CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

MANUFACTURING AUTOMATION

Second Edition

Metal cutting is one of the most widely used methods of producing the final shape of manufactured products. The technology involved in metal cutting operations has advanced considerably in recent years, along with developments in materials, computers, and sensors.

This book treats the scientific principles of metal cutting and their practical application to solving problems encountered in manufacturing. The subjects of mathematics, physics, computers, and instrumentation are discussed as integration tools in analyzing or designing machine tools and manufacturing processes.

The book begins with the fundamentals of metal cutting mechanics. The basic principles of vibration and experimental modal analysis are applied to solving problems on the shop floor. A special feature is the in-depth coverage of chatter vibrations, a problem experienced daily by practicing manufacturing engineers. The essential topics of programming, design, and automation of computer numerically controlled (CNC) machine tools, numerically controlled (NC) programming, and computer-aided design/computer-aided manufacturing (CAD/CAM) technology are discussed. The text also covers the selection of drive actuators, feedback sensors, the modeling and control of feed drives, the design of real-time trajectory generation and interpolation algorithms, and CNC-oriented error analysis in detail. Each chapter includes examples drawn from industry, design projects, and homework problems.

Advanced undergraduate and graduate students, and practicing engineers, as well, will find in this book a clear and thorough way to learn the engineering principles of metal cutting mechanics, machine tool vibrations, CNC system design, sensor-assisted machining, and CAD/CAM technology.

Yusuf Altintas is a Fellow of the Royal Society of Canada and NSERC Pratt & Whitney Canada Research Chair Professor of Mechanical Engineering and Director of the Manufacturing Automation Laboratory at the University of British Columbia.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

MANUFACTURING AUTOMATION

METAL CUTTING MECHANICS, MACHINE TOOL VIBRATIONS, AND CNC DESIGN

Second Edition

YUSUF ALTINTAS

University of British Columbia

CAMBRIDGE UNIVERSITY PRESS

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Tokyo, Mexico City

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521172479

© Yusuf Altintas 2012

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without the written
permission of Cambridge University Press.

First published 2012

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication data

Altintas, Yusuf, 1954–
Manufacturing automation : metal cutting mechanics, machine tool vibrations, and CNC design /
Yusuf Altintas. – 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-107-00148-0 (hardback) – ISBN 978-0-521-17247-9 (paperback)
1. Machining – Automation. 2. Machine-tools – Vibration. 3. Machine-tools – Numerical control. I. Title.
TJ1185.5.A48 2011
670–dc23 2011041033

ISBN 978-1-107-00148-0 Hardback
ISBN 978-0-521-17247-9 Paperback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party Internet Web sites referred to in this publication and does not guarantee that any content on such Web sites is, or will remain, accurate or appropriate.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

CONTENTS

Preface *page* ix

1 INTRODUCTION 1

2 MECHANICS OF METAL CUTTING 4

2.1 Introduction 4
2.2 Mechanics of Orthogonal Cutting 4
2.3 Mechanistic Modeling of Cutting Forces 15
2.4 Theoretical Prediction of Shear Angle 18
2.5 Mechanics of Oblique Cutting 19
2.5.1 Oblique Cutting Geometry 19
2.5.2 Solution of Oblique Cutting Parameters 21
2.5.3 Prediction of Cutting Forces 25
2.6 Mechanics of Turning Processes 27
2.7 Mechanics of Milling Processes 35
2.7.1 Mechanics of Helical End Mills 41
2.8 Analytical Modeling of End Milling Forces 43
2.8.1 Mechanistic Identification of Cutting Constants in Milling 46
2.9 Mechanics of Drilling 47
2.10 Tool Wear and Tool Breakage 54
2.10.1 Tool Wear 56
2.10.2 Tool Breakage 61
2.11 Problems 62

3 STRUCTURAL DYNAMICS OF MACHINES 66

3.1 Introduction 66
3.2 Machine Tool Structures 66
3.3 Dimensional Form Errors in Machining 68
3.3.1 Form Errors in Cylindrical Turning 68
3.3.2 Boring Bar 70
3.3.3 Form Errors in End Milling 71
3.4 Structural Vibrations in Machining 74
3.4.1 Fundamentals of Free and Forced Vibrations 75
3.4.2 Oriented Frequency Response Function 82

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

3.4.3 Design and Measurement Coordinate Systems 83
3.4.4 Analytical Modal Analysis for Multi–Degree-of-Freedom Systems 85
3.4.5 Relative Frequency Response Function between Tool and Workpiece 90
3.5 Modal Testing of Machine Structures 92
3.5.1 Theory of Frequency Response Testing 92
3.5.2 Experimental Procedures in Modal Testing 97
3.6 Experimental Modal Analysis for Multi–Degree-of-Freedom Systems 98
3.7 Identification of Modal Parameters 109
3.7.1 Global Nonlinear Optimization of Modal Parameter Identification 113
3.8 Receptance Coupling of End Mills to Spindle-Tool Holder Assembly 115
3.8.1 Experimental Procedure 118
3.9 Problems 120

