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Manufacturing Automation

Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design

Second Edition

制造自动化

金属切削力学、机床振动和CNC设计

（第二版）（英文版）

［加］ Yusuf Altintas 著◎

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内 容 简 介

本书重点介绍了金属切削过程力学、机床动力学及振动、进给驱动设计和控制、CNC设计原理、传感器辅助加工和数控编程技术等知识。从切削过程力学的基本原理开始，深度讨论了振动及颤振问题；也讨论了数控编程和计算机辅助设计/计算机辅助制造（CAD/CAM）技术。文中还详细介绍了驱动执行机构、反馈传感器的选择、进给驱动系统的建模与控制、轨迹实时生成和插补算法的设计、面向数控系统的误差分析等。每一章都包括从企业实际、设计项目和工作问题中筛选的案例。

本书特别适合高年级本科生和研究生，以及研发工程师阅读。读者将在这本书中找到清晰而彻底的方式来学习金属切削力学的工程原理、机床振动、数控系统设计、传感器辅助加工，以及CAD/CAM技术等。

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导 读

制造业是我国国民经济的支柱产业，也是我国经济增长的主导部门和经济转型的基础。我国正面临着从制造业大国向制造业强国转变的关键时期，用先进制造技术振兴制造业，提升自主研发能力，树立“中国制造”“中国创造”“中国智造”的品牌是迫在眉睫的任务。

切削加工是机械制造中最基本的加工方法之一，利用刀具切除被加工对象上的多余材料，从而得到形状、精度和表面质量都符合预定要求的表面。“工欲善其事，必先利其器”，选择合理的刀具及切削参数进行切削加工，是保证加工效率和加工质量的重要要素。影响切削加工效率的因素很多，如切削参数选择、工艺过程设计、工艺系统设计和生产管理等，但切削参数的选择是制约加工效率提高的主要因素。

基于切削加工过程的建模和仿真旨在通过建立适当的模型，通过仿真结果来研究切削加工参数对不易观察到的切削现象的影响，从而更加深入地了解切削加工机理和评判选择该切削参数的合理性。加工过程仿真包括几何仿真和物理仿真（主要是动力学仿真），然而前者只能解决干涉验证的问题，却无法对直接影响加工效率和质量的各种物理因素（如切削力、振动、变形、温度等）提供必要的仿真和预测功能。随着企业对生产加工过程高效率、高精度的要求，单纯的几何仿真技术已经不能满足现代生产的需要。在实际应用中，铣削力、振动和变形等因素已经成为直接影响加工过程优劣的关键。基于加工过程的动力学仿真技术在几何仿真的基础上，从动力学角度对整个加工过程中的各种物理量、物理因素进行建模和仿真分析，从而在实际加工前预测出不同切削参数与物理量之间的相互关系，预先对加工质量进行评估。

西方发达国家对数控加工领域内的切削过程仿真优化技术进行了较早且较为深入的理论研究和实际应用，具有较高的技术水平，其主要研究成果已经成为相应的商业化应用软件。同时，作为现代先进制造技术领域内的一个研究方向，也有必要对加工过程动力学仿真优化技术进行深入、系统的研究。因此，着眼于加工过程动力学建模和仿真的研究具有重要的理论价值和创新意义。

本人自1996年起至今，一直从事数控编程、数控加工技术、数控机床等方面的教学及科研工作。2003年，本人于南京航空航天大学攻读博士学位期间，有幸阅读了2002年由化学工业出版社出版的《数控技术与制造自动化》（罗学科翻译）及其原著（Yusuf Altintas著）。后来，2008年本人南京航空航天大学博士后流动站学习和科研期间，多次关注Yusuf Altintas教授所在团队发表的论文和科研工作，特别是2011年参加的在北京航空航天大学由刘强教授主持的学术研讨会期间，亲自聆听了Yusuf Altintas的学术报告。在2013年1月至2014年2月，本人在加拿大英属哥伦比亚大学（UBC）的制造自动化实验室（MAL）访学1年多，有幸师从国际制造自动化领域知名学者Yusuf Altintas教授。Yusuf Altintas教授现任加拿大皇家科学院

（RSC）院士、国际生产工程学会（CIRP）主席、加拿大工程院院士、美国机械工程师学会（ASME）和国际制造工程师学会（SME）会士，加拿大英属哥伦比亚大学机械工程系终身教授。Yusuf Altintas教授是享誉世界的制造领域著名专家，主要研究方向为金属切削、机床振动、控制和虚拟加工等，其著作*Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design*, Second Edition被广泛使用。他领导的实验室开发了先进加工过程仿真工具（CUT*PRO）、虚拟加工过程仿真工具（MACH*PRO），以及开放式模块化数控加工系统（Virtual CNC），这些产品已被全球机械加工领域超过200家公司和研究机构使用。

