Propulsion and Power
An Exploration of Gas Turbine Performance Modeling
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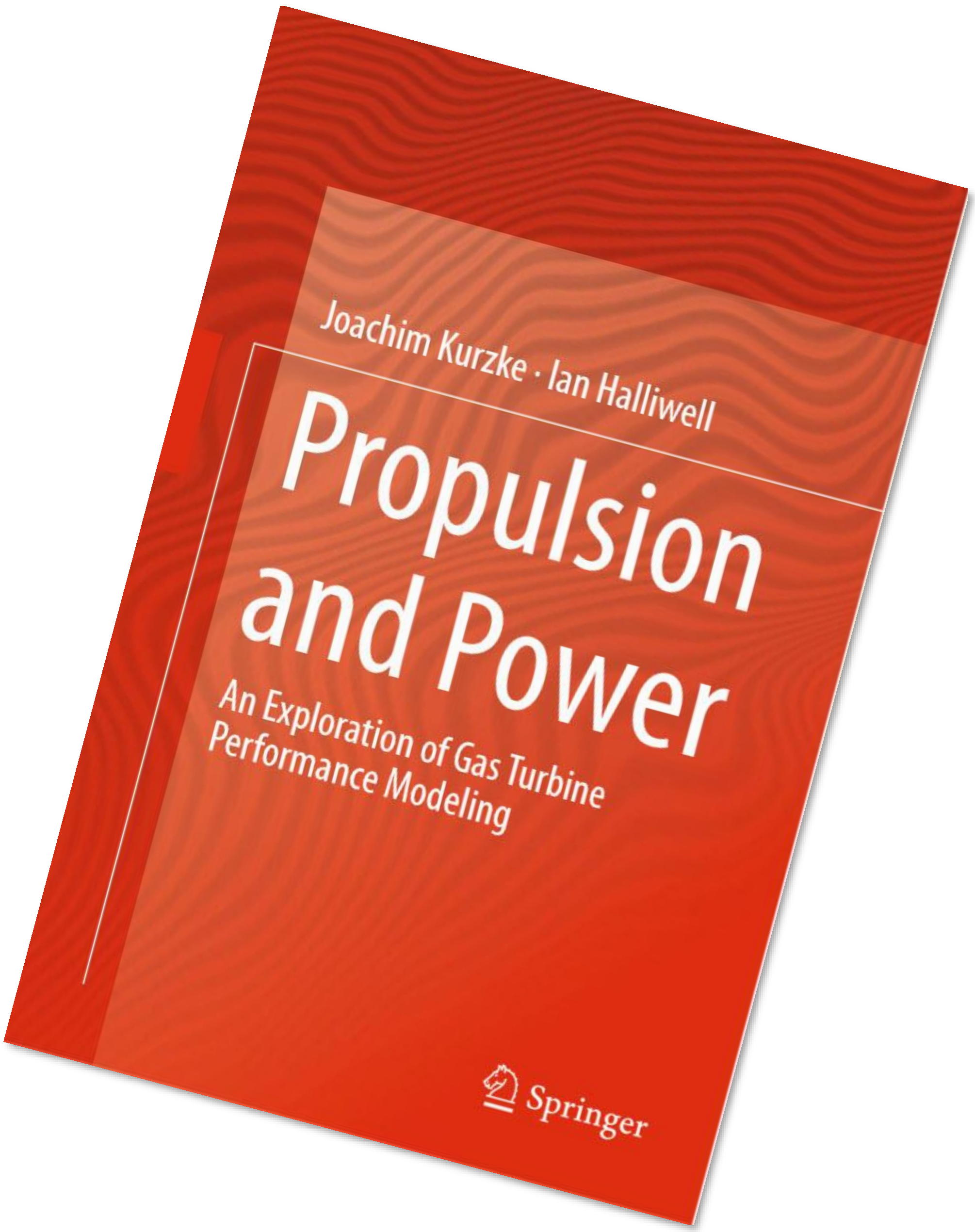

