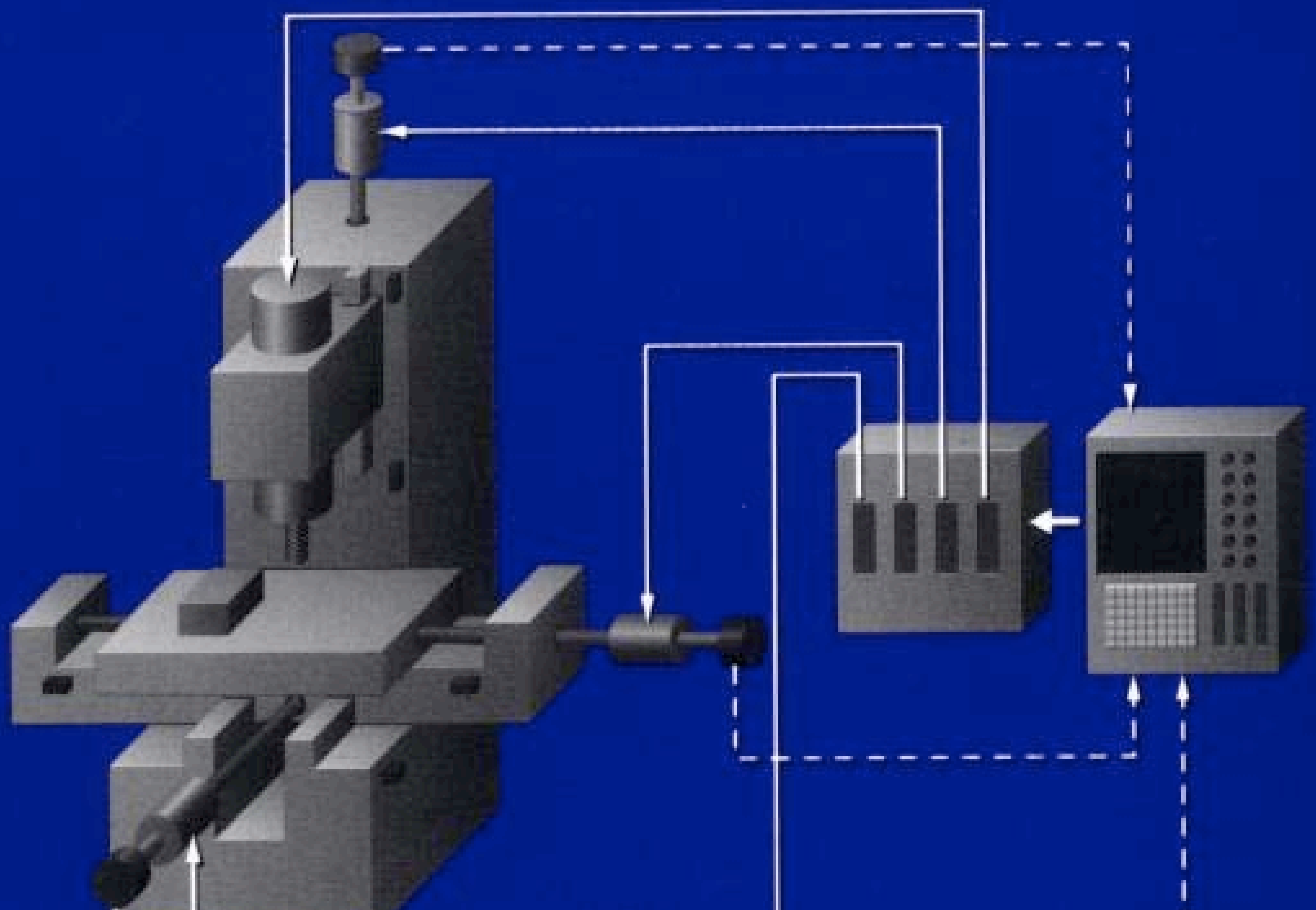
Manufacturing Automation

Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design



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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, software, 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. 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 CNC (computer numerical control) machine tools; NC (numerical control) programming; and CAD/CAM technology are fully discussed. The text also covers 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 in detail. Each chapter includes examples drawn from industry, design projects, and homework problems.