在电子工业出版社的努力下，Yusuf Altintas教授的这本著作得以出版影印版。本书基于120多篇期刊文章和60多篇反映作者工程、研究和教学经验的研究论文，重点介绍了金属切削过程力学、机床动力学及振动、进给驱动设计和控制、CNC设计原理、传感器辅助加工和数控编程技术等知识。

本书的主要内容如下。

第1章为绪论；第2章介绍了金属切削过程力学的基本理论及原理；第3章讨论了切削加工过程中的静态变形和振动；第4章分别从频率域和离散时域两个方面介绍了正交切削和斜向切削的颤振理论；第5章介绍了数控技术及其操作和编程原理；第6章介绍了CNC系统设计的基本原理，详细介绍了进给伺服机构的数学模型；第7章介绍了传感器辅助加工，机床上安装了多种传感器，可以测量机械加工过程中的力、振动、温度和声音等。本书论述了金属切削的科学原理及其在解决制造过程中遇到的问题。数学、物理、计算机、仪器仪表等学科被认为是分析或设计机床和制造过程的集成工具。

本书从切削过程力学的基本原理开始，深度讨论了振动及颤振问题；也讨论了数控编程和计算机辅助设计/计算机辅助制造（CAD/CAM）技术。文中还详细介绍了驱动执行机构、反馈传感器的选择、进给驱动系统的建模与控制、轨迹实时生成和插补算法的设计、面向数控系统的误差分析等。每一章都包括从企业实际、设计项目和工作问题中筛选的案例。

本书特别适合于高年级本科生和研究生，以及研发工程师阅读，并能帮助读者在这本书中找到清晰而彻底的方式来学习金属切削力学的工程原理、机床振动、数控系统设计、传感器辅助加工，以及CAD/CAM技术等。

PREFACE

Metal cutting is one of the most widely used manufacturing processes to produce the final shape of products, and its technology continues to advance in parallel with developments in materials, computers, sensors, and actuators. A blank is converted into a final product by cutting extra material away by turning, drilling, milling, broaching, boring, and grinding operations conducted on computer numerically controlled (CNC) machine tools. The second edition of this book helps students and engineers understand the scientific principles of metal cutting technology and the practical application of engineering principles to solving problems encountered in manufacturing shops. The book reflects the author's industrial and research experience, and his manufacturing engineering philosophy as well.

Engineers can learn best by being shown how to apply the fundamentals of physics to actual machines and processes that they can feel and visualize. Mathematics, physics, computers, algorithms, and instrumentation then become useful integration tools in analyzing or designing machine tools and machining processes.

Metal cutting operations take place between a cutting tool and workpiece material mounted on a machine tool. The motion of the machine tool is controlled by its CNC unit, and the numerically controlled (NC) commands to CNC are generated on computer-aided design/computer-aided manufacturing (CAD/CAM) systems. The productivity and accuracy of the metal removal operation depend on the preparation of NC programs, planning of machining process parameters and cutting conditions, cutter geometry, work and tool materials, machine tool rigidity, and performance of the CNC unit. Manufacturing engineers who are involved in machining and machine tool technology must be familiar with each of these topics. It is equally important to link them and to be able to apply them in an interdisciplinary fashion to solve machining problems.

The beginning chapters of this book provide detailed mathematical models of metal cutting, milling, turning, and drilling operations. The macromechanics of cutting, which is applicable to solving problems on the shop floor and in machine tool design, is emphasized. Although required in work and tool material design – the micromechanics of cutting – basic principles of machinability, tool wear mechanisms, and chipping are briefly introduced to provide a complete picture. The design of machine tools requires knowledge of structures, mechanics of solids, vibrations, and kinematics, subjects that are covered in dedicated mechanical engineering texts. This text builds on that knowledge, applying the principles of vibration and experimental modal analysis to machine tools and metal cutting. Mathematical methods are simplified so that they can be easily used to solve machining vibration problems. Chatter vibrations in machining are treated in depth in this text because the problem is experienced daily by practicing manufacturing engineers.