Summary

PART A: Simulation Tasks

A1 New Engine Design

In this chapter we address engine modeling basics encountered when designing an engine concept. Typical fundamental design choices are explained, such as separate vs mixed exhaust streams, single- vs multi-stage turbines and dry vs augmented cycles. The commonality of the core components when used in either an aircraft propulsion device or for ground-based power-generation is illustrated and the use of parametric studies to survey a design space and assess the influence of components and their performance characteristics is demonstrated. There is a detailed discussion about turbofans with a reduction gearbox which evaluates the potential benefit as well as the interactions between the components. Introductions are made to efficiency and the mechanics and aerodynamics of a gas turbine engine, along with some of the inevitable compromises. This material is preceded by an outline of basic gas turbine cycles, which evolves from an ideal scenario to realistic cases with losses. Finally, the aircraft mission is considered, as it defines the deliverables and is the foundation of a multitude of design selections. Here, the transition is made from subsonic commercial operation to high-speed, multi-mission requirements and some of options available to the designer are described.

A2 Engine Families

The costs of designing, testing and validating a new engine concept are very high. Therefore, industry is highly motivated to take an existing engine and create a family of derivative engines covering a range of applications, while implementing incremental advances in technology. The heart of an engine is the core, so a frequent approach is to retain the core and design a series of LP/IP spools around it. In this chapter we take a baseline engine from a small business jet and study how to both increase the thrust capability and improve SFC, while limiting major changes to the LP system. In the worked example, we first define the design variables and select a figure of merit for the derivative engine. We then identify any design constraints, which may come from a range of items such as available technology or installation requirements, environmental regulations or simply cost of manufacture. The results of the optimization study using GasTurb are evaluated in a series of design space graphs, which identify where design limits are reached.

A3 Modeling an Engine

Engine manufacturers model their engines in great detail, always based on a vast amount of established corporate knowledge and new information from contemporary programs. Outside of the OEM, however, optimal use may be made of much smaller pools of experience and data to generate reliable representations of detailed engine geometry and performance. This chapter identifies and characterizes typical sources of information that may be used for such purposes. These can be acquired from officially published data, pass-off tests by an operator or from measurements in a maintenance facility. Consistency of the data must also be considered. With few exceptions, the key to their successful utilization in an engine performance model lies in correcting the available values to the model conditions appropriately. Issues to be considered are departures from standard day conditions as well as humidity and condensation. Which condition to choose as the cycle reference point is especially important before selecting compressor and turbine maps and moving on to off-design conditions. We give general advice in this chapter on common pitfalls and how to fill gaps with derived or hybrid data.

A4 Engine Model Examples

In this chapter, we describe the calibration of three real engines in GasTurb performance models, using only measured data and information from the public domain. We recommend following a specific sequence of tasks and show that starting from relatively little input data the analysis evolves to make reliable performance predictions down to component level across a wide range of power settings and operating conditions. We describe in detail how to check the input data for consistency and create a Cycle Reference Point. The focus then moves to the compressor and turbine maps with advice on positioning the reference point in the map, scaling and finally modifying efficiency and speed. Equally important are the hints on how to implement information on active control items such as variable guide vanes or tip clearance systems. The engines modeled are the Pratt & Whitney J57, a two-spool turbojet run in an altitude test facility, the CFM56-3, a high bypass ratio turbofan run on a maintenance test bed and the Williams F107, a low bypass ratio turbofan with mixed exhaust and data taken from a specification.

A5 Model Based Performance Analysis

Model based performance analysis is also known as Analysis by Synthesis, abbreviated to *AnSyn*. The method combines test analysis and performance prediction in a single program. The program calculates modifiers for the component models – the AnSyn factors - in a special test analysis mode, which make the model agree exactly with the measured data.

In this chapter we describe how AnSyn is used in GasTurb across a range of engine configurations and degrees of instrumentation. We give an example of test analysis on a heavily instrumented development engine as well as a production engine returned to a maintenance shop with much fewer sensors. The chapter concludes with a real-world example of trend monitoring using the very limited instrumentation available during airline operations, and this illustrates compressor deterioration after thousands of flight cycles.

Model based performance analysis is the industry standard during engine development and can identify small differences between components when hardware is modified. It also provides a simple method to correct measured performance to standard conditions.

