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Dipankar Deb · Jason Burkholder ·
Gang Tao

Adaptive Compensation of Nonlinear Actuators for Flight Control Applications

Springer

Dipankar Deb
Institute of Infrastructure,
Technology, Research and Management
Ahmedabad, Gujarat, India

Jason Burkholder
Barron Associates
Charlottesville, VA, USA

Gang Tao
Electrical Engineering
University of Virginia
Charlottesville, VA, USA

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Preface

Actuation is an indispensable aspect of flow control. New actuation devices can potentially lead to the rapid deployment of advanced control system applications. However, there is a need for appropriate compensation of nonlinearities inherent in such actuators. One such type of actuating device is the synthetic jet actuators which have seen active interest in the last couple of decades for next-generation flight control. In this context, many leading research organizations like the NASA Langley Research Center have invented several serial high-performance, piezo-electric, and hybrid synthetic jet actuators to provide active flow control for wing-borne vehicles in subsonic, transonic, and supersonic flow. Efficient flow control results in reduced vehicle drag and the prevention of events that can lead to catastrophic loss. Understanding the correlation between the actuator attributes and resulting flow field, ascertaining the effect of interactions of synthetic jet actuators with the turbulent flow, and determining the correlation of the actuator attributes with surface pressure distribution for control law development are all important aspects in this work.

The traditional objectives of an aircraft design mandate an adequate aerodynamic performance for the entire flight envelope. However, for military aircraft, with unconventional design requirements, the desirables are much more diverse. With the advancement in stealth aircraft, the need to have a low level of radar observability creates an environment where the importance of vehicle geometry and the need to optimize it precedes aerodynamic ruggedness.

Synthetic jet actuators produce a jet flow using the surrounding air rather than relying on a secondary fluid. Synthetic jets exhibit a highly nonlinear relationship between their different parameters. Synthetic jets are currently being investigated for applications such as virtual shaping of jet engine intakes and subsonic projectiles. The core of this approach is establishing a feedback loop between new computational models, lab tests, and field experiments in order to mature the actuation system design in a time-efficient and cost-effective and ready-implementable manner. A model-based environment is needed for the advancement of design and performance validation of synthetic jet actuators. However, formulating a comprehensive, wind tunnel-validated synthetic jet model is technically challenging and expensive.

Given the varied and growing list of synthetic jet applications, adaptive control can cancel the actuator nonlinearities to achieve performance objectives without requiring comprehensive models. Synthetic jets are useful for aerodynamic and flight control.

Adaptive feedback control techniques for actuator nonlinearity compensation have been studied for the last several decades to achieve desired control objectives in numerous critical applications. However, the parametrized actuator nonlinearity model structure is static, and only the parameters vary. An advantage is that the adaptive inverse compensator can be built upon the nominal guidance and control system without the need for a complete controller redesign. Many actuator models, though, have a state-dependent model characteristic as has been seen in synthetic jets. Adaptive control theorists attempt to utilize constrained state-dependent switching algorithms to achieve control objectives when the actuator model is highly uncertain, and a single continuous model is not feasible. However, when the actuator model is dependent on the angle of attack (a state of the aircraft dynamics), switching would not achieve a corresponding mathematical model of the actual actuator physical characteristics. Such state-dependent actuator nonlinearity models are present in several control applications such as electro-hydraulic actuator systems, where in addition to the electrical input signal, the actuator model is also dependent on the sensed position of the valve control element.

This book presents design conditions, control designs, stability analysis, and performance evaluations of adaptive schemes for linear and nonlinear aircraft dynamic systems with simulation results to illustrate the effectiveness. Chapter 1 introduces linear and nonlinear actuators, and specifically, a type of nonlinear actuators called synthetic jet actuators which are useful in flight control and active cooling of microelectronics. Chapter 2 presents the physical characteristics of a synthetic jet actuator, followed by the mathematical model of the actuator and adaptive compensation of the uncertainties. We also present the control of next-generation aircraft with synthetic jet actuation-based virtual aerodynamic wing shaping. The adaptive inverse formulation helps cancel the jet nonlinearities. A robust state feedback law controls the aircraft dynamics with modeling errors and parametric uncertainties. Parameter projection-based update laws ensure a stable system with desired signal boundedness.

Chapter 3 extends the adaptive scheme to a nonlinear aircraft. Adaptive inversion is employed to compensate for the jet nonlinearities at low angles of attack. A nonlinear state feedback law controls the aircraft dynamics with other states providing the intermediate control laws, apart from the lift forces. Chapter 4 presents an adaptive compensation scheme at high angles of attack. We deploy a linearly parametrized function to approximate a nonlinearly parametrized actuator model. Adaptive inverse arrays are robust in compensating the uncertainties both in the true jet nonlinearity model and also the linearly approximated model. A nonlinear state feedback law controls the aircraft dynamics.

Chapter 5 develops a unified adaptation scheme to control state-dependent actuator nonlinearities in a class of nonlinear systems using two approximators. A linearly parametrized function approximates the nonlinearly parametrized actuator model. Adaptive compensation takes place through a second approximator that is used as a feedforward function. Chapter 6 develops an improved high-order parametrization scheme using twin neural networks. One of the neural networks represents the signal-dependent actuator nonlinearities, and the other represents the adaptive compensator. Higher order parametrization improves the accuracy of the approximation presented as evidenced by the application to a nonlinear pitch plane dynamic model. Chapter 7 extends this adaptive control technology for control of state-dependent actuator nonlinearities to a six degrees of freedom aircraft dynamical system for a wide range of angles of attack using two Taylor series approximators.

The authors would like to thank Dr. Douglas Smith who is a Former Assistant Professor, University of Wyoming, and presently with the Office of Naval Research, Govt. of the USA. Dr. Smith's wind tunnel tests were instrumental in the development of synthetic jet actuator models at low and high angles of attack. Funding received from US Air Force for a Project titled, "Robust Adaptive Control of Innovative Actuation Devices for Aircraft," 06-HYP-06-0049, and another under a NASA STTR grant titled, "Active Flow Control with Adaptive Design Techniques for Improved Aircraft Safety," proposal number: 05 T2.02-9831, are duly acknowledged.

Ahmedabad, Gujarat, India — Dipankar Deb
Charlottesville, Virginia, USA — Jason Burkholder
Charlottesville, Virginia, USA — Gang Tao

The original version of the book was revised: Affiliation of the author Dipankar Deb has now been corrected. The correction to the book is available at https://doi.org/10.1007/978-981-16-4161-9_8

Contents

Acronyms and Symbols

AIC	Adaptive Inverse Compensation
AoA	Angles of Attack
BANTAM	Barron Associates Nonlinear Tailless Aircraft Model
IMU	Inertial Measurement Unit
LES	Large Eddy Simulations
NN	Neural Network
R_n	Reynolds Number
SJ	Synthetic Jet
SJA	Synthetic Jet Actuator
SJAA	Synthetic Jet Actuator Arrays

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