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总主编　顾诵芬

Axial Turbine Aerodynamics for Aero-engines: Flow Analysis and Aerodynamics Design

航空燃气轮机涡轮气体动力学：流动机理及气动设计（英文版）

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Abstract

This book is a monograph on turbine aerodynamics. It gives a brief introduction to the concepts related to turbine aerodynamics, systematically expounds the mechanisms of flows in axial turbines, inter-turbine ducts, and turbine rear frame ducts, analyzes the numerical evaluation methods in different dimensions, introduces the latest research achievements in the field of gas turbine aerodynamic design and flow control, and explores multidisciplinary conjugate problems involved with turbines.

This book should be helpful for scientific and technical staffs, college teachers, graduate students, and senior college students, who are engaged in design and research of gas turbines.

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总　序

国务院在2007年2月底批准了大型飞机研制重大科技专项正式立项，得到全国上下各方面的关注。“大型飞机”工程项目作为创新型国家的标志工程重新燃起我们国家和人民共同承载着“航空报国梦”的巨大热情。对于所有从事航空事业的工作者，这是历史赋予的使命和挑战。

1903年12月17日，美国莱特兄弟制作的世界第一架有动力、可操纵、比重大于空气的载人飞行器试飞成功，标志着人类飞行的梦想变成了现实。飞机作为20世纪最重大的科技成果之一，是人类科技创新能力与工业化生产形式相结合的产物，也是现代科学技术的集大成者。军事和民生对飞机的需求促进了飞机迅速而不间断的发展和应用，体现了当代科学技术的最新成果；而航空领域的持续探索和不断创新，为诸多学科的发展和相关技术的突破提供了强劲动力。航空工业已经成为知识密集、技术密集、高附加值、低消耗的产业。

从大型飞机工程项目开始论证到确定为《国家中长期科学和技术发展规划纲要》的十六个重大专项之一，直至立项通过，不仅使全国上下重视我国自主航空事业，而且使我们的人民、政府理解了我国航空事业半个多世纪发展的艰辛和成绩。大型飞机重大专项正式立项和启动使我们的民用航空进入新纪元。经过50多年的风雨历程，当今中国的航空工业已经步入了科学、理性的发展轨道。大型客机项目产业链长、辐射面宽、对国家综合实力带动性强，在国民经济发展和科学技术进步中发挥着重要作用，我国的航空工业迎来了新的发展机遇。

大型飞机的研制承载着中国几代航空人的梦想，在2016年造出与波音B737和

空客公司 A320 改进型一样先进的“国产大飞机”已经成为每个航空人心中奋斗的目标。然而，大型飞机覆盖了机械、电子、材料、冶金、仪器仪表、化工等几乎所有工业门类，集成数学、空气动力学、材料学、人机工程学、自动控制学等多种学科，是一个复杂的科技创新系统。为了迎接新形势下理论、技术和工程等方面的严峻挑战，迫切需要引入、借鉴国外的优秀出版物和数据资料，总结、巩固我们的经验和成果，编著一套以“大飞机”为主题的丛书，借以推动服务“大飞机”作为推动服务整个航空科学的切入点，同时对于促进我国航空事业的发展和加快航空紧缺人才的培养，具有十分重要的现实意义和深远的历史意义。

2008 年 5 月，中国商用飞机有限公司成立之初，上海交通大学出版社就开始酝酿“大飞机出版工程”，这是一项非常适合“大飞机”研制工作时宜的事业。新中国第一位飞机设计宗师——徐舜寿同志在领导我们研制中国第一架喷气式歼击教练机——歼教 1 时，亲自撰写了《飞机性能及算法》，及时编译了第一部《英汉航空工程名词字典》，翻译出版了《飞机构造学》《飞机强度学》，从理论上保证了我们的飞机研制工作。我本人作为航空事业发展 50 多年的见证人，欣然接受上海交通大学出版社的邀请担任该丛书的主编，希望为我国的“大飞机”研制发展出一份力。出版社同时也邀请了王礼恒院士、金德琨研究员、吴光辉总设计师、陈迎春副总设计师等航空领域专家撰写专著、精选书目，承担翻译、审校等工作，以确保这套“大飞机”丛书具有高品质和重大的社会价值，为我国的大飞机研制以及学科发展提供参考和智力支持。

编著这套丛书，一是总结整理 50 多年来航空科学技术的重要成果及宝贵经验；二是优化航空专业技术教材体系，为飞机设计技术人员的培养提供一套系统、全面的教科书，满足人才培养对教材的迫切需求；三是为大飞机研制提供有力的技术保障；四是将许多专家、教授、学者广博的学识见解和丰富的实践经验总结继承下来，旨在从系统性、完整性和实用性角度出发，把丰富的实践经验进一步理论化、科学化，形成具有我国特色的“大飞机”理论与实践相结合的知识体系。

“大飞机出版工程”丛书主要涵盖了总体气动、航空发动机、结构强度、航电、制造等专业方向，知识领域覆盖我国国产大飞机的关键技术。图书类别分为译著、专著、教材、工具书等几个模块；其内容既包括领域内专家们最先进的理论方法和技术