A6 Inlet Flow Distortion

In this chapter we discuss the phenomenon of inlet flow distortion and how to model its effect on engine stability and performance. We explain why circumferential distortion is more important than radial distortion and the background to the suitability of the pressure distortion coefficient, DC_{60}, as a descriptor. This is followed by a worked example of parallel compressor theory in GasTurb, which is a simple method to quantify the change in surge margin with varying degrees of distortion.

The theory is then extended to cover a multi-spool compression system. The effect of aerodynamic coupling between sequential compressors connected by short ducts with many struts is addressed in detail.

The chapter concludes with a discussion of the response of the engine control system to distortion, including the sensitivity to the choice of the thrust (power) setting parameter.

A7 Transient Performance Simulation

In this chapter we explain the fundamentals of transient engine performance. Starting with the simplest approach of considering only moments of inertia, we compare the two main options for fuel scheduling (Ndot and $W_F/(N\ P_3)$) and their effect on the compressor operating line. We then

extend the simulation to include mechanical and thermal aspects and illustrate why consideration of compressor and turbine tip clearances is essential for a realistic assessment of transient behavior and operability.
We show that by using the data available from the conceptual design feature in GasTurb it is possible to generate a simple but realistic simulation of the effects of tip clearance in a turbofan, which can easily be calibrated to real engine measurements or analytical data.
Finally, we illustrate the benefits of considering tip clearance with examples of two engine transients, acceleration of a cold engine and a hot-reslam, where a deceleration is followed by an acceleration.

PART B: Preliminary Design

B1 The Engine

Engineering design is how we turn ideas into hardware and engine models are used to capture a design concept and demonstrate how well it performs before the hardware is produced. Preliminary design is where many decisions are made in a new engine program and where the results will determine how significant corporate resources will be committed for many years. In this chapter we look at the preliminary design of a complete engine system and consider how it fits into the bigger picture and relates to the mission, the cycle, component design and development, and on to manufacture and testing. We propose a workflow starting from the core compressor and then working aft and forward until all components are included. We describe the relationships between components, how to integrate design constraints into the overall model and the use of trade studies to make the major design decisions.
We illustrate the role played by performance beyond preliminary design in both supplying the specialist component designers with the information they require as well as validating the cycle deliverables during the development phase of a program.

B2 Compressors

The compression system is a major working part of any gas turbine and, aerodynamically, it is the most complex. Its successful operation in all segments of a mission is critical. In this chapter we address the duties and lay out the fundamentals of compressor design and definitions of performance parameters. We emphasize the construction and interpretation of velocity diagrams, a vital element in any engineer’s understanding, from which a great deal can be learned about performance and trends caused by simple changes. We derive and explain the three non-dimensional stage characteristics loading coefficient, flow coefficient and stage reaction. We then discuss preliminary compressor design addressing diffusing flow, limits on turning, deviation and the resulting blockage and mean line analysis. We give a brief history of mean line design codes and their intrinsic loss models. before tackling flow features in a blade passage and the loss elements themselves. We cite two mean line codes, CSPAN and that used in GasTurb, and use them to illustrate how total pressure losses are accounted for in practice. Finally, compressor design envelopes are introduced as a means of managing multiple design limits simultaneously.

B3 Turbines

Turbines are a major working component in a gas turbine, which operate in a hostile environment in terms of the extreme temperature, unsteady flow and often need cooling air to provide structural integrity and guarantee component life. The different turbine roles for propulsion and power generation are explained. In this chapter we describe the flow process through a turbine stage and derive the simple (uncooled) efficiency parameter. We show how to construct turbine velocity diagrams and discuss their use to determine responses to change. We derive and explain the use of the non-dimensional turbine stage characteristics – stage loading coefficient, flow coefficient and reaction. The Zweifel coefficient is also used to quantify blade loading. We introduce the Smith Chart as the first performance correlation of efficiency versus stage loading and flow coefficients. The development and structure of mean line design codes is laid out and an account of flow features in a blade passage and their associated loss elements is presented. We then work through an example of a turbine design envelope integrating multiple constraints to derive a solution space. Lastly, we present the vaneless counter-rotation turbine as an alternative design concept.

B4 Mechanical Design

In preliminary design we run trade studies to make design choices. The figure of merit for optimization should consider the aircraft mission. In this chapter we show how it is possible at an early stage of the design to generate the flow path and make a reasonable estimate of the system weight.