The last three chapters of the book are dedicated to programming, design, and automation of CNC machine tools. Numerically controlled programming and CAD/CAM technology are briefly covered, but with sufficient explanation so that the reader can start programming and using CNC machine tools. The selection of drive actuators, feedback sensors, modeling and analysis of feed drives, the design of real-time trajectory generation and interpolation algorithms, and CNC-oriented error analysis are presented in more detail than can be found in other texts. Open CNC design philosophy and improvement of accuracy and productivity by adding sensors and algorithms to CNC machine tools are also covered.

Students learn best by dealing with real manufacturing problems. The contents of this book are based on experimentally proven engineering principles that are widely used in applied research laboratories and industry. The examples and problems presented in each chapter originate from the research and industrial problems solved by the author and his graduate students. Interdisciplinary problems are posed as industrial projects so that readers can apply all the necessary techniques simultaneously. They solve the basic metal cutting mechanics problem first, followed by milling mechanics, static deflection of end mills and corresponding surface-form error modeling, and vibration model of the end mill and chatter stability. For example, the chain of knowledge is exercised in solving problems associated with milling of an aircraft structure, a project that originated from industry. Similarly, in another project, the reader is guided step by step through the programming, real-time modeling, and control of a CNC machine tool. Because all the projects were tried in the author's laboratory, a number of teaching and research setups are provided in the book to aid instructors.

The book is intended as a text for senior undergraduate and graduate students and practicing manufacturing engineers who wish to learn the engineering principles of metal cutting, machine tool vibration, experimental modal analysis, NC programming and CAD/CAM technology, CNC system design, and sensor-based machining. The book can also be used by researchers who wish to study metal cutting mechanics, machine tool vibrations, feed drive design and control, and CNC and sensor-based machining.

Acknowledgments

The contents of each chapter mostly originated from the author's own engineering, research, and teaching experience. Each chapter is based on a number of graduate student theses supervised at the Manufacturing Automation

Laboratory founded and directed by the author at the University of British Columbia.

The studies of former graduate students and associates E. Budak, A. Spence, E. Shamoto, I. Lazoglu, Haikun Ren, and F. Atabey contributed to Chapter Two, which deals with metal cutting. The theses of E. Budak, S. Engin, P. Lee, S. Park, M. Namazi, D. Merdol, J. Roukema, Z. Dombavari, and M. Eynian were very helpful in writing Chapters Three and Four, where machine tool vibrations are presented. The theses of K. Erkorkmaz, B. Sencer, and C. Okwudire were helpful in writing Chapters Five and Six, which presents the principles of CNC design. The graduate research theses of N. A. Erol and K. Munasinghe were instrumental in forming the final chapter, which deals with sensor-fused machining. The author acknowledges the contributions of all of his former and present graduate students to the accumulation and dissemination of knowledge in machining, machine tools, machine tool vibrations, and control.

Several machinists, engineers, and professors contributed to the author's manufacturing engineering experience. The author received significant practical training from the machine tool design engineers, technologists, and machinists at M.K.E. Top Otomotiv Factory in Kirikkale, Turkey; the machinists and the process planners at Pratt & Whitney Canada in Montreal; and those at Canadian Institute of Metal Working in Hamilton. The author's basic engineering education with rich machine design and analytical content from Istanbul Technical University, CAD/CAM education from the University of New Brunswick, and machine tool engineering background from McMaster University were most valuable in overall development of his manufacturing engineering and research skills. Professors G. Pritschow, U. Heisel, T. Moriwaki, F. Klocke, M. Weck, H. van Brussel, G. Bryne, G. Stepan, T. Altan, and A. G. Ulsoy and industrial colleagues Dr. M. Zatarin (Ideko), Dr. M. Fujishima (Mori Seiki), M. Lundblad (Sandvik), and D. McIntosh (Pratt & Whitney Canada) provided strong personal friendship and research partnership. Machine Tool Technology Research Foundation (MTTRF) and Mori Seiki loaned the experimental machine tools, and Sandvik Coromant and Mitsubishi Materials donated the cutting tools for research. The author was most influenced by the research and machine tool engineering style and philosophy of his mentor the late Professor J. Tlusty.

I acknowledge the valuable editorial support provided by the Cambridge University Press editor, Peter Gordon. I thank those at Cambridge University Press and Aptara for their cooperation and assistance.

