PRINCIPLES OF TURBOMACHINERY IN AIR-BREATHING ENGINES

This book is intended for advanced undergraduate and graduate students in mechanical and aerospace engineering taking a course commonly called Principles of Turbomachinery and Aerospace Propulsion. The book begins with a review of basic thermodynamics and fluid mechanics principles to motivate their application to aerothermodynamics and real-life design issues. This approach is ideal for the reader who will face practical situations and design decisions in the gas turbine industry. Among the features of the book are:

- an emphasis on the role of entropy in the process of performance assessment;
- a timely review of different flow structures;
- revisiting the subsonic and supersonic De Laval nozzle as it applies to bladed turbomachinery components;
- an applied review of the boundary layer principles; and
- highlighting the importance of invariant properties across a turbomachinery component in carrying out real computational tasks.

The text is fully supported by 398 figures, numerous examples, and homework problems.

Dr. Erian A. Baskharone joined Texas A&M University in 1985, where he was tenured as Associate Professor of Mechanical and Aerospace Engineering, and a faculty member of the Rotordynamics/Turbomachinery Laboratory. Upon receiving his Ph.D. at the University of Cincinnati, he was appointed as Senior Engineer with Allied-Signal Aerospace Corporation, responsible for the aerothermodynamic design of various turbofan and turboprop engine components. His research at Texas A&M University covered a wide range of turbomachinery topics, including the unsteady stator/rotor flow interaction, and the fluid-induced vibration of the Space Shuttle Main Engine turbopumps. His perturbation approach to the problem of fluid-induced vibration was a significant breakthrough. Dr. Baskharone is a member of the ASME Turbomachinery Executive Committee. He is the recipient of the General Dynamics Award of Excellence in Engineering Teaching (1991), and the Amoco Foundation Award for Distinguished Teaching (1992).

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Principles of Turbomachinery in Air-Breathing Engines

ERIAN A. BASKHARONE

Texas A&M University

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To

Magda

Daniel

Christian

Richard

and

Robert

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Preface

Beginning with the class-notes version, this book is the outcome of teaching the courses of Principles of Turbomachinery and Aerospace Propulsion in the mechanical and aerospace engineering departments of Texas A&M University. Over a period of fourteen years, the contents were continually altered and upgraded in light of the students' feedback. This has always been insightful, enlightening, and highly constructive.

The book is intended for junior- and senior-level students in the mechanical and aerospace engineering disciplines, who are taking gas-turbine or propulsion courses. In its details, the text serves the students in two basic ways. First, it refamiliarizes them with specific fundamentals in the fluid mechanics and thermodynamics areas, which are directly relevant to the turbomachinery design and analysis aspects. In doing so, it purposely deviates from such inapplicable subtopics as external (unbound) flows around geometrically standard objects and airframe-wing analogies. Instead, turbomachinery subcomponents are utilized in such a way to impart the element of practicality and highlight the internal-flow nature of the subject at hand. The second book task is to prepare the student for practical design topics by placing him or her in appropriate real-life design settings. In proceeding from the first to the second task, I have made every effort to simplify the essential turbomachinery concepts, without compromising their analytical or design-related values.

Judging by my experience, two additional groups are served by the book. First, practicing engineers including, but not necessarily limited to, those at the entry level. As an example, the reader in this category will benefit from the practical means of estimating the stage aerodynamic losses. These stem from special well-explained flow behavioral features within the blade-to-blade, hub-to-casing flow passages and are hardly known a priori in a real-life design procedure. Another example of practical topics involves the different means of improving the overall efficiency through minor hardware adjustments, without having to undergo a tedious and expensive redesign procedure. To the same group of young engineers, the mere exposure to the different stacking patterns of stationary and rotating blades, as well as the drastic aerodynamic consequences of seemingly minor blade-surface irregularities, should both bring the student much closer to real problems in the turbomachinery industry.

