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Adaptive Compensation of Nonlinear Actuators for Flight Control Applications

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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.

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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

1	Introduction	1
2	Synthetic Jet Actuators and Arrays: Modeling and Control	11
3	Adaptive Compensation at Low Angles of Attack: Nonlinear Aircraft Model	43
4	Adaptive Compensation at High Angles of Attack	65
5	Signal-Dependent Uncertainty Compensation: A General Framework	83
6	NN-Based High-Order Adaptive Compensation Framework for Signal Dependencies	99
7	Adaptive Synthetic Jet Actuation for Aircraft Control	113
	Correction to: Adaptive Compensation of Nonlinear Actuators for Flight Control Applications	C1

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

List of Figures

Fig. 1.1	A typical Synthetic Jet Actuator for active control action.	4
Fig. 1.2	A typical design with SJA in the trailing edge for virtual airfoil shaping.	5
Fig. 2.1	Angle of attack (Low and High).	12
Fig. 2.2	SJA: a suction and b exhaust stage of operation	12
Fig. 2.3	Actuator cavity (blue) and orifice (red) dimensions (in inches).	13
Fig. 2.4	Illustration of modified streamlines with virtual shaping.	14
Fig. 2.5	Illustration of flow streamlines at high AoA.	15
Fig. 2.6	Virtual airfoil deflections with actuation voltage.	17
Fig. 2.7	Adaptive inverse control action with state feedback	19
Fig. 2.8	Plant and reference states	23
Fig. 2.9	State tracking errors	24
Fig. 2.10	a Input signal $v(t)$, b desired control signal $u_d(t)$, c control error $u_a(t) - u_d(t)$, d parameter error $\theta_a(t) - \theta_a^*$	24
Fig. 2.11	Reference and plant states.	25
Fig. 2.12	State tracking errors (under saturation)	26
Fig. 2.13	a Input $v(t)$, b control law $u_a(t)$, c modified control $\bar{u}_d(t) - (\theta_b - \delta)$, and d parameter error $\theta_a - \theta_a^*$	26
Fig. 2.14	Adaptive compensation for SJ arrays	28
Fig. 2.15	State feedback inverse control system.	29
Fig. 2.16	Aircraft model with jet nonlinearities in presence of gain uncertainties and disturbances.	32
Fig. 2.17	BANTAM airfoil with six SJAA's (measurements in feet)	35
Fig. 2.18	Tracking errors $e_i(t)$	35
Fig. 2.19	Parameter errors $\hat{\theta}_{1i}(t)$	36
Fig. 2.20	Parameter errors $\hat{\theta}_{2i}(t)$	37
Fig. 2.21	Input signals for the six arrays	38
Fig. 2.22	Control errors for the six arrays	39
Fig. 3.1	Adaptive actuator compensation scheme.	46

Fig. 3.2	Definition of aircraft body axis states	47
Fig. 3.3	Tracking errors for nonadaptive nonlinearity inverse controller.	57
Fig. 3.4	Tracking errors for adaptive nonlinearity inverse controller	57
Fig. 3.5	True and estimated parameters for Middle flap arrays.	58
Fig. 3.6	True and estimated parameters for Outer flap arrays.	58
Fig. 3.7	True and estimated parameters for Spoiler arrays	59
Fig. 3.8	Voltage signals for the mid-flap arrays	59
Fig. 3.9	Voltage signals for the outer-flap arrays	60
Fig. 3.10	Voltage signals for the spoiler arrays	60
Fig. 3.11	Tracking errors for adaptive nonlinearity inverse controller in the presence of measurement error	61
Fig. 3.12	Body axis tracking errors in the presence of measurement error	62
Fig. 3.13	Middle arrays (true and estimated parameters) with measurement error	62
Fig. 3.14	Outer arrays (true and estimated parameters) with measurement error	63
Fig. 3.15	Spoiler arrays (true and estimated parameters) with measurement error	63
Fig. 4.1	SJA integrated tailless aircraft model at the leading edge in the wind tunnel.	67
Fig. 4.2	Wing model with SJAs along the leading edge: a top view, b side view.	68
Fig. 4.3	Variations of lift coefficient with angle of attack	69
Fig. 4.4	Variations of pitch moment coefficient with angle of attack	70
Fig. 4.5	Variations of lift coefficient for baseline uncontrolled case and the controlled cases with in-board subsets of actuators activated	70
Fig. 4.6	Variations of lift coefficient for baseline uncontrolled case and the controlled cases with out-board subsets of actuators activated	71
Fig. 4.7	Variations of lift coefficient versus actuator voltage magnitude: a different values of θ_1^{h*} , and fixed $\theta_2^{h*}, \theta_3^{h*}$, b different values of θ_3^{h*} , and fixed $\theta_1^{h*}, \theta_2^{h*}$	74
Fig. 4.8	Approximate coefficient errors against actuator voltage: a $\Delta C_L(t)$ versus $v(t)$, b $\Delta C_M(t)$ versus $v(t)$	75
Fig. 4.9	Closed-loop inverse compensation system for pitch moment	77
Fig. 5.1	Twin approximator-based adaptive compensation system	87
Fig. 5.2	Tracking errors: without SJs and without inverse (blue); with SJs and fixed inverse (green); and with jets and adaptive inverse (red)	96
Fig. 6.1	AIC scheme with twin NNs	104

List of Tables

Table 2.1	Physical Attributes of BANTAM	34
Table 3.1	Controller gains and Product inertias	56
Table 5.1	Twin Approximator-based Controller Parameters	96