We look at each of the major components or sub-assemblies in a gas turbine and identify the main parameters which influence the flow path and weight. Seeing a diagram of the layout is a good way to check the compatibility and alignment of components. Special attention is placed on disk design as disks are such large contributors to engine weight.

While it is recognized that absolute numbers generated by these simple methods, exemplified by GasTurb, may not be very accurate, the trends that they identify are useful in making design decisions. Moreover, if more details are available the results may easily be calibrated against real engines. A by-product of the mechanical design is valuable information such as rotor polar moment of inertia and heat capacity of casings, which heavily influence the transient performance.

PART C: Off-Design

C1 Component Performance

In this chapter we discuss the off-design performance of individual gas turbine components. Since compressor maps are the key to a high quality performance model and realistic maps are typically only available to the manufacturers, we describe in great detail how to scale and adapt existing maps. Examples of simple and advanced scaling methods are illustrated using the features in Smooth C combined with GasTurb. We review the pros and cons of alternative formats for turbine maps, using Smooth T. We discuss the options in use for modeling intakes, covering the range of subsonic and supersonic aircraft as well as land-based gas turbines. We describe how to model combustors and show the good correlation to empirical data. We look at the potential benefits of mixing the hot and cold exhaust streams, with a worked example of a mixing calculation. The chapter concludes with detailed discussions on modeling afterburners as well as nozzles, both convergent and variable convergent-divergent.

C2 Understanding Off-Design Behavior

In this chapter we describe the principles of gas turbine off-design behavior. Understanding the interactions between individual components is a prerequisite of the effective and professional use of any gas turbine performance program. We start with the simplest configuration of a single spool turbojet and study the operating lines in the compressor and turbine maps. We use mainly non-dimensionals to explain the relationships between the components, including the lack of influence of variable guide vanes on a compressor operating line. The discussion is then extended to cover two-spool turbojets and turbofans. We describe why the operating line of the fan is dependent on the bypass nozzle flow characteristic and pay special attention to why subsonic and transonic boosters behave differently at part power. We also explain why the operating line of an LP turbine is determined by the core nozzle pressure ratio and hence varies with bypass ratio. Finally we look at the behavior of the components in both single and multi-spool turboshafts with constant speed power turbines. The validity of all the results is illustrated extensively by calculations from GasTurb.

PART D: Basics

D1 Gas Properties and Standard Atmosphere

We show how the gas properties gas constant, specific heat, enthalpy and entropy function for a half-ideal gas, are derived from basic thermodynamics. GasTurb reads gas properties from tables calculated with the NASA program CEA.

Environmental conditions are defined by the International Standard Atmosphere (ISA), which derives ambient pressure and temperature from the altitude.

D2 Spreadsheet Calculations

We first summarize the equations used for describing component performance, including non-dimensional parameters, such as corrected mass flow, Mach number total/static ratios. The isentropic and polytropic efficiency definitions for compressors and turbines, are compared.

We then follow with a detailed hand-calculation through the cycle of a turbojet engine in-flight. We cover each component from the inlet to the nozzle and evaluate the differences caused by using the mean specific heat rather than the entropy function (as used in GasTurb).

D3 Non-Dimensional Performance

We illustrate that if the velocity triangles for a compressor, run to two different conditions, have the same angles and Mach numbers, then the non-dimensional parameters (speed, pressure ratio, temperature ratio, etc.) will also be the same. Without resorting to higher mathematics, this method is extended to cover whole engine parameters such as fuel flow, thrust and power.

We show how to correct the non-dimensional parameters to standard conditions using exponents for δ (P/P_{ISA}) and Θ (T/T_{ISA}) and the use of the cycle model to derive the exponent values for each parameter including humidity and "real engine" effects.

D4 Reynolds Number Corrections

We explain why the ratio of inertia to friction forces, as characterized by the Reynolds number, influence gas turbine performance. We describe how the use of the Reynolds Number Index can simplify performance calculations.

How to correlate Reynolds number corrections to real data is illustrated through use of a pipe flow analogy and Moody charts.