Machine tool and metal cutting engineering is a multidisciplinary area that demands knowledge from various fields if one is to be an effective manufacturing engineer and researcher. This requires significant work and effort that cannot be accomplished without the sacrifices of close family members. The author's wife Nesrin, daughter Cagla, and son Hasan bore with the author, who missed an endless number of family days in establishing the Manufacturing Automation Research Laboratory at the University of British Columbia, where

the book has been developed and improved for twenty-five years. The author's mother Hatice and late father Hasan, who were hard-working, honest, and warm wine makers living in the little town Bekili (Denizli, Turkey), were more than role models and a source of support for the author. The author's brother Asim and sister Ummuhan and her husband Ibrahim have been more than family members; they have been very close friends. The author owes the completion of the book to those who supported him throughout his career and life.

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INTRODUCTION

The areas of machine tools, metal cutting, computer numerically controlled (CNC), computer-aided manufacturing (CAM), and sensor-assisted machining are quite wide, and each requires the academic and engineering experience to appreciate a manufacturing operation that uses all of them in an integrated fashion.

Although it is impossible to be an expert in all these subjects, a manufacturing engineer must be familiar with the engineering fundamentals for the precision and economical manufacturing of a part. This book emphasizes only the fundamentals of metal cutting mechanics, machine tool vibrations, feed drive design and control, CNC design principles, sensor-assisted machining, and the technology of programming CNC machines. The book is based on more than 120 journal articles and more than 60 research theses that reflect the engineering, research, and teaching experience of the author.

The book is organized as follows.

Chapter Two covers the fundamentals of metal cutting mechanics. The mechanics of two-dimensional orthogonal cutting is introduced first. The laws of fundamental chip formation and friction between the rake and flank faces of a tool during cutting are explained. The relationships among the workpiece material properties, tool geometry, and cutting conditions are presented. Identification of the shear angle, the average friction coefficient between the tool's rake face and moving chip, and the yield shear stress during machining is explained. The oblique geometry of practical cutting tools used in machining is introduced. The mechanics of oblique cutting for three-dimensional practical tools are explained, and methods in predicting the cutting forces in all directions are presented with the use of the laws of oblique cutting mechanics. The mechanics of turning, milling, and drilling, which constitute the majority of machining operations in the manufacturing industry, are presented. Algorithms for predicting the milling forces in three Cartesian coordinates are derived and illustrated with sample experimental results. Efficient force prediction algorithms for widely used helical end mills are presented. The chapter also briefly discusses the modes and causes of tool wear and breakage, that are important in evaluating the machinability of parts.

Chapter Three deals with static deformations and vibrations during machining. The static deformations occur because of the elastic deflections of both parts and machine during machining. When the static deformation is beyond the tolerance limit, the part is scrapped. Sample formulations are provided to predict the magnitude and location of static deformations in bar turning and end milling. The methods can be extrapolated to other machining operations such as grinding and drilling. One of the most common problems in machining originates from dynamic deformations (i.e., relative structural vibrations between the tool and workpiece). The most common vibrations are due to self-excited chatter vibrations, which grow until the tool jumps out of the cutting zone or breaks because of the exponentially growing dynamic displacements between the tool and workpiece. To understand the machine tool vibrations, the fundamental principles of single – and multi–degree-of-freedom vibration theory are summarized first. Because the machine tool chatter is mainly investigated by analyzing experimental data, the fundamentals of the experimental modal analysis techniques are presented. The modal analysis technique allows the engineer to represent a complex machine tool or workpiece structure by a set of commonly used mathematical expressions that engineers can understand. The technique not only allows one to analyze the chatter vibrations, but it gives a clear message to the machine tool engineer about the structural source of the vibrations during machining, which leads to the improved design.

Chapter Four presents the theory of chatter vibrations in both orthogonal and oblique machining operations both in the frequency and discrete time domain. The mathematical model of regenerative vibrations, which occur in subsequent tool passes during machining, is presented. The methods of determining chatter vibration–free axial depths of cuts and spindle speeds in orthogonal cutting operations are presented with and without process damping. Mathematical models of predicting chatter stability in turning, drilling, and milling operations are introduced. The techniques are explained with the aid of results obtained from simulation and machining tests. The engineer is presented with methods that increase the machining productivity by avoiding chatter vibrations.

Chapter Five introduces the CNC technology and its principles of operation and programming. First, standard NC commands accepted by all CNC machine tools are summarized. These include the format of an NC code accepted by the CNC of the machine tool, motion commands such as linear and circular contouring along a tool path, miscellaneous commands such as spindle and coolant control, and automatic cycles. Later, the introductory principles of CAM are presented. NC programs generated by CAM systems are processed by CNC units that generate position commands to each drive based on trajectory generation and real-time interpolation algorithms. The mathematical details of generating smooth trajectory with velocity, acceleration, and jerk limits of the machine are covered. Real-time interpolation of linear, circular, and splined paths are presented with examples.