Also served by the book contents are those who are considering a research career in the turbomachinery area. The book, in many sections, makes it clear that there are topics which are in need of research contributions, not only for improving the aerodynamic performance, but also for elongating the life of a turbomachine or avoiding a premature mechanical failure. Two such topics are the unsteady fatigue-causing stator/rotor flow interaction and the role of secondary (casing-to-shroud) flow stream in causing an unstable rotor operation. The latter has to do, in particular, with the swirling motion of this flow stream. Publicized by frequent mechanical failures in an early development phase of the Space Shuttle Main Engine turbopumps, extensive exploratory work identified this motion component as the major contributor in an unstable and potentially catastrophic shaft motion, termed *whirl*, where the shaft centerline undergoes an eccentric motion around the housing centerline at a finite "whirl" frequency. Other research-needing topics, also indicated in the text, involve the design and performance-related area. Examples of these include proper casing (or housing) treatment for tip-leakage control and yet unevaluated ways to improve the blading efficiency and flow guidedness. With the foundation laid in Chapter 3 and through a heavy exploitation of graphical means, another research-worthy subject I am identifying is that of variable-geometry turbomachines. These, in my opinion, remain today as poorly researched and insufficiently tested.

Solved and unsolved, the problems contained in the text are so constructed to underscore the different design and analysis topics within each individual chapter. Because of their critical role, the objective of each solved problem is clearly stated ahead of the problem or during the numerical solution. On more than just a few occasions, I chose to write specific problems in such a format to impart specific concepts from previous chapters, in an effort to contrast the performance of, and limitations on, a given component to those of another. Unique about many solved problems is that common mistakes are intentionally made, upon warning the student, with the wrong solution segment clearly marked. The segment is, at an appropriate point, terminated, and the lastly obtained unrealistic result examined, prior to taking the student back to the correct sequence of calculations.

Briefly outlined in Chapter 11, my experience in the research area of turbomachinery fluid-induced vibration led me to conclude that the efforts of competent vibration investigators often remain incomplete in the absence of contributions from modest-level fluid-dynamicists. Perhaps the most revealing example of this fact is the occasion when I undertook, as a side issue, the task of designing a swirl "brake" for use in the Space Shuttle Main Engine booster impeller. The stated objective, then, was to practically destroy the circumferential velocity component of the secondary-flow stream just upstream from its inlet station. Given that virtually any serious reader of Chapter 10 is capable of designing such a stationary device, I had the device T.L. (technical layout) ready in a rather short time. Upon fabrication and testing, it was clear that this simple component helped stabilize the impeller operation. This particular incident reminded me of a long-held principle; that thoughtfully presented fundamentals can pave the student's way to positively contribute to serious turbomachinery issues, for even the simplest of ideas may well escape the minds of specialists.

Some of the book chapters are notably different in size by comparison. Chapter 3, for instance, is one of the largest, as it sets the aerothermodynamic foundation for the subsequent chapters to utilize. The chapter begins with the most essential flow-governing equations, with emphasis on the need for a rotating frame of reference, and the corresponding set of relative thermophysical properties. For a rotor blade-to-blade passage, as indicated in the text, many physical phenomena, including the boundary-layer "blockage" effect and the onset of passage choking, lend themselves to such a reference frame. The chapter then proceeds to introduce the student to the flow total and total-relative properties in the stage stationary and rotating subdomains, respectively. In doing so, the concept of critical velocity is presented as a turbomachinery-suited deviation from the traditional sonic speed in the Mach number definition. Furthermore, this same chapter exclusively covers the flow structure in an exhaust diffuser, a critical flow passage which, in a typical turboshaft engine, determines whether a much-feared flow reversal, back to as far upstream as the turbine section, could indeed take place. Despite its obvious classification as a non-turbomachinery component, an exhaust diffuser is potentially capable of causing an unmatched performance deterioration, under off-design operation modes depending, primarily, on the turbine-exit swirl angle. I came to better comprehend and appreciate the role of this component during my design of it for the TPE 331-14 turboprop engine, in the early 1980s. Prior denial of the FAA certification, in this case, had to do with unacceptable power-decline magnitudes under FAA-specified off-design modes, with the exhaust-diffuser pressure-recovery characteristics being at the heart of the problem.

