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Preface

Machine tool design and manufacturing are tightly associated with innovation. They have been the key areas that support and influence a nation's economy since the eighteenth century. This is especially true for the machine tool industry. As the mother machines, machine tools form the basis for the development of many other products. In the past centuries, machine tool design and manufacturing have contributed significantly to modern civilisation and created the momentum that drives today's economy. Despite various achievements, we are still facing challenges due to the growing complexity in machine tool design and development.

The complexity comes from multiple directions. On one hand, the complex shape and geometry of new products require more sophisticated machining capability of machine tools to produce the new products to specifications. On the other hand, the ever-growing quality requirements of customers demand tight tolerance for the manufactured products. Consequently, a machine tool must perform accurately, reliably and with high repeatability over time.

It is a common practice that a machine tool is designed and analysed in static state with constraints and under assumptions. A so-designed machine may not perform consistently over time in running state. Among varying working conditions in reality, uneven temperature distribution across the machine components is most influential to machining accuracy due to thermal deformation during metal cutting operations. This thermal deformation alters the cutter–workpiece relationship dynamically, resulting in unsatisfactory machined surfaces. Although modern computer-aided techniques are helpful in addressing some of the problems in machine tool design, there still remains a big gap between the required performance and the real performance of a machine because of the static nature of problem-solving capability of current software tools and applied technology. Two significant problems remain to be solved: (1) how to effectively share information between solid modelling and engineering analysis modules, and (2) how to satisfactorily enable dynamic analysis to simulate the true behaviours of machine tools in running state.

To bridge the gap and present the state-of-the-art of machine tool design and development to a broad readership, from academic researchers to practicing engineers, is the primary motivation behind this book.

This book summarises basic concepts, fundamental considerations and problem-solving algorithms relevant to machine tool design and analysis in running state. The book is composed of six chapters, and a brief outline of each chapter is given below. Chapter 1 provides an introduction of the historical background of relevant research, and clarifies why this research is necessary to be carried out and what the objectives of the research are. Based on the literature analysis, the motivation of this book on dynamic thermal analysis for machine design is carefully laid out. Chapter 2 provides a detailed description of the techniques for representation of machine tool models. Constructive Solid Geometry (CSG) is adopted as the primary representation in this book, among contemporary solid modelling methods, for the ease of modelling of machine tool structures. A low-level data structure is documented for establishing a primitive library with the characteristics of machine tool structures. Chapter 3 presents a method to implement a product modelling system for machine tool design. Based on the design process of machine tools, considerable requirements to be met in the product modelling system are specified, together with the definition of product models. For the purpose of system development, a high-level data structure for both components and an entire machine tool is proposed. Kinematic simulations, as case studies, are carried out by using the product modelling system. The connection between the product modelling system and an integrated CAD/CAE system is emphasised.

Moving from modelling to analysis, Chap. 4 presents a new method for dynamic finite element mesh generation, called Coded Box Cell (CBC) substitution approach in this book. Hexahedrons are chosen as the mesh elements for the convenience of automatic generation and modification of FEM meshes, since machine tools are mostly composed of cuboids and box-type primitives. The extension of the CBC substitution to curved objects is introduced by using mapping and inverse mapping techniques. Full details of the CBC substitution approach are described in this chapter. A new data structure of machine tool model for its utilisation in FEM mesh generation is also given, based on which several practical case studies are carried out. Chapter 5 showcases an application of the CBC substitution approach to finite element analysis. Since thermal error is the major factor that affects the machine tool designs, the thermal analysis is taken into consideration. The table and the base of a machine tool is simplified as the model of the thermal analysis. The Emphasis is given to the interpolation of intermediate results between consecutive analytical steps for the purpose of a continuous calculation, when relative motions take place between the table and the base. The corresponding experiments under the same running conditions are conducted. Based on the analytical and experimental results, discussions and evaluations are documented. Finally, Chap. 6 draws to the conclusions of this book. After summarising each chapter and the research findings, challenges and future research directions are pointed out for interested readers working in the same field.

Finally, the author would like to take this opportunity to express his appreciation to Springer for supporting this book, and would especially like to thank Anthony Doyle, Senior Editor for Engineering, and Christine Velarde, Senior

Editorial Assistant, for their patience, constructive assistance and earnest cooperation, both with the publishing venture in general and with the editorial details. We hope that readers find this book informative and useful.