4 MACHINE TOOL VIBRATIONS 125
4.1 Introduction 125
4.2 Stability of Regenerative Chatter Vibrations in Orthogonal Cutting 126
4.2.1 Stability of Orthogonal Cutting 126
4.2.2 Dimensionless Analysis of Stability Lobes in Orthogonal Cutting 132
4.2.3 Chatter Stability of Orthogonal Cutting with Process Damping 135
4.3 Chatter Stability of Turning Operations 139
4.4 Chatter Stability of Turning Systems with Process Damping 142
4.4.1 Metal Cutting Forces 144
4.4.2 Process Damping Gains Contributed by Flank Wear 145
4.4.3 Stability Analysis 147
4.5 Experimental Validation 148
4.6 Analytical Prediction of Chatter Vibrations in Milling 149
4.6.1 Dynamic Milling Model 149
4.6.2 Zero-Order Solution of Chatter Stability in Milling 154
4.6.3 Multi-Frequency Solution of Chatter Stability in Milling 160
4.7 Chatter Stability of Drilling Operations 172
4.7.1 Dynamic Drilling Force Model 173
4.8 Frequency Domain Solution of Drilling Stability 176
4.9 Semidiscrete Time Domain Solution of Chatter Stability 178
4.9.1 Orthogonal Cutting 178
4.9.2 Discrete Time Domain Stability Solution in Milling 182
4.10 Problems 186

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

5 TECHNOLOGY OF MANUFACTURING AUTOMATION 191

5.1 Introduction 191
5.2 Computer Numerically Controlled Unit 191
5.2.1 Organization of a CNC Unit 191
5.2.2 CNC Executive 193
5.2.3 CNC Machine Tool Axis Conventions 193
5.2.4 NC Part Program Structure 193
5.2.5 Main Preparatory Functions 196
5.3 Computer-Assisted NC Part Programming 201
5.3.1 Basics of Analytical Geometry 201
5.3.2 APT Part Programming Language 206
5.4 Trajectory Generation for Computer-Controlled Machines 211
5.4.1 Interpolation with Constant Displacement 212
5.4.2 Acceleration-Limited Velocity Profile Generation with Constant Interpolation Period 216
5.4.3 Jerk-Limited Velocity Profile Generation 220
5.5 Real-Time Interpolation Methods 229
5.5.1 Linear Interpolation Algorithm 230
5.5.2 Circular Interpolation Algorithm 234
5.5.3 Quintic Spline Interpolation within CNC Systems 239
5.6 Problems 245

6 DESIGN AND ANALYSIS OF CNC SYSTEMS 250

6.1 Introduction 250
6.2 Machine Tool Drives 250
6.2.1 Mechanical Components and Torque Requirements 251
6.2.2 Feedback Devices 256
6.2.3 Electrical Drives 257
6.2.4 Permanent Magnet Armature-Controlled dc Motors 258
6.2.5 Position Control Loop 263
6.3 Transfer Function of the Position Loop 264
6.4 State Space Model of Feed Drive Control Systems 268
6.5 Sliding Mode Controller 281
6.6 Active Damping of Feed Drives 285
6.7 Design of an Electrohydraulic CNC Press Brake 293
6.7.1 Hydraulic Press Brake System 293
6.7.2 Dynamic Model of Hydraulic Actuator Module 296
6.7.3 Identification of Electrohydraulic Drive Dynamics for Computer Control 299
6.7.4 Digital Position Control System Design 301
6.8 Problems 307

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

7 SENSOR-ASSISTED MACHINING 313

7.1 Introduction 313
7.2 Intelligent Machining Module 313
7.2.1 Hardware Architecture 314
7.2.2 Software Architecture 315
7.2.3 Intelligent Machining Application 316
7.3 Adaptive Control of Peak Forces in Milling 317
7.3.1 Introduction 317
7.3.2 Discrete Transfer Function of the Milling Process System 319
7.3.3 Pole-Placement Control Algorithm 321
7.3.4 Adaptive Generalized Predictive Control of Milling Process 325
7.3.5 In-Process Detection of Tool Breakage 330
7.3.6 Chatter Detection and Suppression 333
7.4 Intelligent Pocketing with the IMM System 334
7.5 Problems 336

APPENDIX A: LAPLACE AND *z* TRANSFORMS 341

A.1 Introduction 341
A.2 Basic Definitions 343
A.3 Partial Fraction Expansion Method 347
A.4 Partial Fraction Expansion Method to Determine Inverse Laplace and *z* Transforms 349

APPENDIX B: OFF-LINE AND ON-LINE PARAMETER ESTIMATION WITH LEAST SQUARES 353

B.1 Off-Line Least-Squares Estimation 353
B.2 Recursive Parameter Estimation Algorithm 355

Bibliography 357
Index 363

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

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 this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

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

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

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

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

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.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-00148-0 - Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design: Second Edition
Yusuf Altintas
Frontmatter
More information

MANUFACTURING AUTOMATION

© in this web service Cambridge University Press www.cambridge.org