Also longer than average are Chapters 8 and 10, covering the theory and design aspects of axial and radial-inflow turbines, compared to their compressor counterparts. One of the reasons here is the substantial arbitrariness of the turbine-blade geometrical features, as a result of the streamwise-favorable pressure gradient, compared to the traditionally standard compressor-blade configurations. Moreover, there is this severe environment surrounding the turbine operation, where a bladed component, spinning at a speed that is rarely below 40,000 rpm, is exposed to a gas-stream temperature which, for an early stage, may very well be in excess of 1300 K. Such environment would naturally give rise to truly punishing thermal and mechanical stress fields which, together with stress-concentration subregions, can be devastating from a mechanical standpoint. With virtually unavoidable early-stage blade and endwall-cooling, serious tip-leakage challenges in early (short-span) rotor blades, and various issues concerning the blade-stacking pattern, the larger emphasis placed on these two turbine chapters is perhaps justified.

The book contents, in many ways, were influenced by my turbomachinery industrial experience, at Garrett Turbine Engine Co. (later Allied-Signal Aerospace Co., and currently Honeywell Aerospace Co.), in the early and mid-1980s, with duties in the aerothermodynamic turbine design of different turboprop and turbofan engines, as well as such power systems as turbochargers and auxiliary power units. As I now revisit the introductory chapters, as well as design-oriented topics in later chapters, it becomes clear to me that these, as well as many other subjects, do share a common thread, namely the element of practicality, one that is gained from hands-on field experience. This same experience taught me to thoroughly examine the downside of a simplifying assumption before adopting it. Perhaps the clearest example of this topic is the introduction to the Radial Equilibrium Theory (Chapter 6). The objective there is to clearly underscore the fact that a casually stated assumption such as "no stator/rotor flow interaction" implies, in plain language, an *infinitely long* distance between the stator vanes and rotor blades. The introduction of Chapter 6 is but one of many commentary sections that address the all important issue of when an assumption can be "engineeringly" acceptable and when its unrealistic implications can destroy its very own credibility.

The bigger question, however, is whether a turbomachinery analyst can "live" with an unrealistic assumption, such as that of the infinitely long stator/rotor gap (above). The short answer to this is yes, depending on the intended use of the results. In this particular instance, a largely simplified form of the radial-momentum conservation principle, namely the radial equilibrium equation, is solved with the hardly demanding objective of having a first look at the flow variables away from the mean radius, in one of these unbladed subregions. During a typical preliminary design phase, the solution of this simple equation would be in the interest of achieving a crude estimate of the hub and tip degrees of reaction. These are then examined, only to see if they are between zero and 100%, a fittingly modest objective with a rather limited final-design impact.

As I look back at the very early educational settings which helped me voice out and gainfully discuss turbomachinery-related issues, it is only fair to acknowledge a group of professionals with whom I was fortunate to interact, almost on a daily basis. This is a group of young engineers I supervised during my tenure at Garrett Turbine Engine Company. In my mind, these individuals perhaps had as much of an educational impact on me as I had on them. For that, I owe them all a great deal of appreciation, one that is definitely overdue.

I am also grateful to Honeywell Aerospace Co. (Phoenix, Arizona) for granting me the permission to publish several hardware pictures, along with relevant design features. The effort of Mr. Robert Desmond, Chief of the Intellectual Property Department, in securing this permission, is greatly appreciated.

In my early years at Texas A&M University, I was indeed fortunate to have Professor Dara Childs, director of the Texas A&M Turbomachinery Laboratory, as a colleague and a mentor. His dedication to, and extreme enthusiasm about, the turbomachinery rotordynamics topic had an impact on me to the point of adopting it as one of my primary research activities for more than a decade.

Finally, I will always be indebted to my wife Magda for her patience and unlimited support. Her relentless effort in typing the major part of this text, including its mathematically involved segments, has been a major contributor to the mere existence of it.

Erian A. Baskharone