alleviation, flight dynamics, and comfort. The last part comprises validation results of the proposed control concepts, especially the achieved loads alleviation and comfort aspects, and a discussion of further work and open issues.

The purpose of this book is two-fold: (i) promote the results obtained in the research project, illustrated at the considered BWB aircraft pre-design model and (ii) present the methods for modeling, control design, and optimization that have been developed. We believe that this book is a valuable source of information to both scientists and engineers active in the aerospace and control communities. It contains specific information about the problems and solutions found in the pre-design of a BWB concept and also demonstrates advanced control design methods on a complex application example.

The ACFA 2020 project answered several fundamental questions, such as the general load alleviation potential, but it was out of scope to produce a complete BWB control architecture or to conduct in-depth optimization of actuators. Therefore, several open issues remained and are addressed in the discussion and outlook.

We are grateful for the dedication, enthusiasm, and continuing support of the ACFA 2020 consortium and the involved individual work groups. Rudolf Maier and Andreas Wildschek from Airbus Group Innovations (formerly EADS Innovation Works) have initiated and led the research project in a cooperative and stimulating way. The members of the project's Scientific Advisory Group contributed invaluable inputs during the project's progress: Gary Balas (University of Minnesota, USA), Dagfinn Gangsaas (Aerospace Control Dynamics LLC, USA), Mark Lowenberg (University of Bristol, UK), and Ilkay Yavrucuk (Middle East Technical University, Turkey). We thank our Scientific Officer at the European Commission, Pablo Perez-Illana, for his understanding of a research project's needs and support during the project. Finally, our personal thanks go to Springer Verlag, where Oliver Jackson and Charlotte Cross proved to be our reliable signposts for guiding us through the long process of publication.

The results presented in this book have been developed within the ACFA 2020 research project. This project has been financially supported by the European Union Framework Programme 7 under the FP7 project number 213321. Many thanks also go to the NACRE consortium, especially to ONERA, DLR, and the NACRE-task 2.2 team, for providing aerodynamic and structure data of a large BWB aircraft configuration which strongly supported the development of methods and tools early in the ACFA 2020 project.

Vienna, July 2014

Martin Kozek
Alexander Schirrer

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Acronyms

BC	Business Class
BFGS	Broyden–Fletcher–Goldfarb–Shanno
BWB	Blended Wing Body
CACSD	Computer-Aided Control Systems Design
CAS	Control Augmentation System
CFD	Computational Fluid Dynamics
CFRP	Carbon-Fiber-Reinforced Polymer
CG	Center of Gravity
CWB	Carry-through Wing Box
DC gain	Static Gain
DLM	Doublet Lattice Aerodynamic Model
DR mode	Dutch Roll Mode
EC	European Commission
EMA	Electro-Mechanical Actuator
FBC	Feedback Control
FCS	Flight Control System
FE	Finite Element
FEM	Finite Element Method
FFCC	Feed-Forward Command Control
FFDC	Feed-Forward Disturbance Control
FIR	Finite-Impulse Response
GAF	Generalized Aerodynamic Forces
GLAS	Gust Load Alleviation System
HIFOO	$\mathcal{H}_\infty$ Fixed-Order Optimization
I/O	Input/Output
ICAO	International Civil Aviation Organization
L/D-ratio	Lift/Drag-ratio
LAS	Load Alleviation System
LFR	Linear Fractional Representation
LFT	Linear Fractional Transformation

LMI	Linear Matrix Inequality
LP	Linear Programing
LPV	Linear Parameter-Varying
LQ	Linear-Quadratic
LQG	Linear-Quadratic Gaussian
LTH	Luftfahrttechnisches Handbuch (engl. Aviation Technology Handbook)
LTI	Linear Time-Invariant
MAC	Mean Aerodynamic Chord
MDO	Multidisciplinary Design Optimization
MIMO	Multi-Input Multi-Output
MISO	Multi-Input Single-Output
OWE	Operating Empty Weight
PAX	Passengers
PM	Phugoid Mode
QP	Quadratic Programming
RANS	Reynolds-Averaged Navier–Stokes
RB	Rigid-Body
RBF	Radial Basis Functions
ROM	Reduced-Order Model
RP	Robust Performance
RS	Robust Stability
SAS	Stability Augmentation System
SISO	Single-Input Single-Output
SPA	Singular Perturbation Approximation
SPM	Short-Period Mode
ST	State Truncation
T/W-ratio	Thrust/Weight-ratio
YC	Economy Class