Stockholm, March 2013 Lihui Wang

Symbols

α_c	Heat transfer coefficient across S_3
c	Specific heat of material
$[C]$	Heat capacity matrix
$d(m, n)$	Distance between nodes m and n
D	Direction of normal vector on the contacting plane of the primitives F and M
$\tilde{D}$	Displacement of relative motion after Δt
δ^F, δ^M	Mesh sizes (lengths between adjacent nodes) of the FEM meshes of the primitives F and M, respectively
δ^{max}	Maximum mesh size of a meshwork
Δt	Time interval of calculation
e	Element
f	Mapping function
F	Fixed primitive
$\{F\}$	Heat flux vector
g	Inverse mapping function
I	Functional
I_{pr}	An image of pr
ID_{CBC}	Set of identification numbers of CBCs to be used for substitution
$[J]$	The *Jacobian* matrix
k	The number of elements
$[K]$	Heat conductivity matrix
L^F, L^M	Node labels of the primitives F and M, respectively
λ_x, λ_y, λ_z	Heat conductivities of material in directions x, y and z, respectively
λ	Heat conductivity of material (for isotropic solid)
M	Movable primitive
M_{id}	Mapping function identifier
$N(\prod)$	Number of nodes in the direction P or V in the FEM mesh of primitive $\prod$
$N(x, y, z)$	Shape function
P	Direction of motion of the primitive M against F
pr	An instance of a primitive

π	*Project* operator
q_0	Heat flux across S_2
$\dot{Q}$	Rate of heat generated in a solid per unit time per unit volume
R^3	Real object space
RP^3	Projective space
ρ	Specific gravity of material
$S_{1,2,3,4}$	Boundary surfaces of heat effects
S^F, S^M	Face labels of the primitives F and M, respectively
σ	The *Stefan–Boltzmann* constant
t	Time
T	Temperature distribution
$\dot{T}$	Incremental rate of T
$\bar{T}$	Prescribed temperature on S_1
T_c	Surrounding temperature
T_r	Temperature of radiation source
θ	Temperature
$\{\theta(t)\}$	Nodal temperature vector at time t
V	Direction perpendicular to both the directions P and D
V^F, V^M	Sets of nodes of the primitives F and M on contacting plane, respectively
(x, y, z)	Coordinates in the real object space R^3
(ξ, η, ς)	Coordinates in the projective space RP^3
^{+}V	Set of nodes with interpolated analytical data
$*$	*Join* operator
$\ominus$	Set operator for subtraction
ε	Rate of heat radiation
$\{\ \}$	Vector
$[\ ]$	Matrix
$[\ ]^{-1}$	Inverse matrix of $[\ ]$
$[\ ]^e, \{\}^e$	Matrix and vector of element, respectively
$[\ ]^T, \{\}^T$	Transpositional forms of $[\ ]$ and $\{\ \}$, respectively
$\vert_i$ or $\vert_j$	Subscript for value of *i*th or *j*th node
$\vert^{new}$	Superscript for values after relative motion took place
$\vert^{old}$	Superscript for values before relative motion takes place
$\vert_{\omega}$	Subscript for values corresponding to x, y and z terms, respectively
$\vert_P$	Subscript for direction of relative motion
$\vert_{\bar{P}}$	Subscript for direction perpendicular to P

Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
AI	Artificial Intelligence
APT	Automatic Programming Tool
B-reps	Boundary Representation
BEM	Boundary Element Method
CAA	Computer-Aided Analysis
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CBC	Coded Box Cell
CIM	Computer Integrated Manufacturing
CNC	Computer Numerical Control
CSG	Constructive Solid Geometry
DBMS	Database Management System
DNC	Direct Numerical Control
EFGM	Element Free Galerkin Method
F-label	Face-label
FEA	Finite Element Analysis
FEM	Finite Element Method
FMS	Flexible Manufacturing System
FPM	Finite Point Method
ID	Identification
LAN	Local Area Network
MIT	Massachusetts Institute of Technology
N-label	Node-label
NC	Numerical Control
PC	Personal Computer
RKPM	Reproducing Kernel Particle Method
SE	Spatial Enumeration

Contents

Chapter 1
Introduction

1.1 Historical Background

The computer-aided technologies, such as computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-aided engineering (CAE), have a history of more than five decades (from 1958 onward) [1–7].