D5 Turbine Efficiency

Starting from a single stage un-cooled turbine, we extend the definition of turbine efficiency to cover both cooled and multi-stage turbines. The consideration of secondary effects such as pumping work, windage and sealing flows is discussed and the concepts of chargeable and non-chargeable flows are introduced. It is shown that there are many options and that performance models typically use a control volume to derive an equivalent single stage definition. The pros and cons of various approaches are discussed, and the calculated values are compared to "thermodynamic efficiency", the ratio of actual power delivered to the cumulative power potential of each individual flow. The chapter concludes with a numerical evaluation of the efficiency loss due to cooling in a real engine

D6 Secondary Air System

In this chapter we show how the very complex secondary air system in a modern gas turbine may be greatly simplified and integrated into a cycle model without compromising the quality of overall performance results.

Calculation examples from single and multi-stage turbines are given which describe in detail how to account for interstage bleed flows and their re-introduction into the main gas path.

D7 Mathematics

In this chapter we explain why off-design performance calculations require an iterative approach to maintain continuity in mass and energy flows in component matching. We start with a simple example of a turboshaft engine with a free power turbine and show how the number of iteration variables increases as the engine architecture becomes more complex. We demonstrate how the use of the Newton-Raphson algorithm may be extended to any number of variables as well as dynamic engine simulations.

We conclude the chapter with some examples of problems that may occur when setting up iteration schemes and give practical advice on how to resolve them.

D8 Optimization

In this chapter we show how to use optimization to evaluate design studies with many variables. The two numerical optimization methods available in GasTurb (using gradient or random search algorithms) are described, with clear illustrations of the difference between local and global optima. Advice is given on the use of constraints and on the definition of the figure of merit when a study has multiple objectives.

D9 Monte Carlo Simulations

The Monte Carlo method is a powerful and simple tool for generating statistical information. Typical examples of its gas turbine applications are in the uncertainty analysis of measurements, the probability of achieving an engine design target and production tolerance estimates.

Engine tests evaluate much more than overall characteristics in terms of thrust and specific fuel consumption; the main objective of performance testing is the efficiency of the engine components. Both random and systematic measurement errors affect the accuracy of the analysis result.

When a new engine is designed, there is always uncertainty about the component performances achievable. That transfers to an uncertainty in the overall engine performance. For example, even though the design target in specific fuel consumption is met ostensibly, the cycle or guaranteed value may need to be modified to improve the level of confidence.

If we simulate a batch of engines with randomly distributed properties, as the result of component manufacturing tolerances, we can predict the effects of various combinations of these on thrust or shaft power, efficiency and specific fuel consumption. The influence of variations in internal air systems can also be accounted for.

GasTurb makes Monte Carlo simulations easy, both for cycle design and off-design applications.

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Propulsion and Power
An Exploration of Gas Turbine Performance Modeling

This book is for students, teachers and practicing engineers and portrays an industrial approach to engine simulation. The principles of performance model creation are described and the viability and accuracy of model-based performance analysis are demonstrated by their application to real-world examples, where measured data are scarce. The influence of inlet flow distortion and heat transfer on engine operability during transient operation is also characterized.

Clear distinctions are made between design and off-design models, the keys to success being the recognition of the importance of scaling and validating compressor and turbine maps. This topic is discussed in more detail than in other sources. New descriptions of turbomachinery basics are also offered, and it is shown how velocity diagrams can capture the quality of a compressor or turbine stage and the effects of changes. Non-dimensional performance is explained in an unusual way, with minimal mathematics. Most of the figures contain numerical results from the publicly available cycle code GasTurb™.

Not only a good engineering text book but also a good read!

Joachim Kurzke spent his engineering life dealing with gas turbine performance, first at the Technical University of Munich, Institute for Flight Propulsion. He then worked for 28 years in the performance department of the company which is now MTU Aero Engines, dealing with a multitude of different engine projects. As a private enterprise he wrote the highly-acclaimed performance program GasTurb™.

Ian Halliwell worked for over 40 years for Rolls-Royce, Pratt & Whitney Canada, GE and three small businesses. For much of that time he enjoyed teaching gas turbine engine design from an industrial base. His teaching activities have been inspired by his extensive involvement in the AIAA International Engine Design Competition for Undergraduate Teams.