成果，也包括来自飞机设计第一线的理论和实践成果。如：2009 年出版的荷兰原福克飞机公司总师撰写的 *Aerodynamic Design of Transport Aircraft*（《运输类飞机的空气动力设计》）；由美国堪萨斯大学 2008 年出版的 *Aircraft Propulsion*（《飞机推进》）等国外最新科技的结晶；国内《民用飞机总体设计》等总体阐述之作和《涡量动力学》《民用飞机气动设计》等专业细分的著作；也有《民机设计 1000 问》《英汉航空缩略语词典》等工具类图书。

该套图书得到国家出版基金资助，体现了国家对“大型飞机”项目以及“大飞机出版工程”这套丛书的高度重视。这套丛书承担着记载与弘扬科技成就、积累和传播科技知识的使命，凝结了国内外航空领域专业人士的智慧和成果，具有较强的系统性、完整性、实用性和技术前瞻性，既可作为实际工作指导用书，亦可作为相关专业人员的学习参考用书。期望这套丛书能够有益于航空领域里人才的培养，有益于航空工业的发展，有益于大飞机的成功研制。同时，希望能为大飞机工程吸引更多的读者来关心航空、支持航空和热爱航空，并投身于中国航空事业做出一点贡献。

顾诵芬

2009 年 12 月 15 日

Preface

With the progress of aviation technology, turbine aerodynamic, as one of the major support subjects for the development of aero-gas turbine, has experienced a rapid development in the recent 20 years, resulting in new physical phenomena being discovered and understood constantly, as well as new design methods emerging continuously. Thanks to these achievements, aerodynamic design capability for aero-gas turbines has increased rapidly, and the design level has reached a new stage. It is exactly the application of the latest fine aerodynamics design technologies in aero-gas turbines greatly improves the aerodynamic load and efficiency of turbines in modern aero-engines. In order to timely introduce the latest achievements and provide some reference for fundamental research on turbine aerodynamics and for the development of engineering design methods, the authors carried out a thorough sorting of research progresses on turbine aerodynamics in the recent 20 years, and based on that, wrote this book. This book systematically introduces the research achievements on mechanisms of complex flows in turbines and aerodynamic design methods, and is expected to be able to make some contributions to the theoretical research on aero-gas turbine aerodynamics and development of turbine aerodynamic design technology.

This book has eight chapters. Chapter 1 introduces the basic turbine aerodynamics concepts involved in this book, particularly highlighting some new concepts, supplements and extensions to original concepts, which were proposed recently, such as the Zweifel coefficient used to represent the blade loading and efficiency definitions of cooled turbines. Chapter 2 expounds the mechanisms of complex flows in high-pressure turbines, including aerodynamic and geometrical features of high-pressure turbines, complex wave systems with its flow structures and organizations, secondary flows and the relevant influencing factors, as well as mixing between cooling flow and the main flow. Chapter 3 presents the complex flows in inter-turbine ducts and its influencing factors, and discuss the relevant aerodynamic design methods. Chapter 4 expounds the geometrical and

aerothermodynamic features of low-pressure turbines, as well as the development trends, thus gives a systematical introduction to the research achievements concerning the current hot issues, such as spatial-temporal evolution of blade boundary layer, interaction between complex flows in shrouds and the main flow, secondary flows in the endwall regions of high-loading low-pressure turbines, as well as flows in low pressure turbines at low Reynolds number. Chapter 5 shows the complex flows in turbine rear frame ducts with its influencing factors and its aerodynamic design methods. Chapter 6 presents the achievements about the aerodynamic design methods for turbines, including loss models, turbine parameters selection in low dimensional design numerical evaluation methods, blade profiling and 3 - D stacking technology, and refined turbine design technology, all of which are research hotspots in recent years. Chapter 7 introduces the application of flow control technologies in turbines, including control of turbine boundary layers, secondary flows and tip leakage flows, and turbine working state adjusting technology, which are also research hotspots in recent years. Chapter 8 gives a brief introduction to multidisciplinary conjugate problems involved with turbines, including conjugate heat transfer, flow-structure interaction, aero-acoustic conjugate, and multidisciplinary design optimization, which are still hot topics in turbine research.

The authors of this book come from Beihang University and Harbin Institute of Technology. Chapter 1 was written by Prof. Zhengping Zou and Dr. Weihao Zhang; Chapter 2 was written by Prof. Songtao Wang; Chapter 3 was written by Prof. Huoxing Liu; Chapter 4 was written by Prof. Zhengping Zou and Dr. Weihao Zhang; Chapter 5 was written by Prof. Huoxing Liu; Sections 6.4.1 and 6.4.2 of Chap. 6 were written by Prof. Songtao Wang, and the rest of this chapter was written by Prof. Zhengping Zou; Chapter 7 was written by Prof. Huoxing Liu; Chapter 8 was written by Dr. Weihao Zhang and Prof. Zhengping Zou.

This book can be used as a reference book for teachers engaged in gas turbine teaching, researchers engaged in fundamental and applied research of aerodynamics of aviation, ground, and ship gas turbines, technicians engaged in engineering design of turbines, as well as graduate students and senior undergraduate students in relevant majors.

Zhengping Zou
Beijing, China
April 2017

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