Preface

Gas turbine engines – in particular, turbofan engines ubiquitously installed in commercial aircraft – must be operated by means of feedback control. In a broad sense, the objective of the control system is to achieve good thrust response qualities while maintaining critical engine outputs within safety limits. The design of controllers capable of delivering this objective represents a challenging problem, even when linear models with known parameters are considered for analysis. The fact that gas turbine engine dynamics are nonlinear and subject to uncertain parameter variations adds many layers of complexity to the problem.

Propulsion control systems installed in operating commercial aircraft, however, are ultimately based on classical, SISO linear compensation loops. Features have been added incrementally over the course of their development to address the exigencies of faster and more powerful, yet more reliable engine installations. Parameter variability from measurable sources – such as altitude and Mach number – has traditionally been accounted for by introducing gain scheduling, while engine safety limits have been addressed by override schemes. Both features still retain classical feedback compensation at their core.

Standard engine control systems have been in use for decades, without major conceptual changes. Concurrently, many new control theories – many of them with demonstrated industrial applications – have been developed. Much control systems research is devoted to the recurrent themes of parametric uncertainty, nonlinearity, and constraints in system variables. These themes are characteristic of the most challenging control problems and certainly arise in gas turbine engines.

The wide gap between the host of available advanced control technologies and the *ad-hoc* implementations of everyday practice may be explained by the simple fact that the latter have been so far sufficient. Recent research thrusts in aircraft control, however, require that the performance that can be extracted from the engines be maximized, given a set of allowable limits on critical variables. Specifically, fast thrust responses are critical in certain emergency flight maneuvers. As elaborated in the book, classical feedback is no longer suitable as a paradigm for the development of advanced propulsion control concepts.

One of the two chief motivations to write this book has been to bring advanced controls closer to the highly relevant application domain of gas turbine engines. Before advanced concepts can be introduced, standard engine controls must be reviewed and made precise. Presenting standard engine controls using a precise control systems framework has been the second major motivation. As a result, the book spans introductory topics such as the engine's principle of operation and dynamic model, followed by classical feedback compensation and ending with advanced research topics.

Book Audience

The book is aimed at readers falling between two ends of a broad spectrum: at one end are aerospace or mechanical engineers with basic knowledge in control systems; at the other are control engineers with little or no knowledge about gas turbines (the typical electrical engineer may fit this category). Of course, any "interpolated" engineer will also benefit from this book, since it includes detailed information on turbine engine systems and introduces advanced control topics.

The material should be accessible to first-year graduates in mechanical, electrical, or aerospace engineering. Readers are assumed to be familiar with classical control concepts such as stability, root locus design, and frequency response, as well as basic pole-placement design. Proficiency in Matlab/Simulink is required to follow the numerical examples and understand simulations.

The book contains numerous nonlinear engine simulations conducted using NASA's CMAPSS package, available to the public in the USA. This package is required only for readers seeking to reproduce the nonlinear engine simulations contained in the book. The linearized state-space matrices for the 90,000-lb and 40,000-lb engine have been included in the appendix for readers not using CMAPSS. The data are useful to follow many control design calculations, and may even be used to generate a custom simulation accounting for parametric changes.

Although the book does not contain end-of-chapter problems, it is written much in the style of a textbook. As such, it may be used as the basis or as reference material for a graduate course in aircraft engine controls. A course with emphasis in fundamental concepts could be designed using Chaps. 1–3, 5, and 7, while a course emphasizing research aspects could be designed using Chaps. 1, 2, 6–9.

Outline

Chapter 1: Introduction reviews the thermodynamic principles explaining the operation of a gas turbine, assuming minimal familiarity with thermodynamic variables. The components of the real gas turbine engine and its operation are described, introducing key quantitative performance measures. Safety and operational limits are discussed, including mathematical descriptions of surge and stall phenomena.

Chapter 2: Engine Models and Simulation Tools offers a brief overview of engine dynamics, aiming at the extraction of linearized models that can be used as a basis for design. The Commercial Modular Aeropropulsion System Simulation (CMAPSS) package developed by the NASA Glenn Research Center is also described.

Chapter 3: Engine Control by Classical Methods reviews and applies classical SISO design techniques (root locus and frequency domain loopshaping) to the problem of fan speed control using fuel flow rate as control input. A model-matching method is also described that is used in CMAPSS as a design tool. The shortcomings associated with the use of fixed linear compensation are illustrated with simulation examples.

Chapter 4: Engine Control by Robust State Feedback reviews linear multivariable theory and introduces polytopic system descriptions of plant variability. This chapter also presents various methods for MIMO state-feedback synthesis, such as: LQR, $\mathcal{H}_2$, $\mathcal{H}_\infty$ and mixed-objective optimization with regional pole placement constraints. A simplified $\mathcal{H}_\infty$ compensator synthesis method is presented for SISO systems. Matlab code and simulations using the CMAPSS nonlinear engine model are included.

Chapter 5: Gain Scheduling and Adaptation introduces gain-scheduling and linear-parameter-varying techniques to address plant variability across the flight envelope. This chapter also introduces the concept of adaptive control and presents a basic model-reference adaptive control design. Matlab code and simulations using the CMAPSS nonlinear engine model are included.

Chapter 6: Sliding Mode Control of Turbofan Engines introduces the concept of sliding mode control and elaborates in its robustness properties and commonly-used tuning approaches. This chapter also presents MIMO versions of the sliding mode regulator and setpoint tracker, as well as a simplified SISO design. Linear and nonlinear engine simulations using CMAPSS are included.

Chapter 7: Engine Limit Management with Linear Regulators describes the min–max logic arrangement used in standard engine control systems to maintain critical variables within permissible bounds. A thorough analysis of this arrangement is conducted using the concept of positive invariance. The shortcomings of the min–max approach are made evident in simulations. A brief description of an acceleration-limiting approach is also included.

Chapter 8: Engine Limit Management with Sliding Modes develops a method to maintain critical engine variables within allowable limits, without the disadvantages associated with the standard min–max approach. Guidelines for the association of sliding mode regulators to logic max or min selectors are given, along with an $\mathcal{H}_2/\mathcal{H}_\infty$ sliding coefficient synthesis method. Simulations using the CMAPSS nonlinear engine model are included.

Chapter 9: Engine Limit Management with Model Predictive Control introduces the concept of model predictive control and develops basic prediction formulas based on linear state-space models. The constrained optimization problem is formulated using compact matrix formulas suitable for incorporation in Matlab's quadratic program solver. Model predictive control is then applied to the engine control problem to address input and output constraints. The chapter also discusses computational complexity and approaches aimed at its reduction. Matlab code and simulations using the CMAPSS nonlinear engine model are included.

Topics Not Covered

Among the most relevant topics not covered are: (a) engine modeling through system identification, (b) observer-based control, (c) engine health estimation, and (d) robust output-feedback synthesis (except for the simplified method of Sect. 4.9).

Note that gas turbine engine control represents a rare (and fortunate) case where the state variables are available as real-time measurements. This explains the intentional omission of (b) and (d). As far as (a) and (c), these topics are vast and could each give rise to an entire volume. At the same time, they can be safely omitted from a controls-oriented treatment. References have been included throughout the book for readers interested in those topics.

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[1] *A cheerful wife is the joy of life – Goethe.*

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