Advanced undergraduate and graduate students, as well as practicing engineers, will find 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.

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CAMBRIDGE
UNIVERSITY PRESS
www.cambridge.org
ISBN 0-521-65973-6
9 780521 659734

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INTRODUCTION

The area of machine tools, metal cutting, computer numerically controlled (CNC), computer-aided manufacturing (CAM), and sensor-assisted intelligent machining is quite wide, and each requires an 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, static and dynamic deformations, design principles of CNC, sensor-assisted machining, and technology of programming CNC machines. Although industrial engineering aspects, such as the scheduling of parts and economics, also play an important role in cost effective manufacturing, the book focuses only on the physical principles of machining 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 shear angle, average friction coefficient between the tool's rake face and moving chip, and 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 using the laws of oblique cutting mechanics. 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, which are important in evaluating the machinability of parts.

Chapter Three deals with static deformations and vibrations during machining. The static deformations occur due to 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 due to exponentially growing dynamic displacements between the tool and workpiece. In order to understand the machine tool vibrations, the fundamental principles of single- and multi–degree-of-freedom vibration theory are summarized first. Since 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. After providing basics of vibration engineering, the chapter presents the theory of chatter vibrations in both orthogonal machining and complex milling operations. The mathematical model of regenerative vibrations, which occur in subsequent tool passes during machining, is presented. Methods of determining chatter vibration–free axial depths of cuts and spindle speeds in orthogonal cutting operations are presented. A special technique that allows the engineer to predict chatter-free conditions in complex milling operations is introduced. The technique is 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 Four 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, computer-aided manufacturing (CAM) is introduced by explaining the difficulties in generating NC codes manually. First, the APT (Automatically Programmed Tooling) programming language is introduced. The structure of parametric definition of part geometry, tool geometry, and tool motions is explained, along with sample APT language commands. The general output of the APT, which is called CL (cutter location) data, is standard and acceptable by all CNC machine tools when it is processed by a postprocessor. The postprocessor converts the machine tool–independent CL data into machine tool–specific manual NC commands automatically. Later, computer-aided design (CAD), used both in designing the parts and generating tool paths by interactive graphical techniques, is explained. The chapter focuses on teaching the basics and the use of CAM technology, but not the theory of computer graphics, which is not within the main mandate of a manufacturing engineer.

Engineers who know how to use and program CNC machine tools must familiarize themselves with the design and internal operational principles of CNC. Chapter Five describes the fundamentals of CNC design, starting with the selection of drive motors and servo amplifiers. Mathematical modeling of feed servo drives is presented in detail. Transfer functions of mechanical drive inertia and friction, servo motor, amplifier, and velocity and position feedback sensors are explained with their practical interpretations. Transforming continuous-time domain models of the physical system into discrete computer time domain models is explained. Design and tuning procedures for digital control of feed drives are presented with real life examples. The CNC design includes real-time tool path generation with linear, circular, and spline interpolations coupled with the scheduling of acceleration, deceleration, and vector feed speed control along the tool paths. The chapter is complemented with the design of electro-hydraulic machine tool drives in order 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 Six. Sensors, which can measure the forces, vibrations, temperature, and sound during machining, are installed on the machine tools. Mathematical models, which correlate the relationship between the measured sensor signals and state of machining, are formed. The mathematical models are coded into real-time algorithms, which monitor the machining process and send commands to CNC for corrective actions. The chapter presents an Intelligent Machining and Open Real Time CNC Operating System that allows modular design and integration of sensor-fused application algorithms into the machine tool. 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. Since 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 square–based identification techniques, are provided in the appendix.