The first period was mainly dominated by varying military research projects. The development of *Sketchpad* was considered the first exciting demonstration of possibilities in the civilian field [2]. For practical reasons of cost-performance of hardware at the time, initial developments were confined to a limited number of universities and research teams.

The second period ushered in an explosive growth in CAD. A new wave of independent software firms, using minicomputers with better hardware cost-performance, has pushed the development of interactive systems using visual displays leading to graphic workstations. The applications of such workstations interfaced with mainframes or host computers to take advantages of previous investments in software, promoted multiseat configurations and developments in local area networks (LAN) using common databases. In terms of software innovation, there were improvements in operating systems, language and graphics tools, with interfaces to link analysis and application packages. Modular systems were also adopted. Integrated design-to-manufacturing systems emerged for the electronics and microelectrics industries, as well as for manufacturing using numerical control (NC) machines.

The third period was characterised by the emphasis on manufacturing, the use of robots in automated cells for manufacturing and assembly and the integration of all aspects of business. The personal computer (PC) and the major improvements in cost-performance of hardware through volume production and 'chip' technology, also emerged. This, with improved raster and vector displays, enabled the ubiquitous PC platform to be offered as a basic graphic workstation. At the same time the first artificial intelligence (AI) and knowledge-based systems became available for use in many industrial sectors.

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In the field of machine tool designs, Massachusetts Institute of Technology (MIT) provided the fertile ground. In the early 1950s, the Computer Applications Group of Electronic System Laboratory (formerly the Servomechanisms Laboratory) pioneered paper tape control of machine tools leading into the late 1950s to the development of the automatic programming tool (APT) language for programming of cutter movements [6]. In 1958, D. Baumann and S. A. Coons of MIT Mechanical Engineering approached D. Ross of MIT Computer Applications Group to see whether it might be possible to take another important step beyond APT [8]. At the Baumann-Coons-Ross meeting, a new system was outlined that would bind man and computer in an intimate co-operative complex, a combination that would use the creative and imaginative powers of humans and the analytical and computational powers of computers, each with the greatest possible economy and efficiency. The outcome of this meeting was a formal arrangement for Computer Applications and Mechanical Engineering to work together in a broad study of what they then named CAD [9].

In the early years, there was some controversy over the nature and characteristics of CAD. For example, did the 'A' stand for automated or aided? Initially, attempts were made to automate the design process by creating a program to duplicate the logical and numerical steps taken by human designers. This approach had many drawbacks, not least the need with batch computing to rerun the program for changes in assumptions or parameters. The more serious objection was the inability to interact with the computer and use human judgement. The breakthrough came when it became possible to control the overall sequence of solving a problem, to think and intervene, feeding information in real time into computers. This interactive concept of a partnership between a designer and a computer transformed problem-solving and decision-making, and was completed with the developments of the storage tube and visual display that allowed designers to 'see what they were doing'.

In 1962, four years on from the Baumann-Coons-Ross meeting, Ivan Sutherland's thesis on the uses of a display for design, with constraints, became well known. His system named *Sketchpad* was the first showpiece of CAD. Following *Sketchpad*, a car panel design system developed by General Motors, with IBM, was presented at the 1964 Spring *Joint Computer Conference* (JCC) as the second showpiece.

The early CAD pioneers were motivated by the need to interact with computers in a new kind of partnership. Much was heard of the man-machine interfaces and the need to develop creative ideas using a graphic display for visual communication. Since translating ideas into reality means describing and defining solid 3D objects, a huge amount of effort was devoted to 3D modelling and visualisation [10–22]. 3D models of objects are necessary communication media in design and manufacturing; whereas computer graphics provided the key to using computers in order to input, manipulate and output the 3D models.

Some practical CAD systems, such as *PADL*-2 [23], *Build*-2 [24], *GMSolid* [25] and *GWB* [26], appeared after *Sketchpad* in late 1970s. At the same time, since the object definition involves a richness of product and material description, and in many cases, the generation of vast volume of data, much attention was paid to the nature and structure of databases to hold such information [27–29]. Language, in respect of the arguments concerning compilers that had raged in the 1960s, ceased to be a problem. Instead it was accepted that job-oriented commands and menus would better serve the purpose of engineers.

Wrestling with major problems led different groups down different paths. Europe was preoccupied with CAD and interactive computing. America pursued the path of batch computing with ever larger mainframes, and pioneered NC manufacturing. Later in the 1970s, with the extension of the activities of the European Community into the realms of advanced technology, regular meetings took place headed by France, Germany and the UK, during which a clear consensus emerged on the nature and importance of CAD.