Engineers who know how to use and program CNC machine tools must familiarize themselves with the design and internal operational principles of CNC. Chapter Six describes the fundamentals of CNC design, starting with the selection of drive motors and servoamplifiers. Mathematical modeling of feed servodrives is presented in detail. The transfer functions of mechanical drive inertia and friction, servomotor, amplifier, and velocity and position feedback sensors are explained with their practical interpretations. The transformation of continuous-time domain models of the physical system into discrete computer time domain models is explained. Design and tuning procedures for the digital control of feed drives are presented with real-life examples. Advanced control techniques for precision tracking and active vibration damping of feed drives are presented. The chapter is complemented with the design of electrohydraulic machine tool drives to show that the CNC design principles are general and can be applied to any mechanical system regardless of the actuators.

The recent trend in machining is to add intelligence to the machine tools and CNC, as discussed in Chapter Seven. Sensors that can measure the forces, vibrations, temperature, and sound during machining are installed on the machine tools. Mathematical models that correlate the relationship between the measured sensor signals and the state of machining are formed. The mathematical models are coded into real-time algorithms that monitor the machining process and send commands to CNC for corrective actions. The chapter includes simple but fundamental machining process control algorithms along with their theoretical foundations. Adaptive control of cutting forces, in-process monitoring of tool failure, and chatter detection algorithms are presented with their experimental validation and engineering application.

Sample problem sets are included at the end of each chapter. The problems mostly originated from the actual design, application, and experiments conducted at the author's manufacturing automation research laboratory; hence, they are designed to give a realistic feeling for engineering students. Because the book contains multiple engineering disciplines applied to machine tool engineering problems in an integrated fashion, most of the basic mechanical engineering concepts are assumed to be understood by the readers. However, the basic principles of Laplace and z transforms, as well as least squares – based identification techniques, are provided in the appendix.

The advanced mathematical models developed in the author's laboratory are simplified to teach the basic principles of metal cutting mechanics, machine tool vibrations, and control in this second edition of the book. The details of the full mathematical models are published in the research theses of graduate students and journal articles supervised by the author. The advanced algorithms are also packaged in CUTPRO © Advanced Machining Process Simulation Software [66], which is licensed to research centers and machining industry worldwide.

MECHANICS OF METAL CUTTING

2.1 INTRODUCTION

The final shapes of most mechanical parts are obtained by machining operations. Bulk deformation processes, such as forging and rolling, and casting processes are mostly followed by a series of metal-removing operations to achieve parts with desired shapes, dimensions, and surface finish quality. The machining operations can be classified under two major categories: cutting and grinding processes. The cutting operations are used to remove material from the blank. The subsequent grinding operations provide a good surface finish and precision dimensions to the part. The most common cutting operations are *turning*, *milling*, and *drilling* followed by special operations such as *boring, broaching, hobing, shaping*, and *form cutting*. However, all metal cutting operations share the same principles of mechanics, but their geometry and kinematics may differ from each other. The mechanics of cutting and the specific analysis for a variety of machining operations and tool geometries are not widely covered in this text. Instead, a brief introduction to the fundamentals of cutting mechanics and a comprehensive discussion of the mechanics of milling operations are presented. Readers are referred to established metal cutting texts authored by Armarego and Brown [25], Shaw [96], and Oxley [83] for detailed treatment of the machining processes.

2.2 MECHANICS OF ORTHOGONAL CUTTING

Although the most common cutting operations are three-dimensional and geometrically complex, the simple case of two-dimensional orthogonal cutting is used to explain the general mechanics of metal removal. In orthogonal cutting, the material is removed by a cutting edge that is perpendicular to the direction of relative tool–workpiece motion. The mechanics of more complex three-dimensional oblique cutting operations are usually evaluated by geometrical and kinematic transformation models applied to the orthogonal cutting process. Schematic representations of orthogonal and oblique cutting processes are shown in Figure 2.1. The orthogonal cutting resembles a shaping process with a straight tool whose cutting edge is perpendicular to the cutting velocity (V). A metal chip with a width of cut (b) and depth of cut (h) is sheared away from the workpiece. In orthogonal cutting, the cutting is assumed to be uniform along the cutting edge; therefore, it is a two-dimensional plane strain deformation