CAD acted as a focal point for a ferment of new ideas that provided the driving force for fundamental changes in the way computers were used. A new philosophy for translating ideas into reality emerged, leading to a convergence of computing, information and communication technologies, together with an integration of activities, skills and disciplines that were formerly separate. The subsequent impact of computers on industry and society took shape and substance as CAD was developed and matured.

Out of this background of CAD came the important interactive graphics developments, the visual display software tools and the workstations as we know them today [30, 31]. This in turn enabled modular application systems to be developed with better economy and cost-performance.

In mechanical industries, various robots were developed and utilised for automating tool and workpiece handlings, machine operation and the assembly and welding of components. The application of robots introduced new requirements for robot recognition, and stimulated further developments in image analysis with consequent need for integration with the established methods of object definition in CAD design and modelling systems. Artificial intelligence, in the form of expert and knowledge-based systems, developed in two forms: as conceptual front ends to CAD systems, to enable 'what if' questions of manufacturability or cost to be asked during the design stage; or as an aid to expand human mental processes and experience (the so-called 'thinking machine'). The notion of hardware and software as a system involving humans and machines emerged, as experiences demonstrated the need to link activities and to integrate what became known as 'islands of automation'. As this need for integration dominated, the term computer integrated manufacturing (CIM) became popular.

The developments in CAM can also be traced back to the development of numerical control of machine tools in the early 1950s. This first application of computers for control of machine tools opened up the potential for optimisation of manufacturing through computer numerical control (CNC) and direct numerical control (DNC), for small batch production, leading to flexible manufacturing systems (FMS). CNC was first introduced in 1977 [6], which made it possible that a machine tool could be connected directly online to either a dedicated microprocessor or, on a shared basis, to the computer display which formed the user–system interface. As for FMS, protocols and procedures that were developed to link the design offices with the manufacturing and assembly operations in the mechanical industries gave a powerful impetus to integration and standards for system and network linking. This demand for integration, coupled with the more general applications of CAD/CAM across industry, made obvious the need to link all the activities of business.

Meanwhile, a new concept of computer-aided engineering (CAE) appeared in the 1980s. CAE could be considered as a team, embracing the related areas of CAD, computer-aided analysis (CAA) and CIM. They are in addition to the many supporting activities, such as planning, management and control of manufacturing plants through either direct or indirect computer interface. CAE is a combination of techniques in which man and machine are blended into a problem-solving team, intimately coupling the best characteristics of each. The result of this combination works better than either man or machine would work alone, and by using a multidisciplinary approach, it offers the advantages of integrated teamwork [32].

CAD/CAM, CAE, FMS, CIM and many other acronyms are simply describing the use of computers in various aspects of design and manufacturing, and represent logical steps in an evolutionary development although in different time-frames. To date, it is interesting to speculate on the way that neural networks or connectivity machines, with appropriate simulation software, could extend the performance of current systems and deal adequately with the accumulated information and experience. The ability to cope with 'fuzzy data' through associative memory, and learn from the stored information rather than catalogue it in a database for search and retrieval, would represent a major advance bringing together design, production, finance and management. In the field of machine tool design and machining by using computer-aided techniques, various methodologies and modelling methods were introduced recently, such as machining feature extraction [33–37], intelligent CAD [38, 39] and form-feature recognition by using neural-network-based techniques [40].

In this new situation, standards for open system architecture, operating system characteristics, graphics and system building tools, data information exchange, interface connections and communication protocols all assume a new importance. Thus, some researches have been carried out in this field [41–44].

Today, almost everyone is aware of the powerful influence of the high-tech based on the computer-aided technologies in our industrial society. But, a few have been aware of the meaningful influence of machine tools in the Industrial Revolution. The main aspects of the Industrial Revolution have been concerned only with *power* (principally the steam engine), new *materials* (mostly steel) and the many types of *production machinery* (principally for textiles). However, only few have considered the technical development without which the steam engine and the machinery could not have been built, the development without which steel would have been of little significance—the *machine tools*. One can hardly say that the existence of machine tools was a sufficient condition for the Industrial Revolution, but we are certain that it was a necessary condition for the development of the industrial society in which we live [45]. It is, therefore, necessary to carry out a thorough research of machine tools to the same meaning.