高等学校"十一五"规划教材
机械设计制造及其自动化系列

DESIGN OF MACHINE ELEMENTS

机械零件设计（双语教程）

主编　翟文杰　敖宏瑞

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哈爾濱工業大學出版社

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Abstract

Design of Machine Elements is particularly written for bilingual machine design course to Chinese students with a balanced consideration of the basic requirements of the course and the students' English proficiency. Hopefully the students can learn not only the skills of machine design but also the usage of English, thus strengthening their ability of solving practical mechanical engineering problems and meeting the challenge of globalization.

There are thirteen chapters in this book. The first three chapters discuss the general concerns of machine design, fundamentals of strength design, and introduction of tribology, respectively. The following chapters deal with the design of various specific machine elements, namely, shafting, sliding bearings, rolling-element bearings, power screws, threaded joints, springs, gears, worm gears, brakes and clutches, and belt drives.

This book can be used as a textbook for teachers and students in mechanical engineering specialty or as a reference for the advanced-level students and the practicing engineers as well.

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高等学校“十一五”规划教材

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总　　序

自1999年教育部对普通高校本科专业设置目录调整以来，各高校都对机械设计制造及其自动化专业进行了较大规模的调整和整合，制定了新的培养方案和课程体系。目前，专业合并后的培养方案、教学计划和教材已经执行和使用了几个循环，收到了一定的效果，但也暴露出一些问题。由于合并的专业多，而合并前的各专业又有各自的优势和特色，在课程体系、教学内容安排上存在比较明显的“拼盘”现象；在教学计划、办学特色和课程体系等方面存在一些不太完善的地方；在具体课程的教学大纲和课程内容设置上，还存在比较多的问题，如课程内容衔接不当、部分核心知识点遗漏、不少教学内容或知识点多次重复、知识点的设计难易程度还存在不当之处、学时分配不尽合理、实验安排还有不适当的地方等。这些问题都集中反映在教材上，专业调整后的教材建设尚缺乏全面系统的规划和设计。

针对上述问题，哈尔滨工业大学机电工程学院从“机械设计制造及其自动化”专业学生应具备的基本知识结构、素质和能力等方面入手，在校内反复研讨该专业的培养方案、教学计划、培养大纲、各系列课程应包含的主要知识点和系列教材建设等问题，并在此基础上，组织召开了由哈尔滨工业大学、吉林大学、东北大学等9所学校参加的机械设计制造及其自动化专业系列教材建设工作会议，联合建设专业教材，这是建设高水平专业教材的良好举措。因为通过共同研讨和合作，可以取长补短、发挥各自的优势和特色，促进教学水平的提高。

会议通过研讨该专业的办学定位、培养要求、教学内容的体系设置、关键知识点、知识内容的衔接等问题，进一步明确了设计、制造、自动化三大主线课程教学内容的设置，通过合并一些课程，可避免主要知识点的重复和遗漏，有利于加强课程设置上的系统性、明确自动化在本专业中的地位、深化自动化系列课程内涵，有利于完善学生的知识结构、加强学生的能力培养，为该系列教材的编写奠定了良好的基础。

本着“总结已有、通向未来、打造品牌、力争走向世界”的工作思路，在汇聚多所学校优势和特色、认真总结经验、仔细研讨的基础上形成了这套教材。参加编

写的主编、副主编都是这几所学校在本领域的知名教授，他们除了承担本科生教学外，还承担研究生教学和大量的科研工作，有着丰富的教学和科研经历，同时有编写教材的经验；参编人员也都是各学校近年来在教学第一线工作的骨干教师。这是一支高水平的教材编写队伍。

这套教材有机整合了该专业教学内容和知识点的安排，并应用近年来该专业领域的科研成果来改造和更新教学内容、提高教材和教学水平，具有系列化、模块化、现代化的特点，反映了机械工程领域国内外的新发展和新成果，内容新颖、信息量大、系统性强。我深信：这套教材的出版，对于推动机械工程领域的教学改革、提高人才培养质量必将起到重要推动作用。

蔡鹤皋
哈尔滨工业大学教授
中国工程院院士
丁亥年八月于哈工大

前　　言

为了适应与国际接轨的趋势及满足21世纪教学内容和课程体系改革要求，加强针对本科生机械设计课程的双语教学，本书编者对国内外机械设计类英文教材进行了比较研究。调研发现，机械工业类专业的原版英文教材与我国的教学大纲及教学体系差异较大，首先表现在原版机械设计类英文教材多侧重理论分析和力学计算，涵盖较多先修内容，如理论力学、材料力学等，而结构设计涉及较少，篇幅较长，不适合我国高校现阶段的教学状况，而且价格也过高。其次，国内大学生现阶段的英文水平参差不齐，大多数学生还不能很好地理解英文原版教材的体系和内容，因此英文原版教材现在还不能在我国一般的高校推广使用。

鉴于此，国内许多高校的专家学者开始编写适合国情的机械设计英文或双语教材。其中杨明忠主编的机械设计(Machinery Design)双语教材，是按照我国通用教学大纲要求，以优秀的中文教材作蓝本并参考国外优秀的英文教材，遵循中文教材结构体系进行编译的。这本书虽然便于学生对照中文参考书进行学习，但缺乏国外教材具备的特色。而重庆大学的李良军教授则直接对国外某一精品教材进行了缩编，虽然保留了原版教材的优点，但是缺少了一些学生必须掌握的知识点。

为尽可能地统筹兼顾，本书编者以国外优秀原版教材作为基本框架，以规范、流畅、地道的语言，采编贴近国内教学大纲的基本要求的内容，使学生能够利用英语作为学习工具充分掌握机械设计基本知识。本书以培养学生机械设计基本理论为主线，介绍通用机械零部件的工作原理、结构特点、基本设计理论和设计计算方法，同时也注重综合机械设计能力的培养。全书文字部分由哈尔滨工业大学翟文杰教授统编定稿，敖宏瑞完成了图表的编辑整理。哈尔滨工业大学王黎钦教授对本书的内容进行了审阅，并提出了许多宝贵意见，如采用最新颁布的国家标准，各章尽量附有例题等。全国机械基础教学指导委员会主任委员邓宗全教授委本书的出版提供了许多参考资料和指导意见，哈尔滨工业大学机电学院领导及机械设计教学专家王连明教授及机械设计基础课程带头人姜洪源教授对本书也给予极大的关注。在此表示深深的谢意。

本书是哈尔滨工业大学“十一五”重点规划教材之一，是在哈尔滨工业大学教务处和机械设计基础教学基地以及本科教学项目的资助下完成编写以及配套的课件制作。

总之，本书以繁简适当的基本课程内容和体系为特色，文字叙述力求规范、通俗易懂，尽量兼顾到教师英语授课的便利和学生的课堂理解，便于国内双语教学的开展，也适合英文水平较好并有一定机械零件设计基础的学生自学使用。但由于编者水平所限，不足在所难免，敬请读者及专家批评指正。

编　者

2007年3月于哈尔滨工业大学

Preface

Main thoughts about the compilation

Mechanical design principles are emphasized in this book, with some basic mechanical components to illustrate these principles. Machine design is not just applications based on mechanics of materials, but requires a range of pre-requisites. For each component, practical considerations of design and selection are discussed, and attention is called, when appropriate, to the modification of theory-based dimensions or chosen materials to meet manufacturing requirements or limitations.

This book is intended for bilingual textbook of machine design, and thus compiled to satisfy the needs from both the teacher and students in China. Textbooks of Machinery Design popular in American and European universities are our main source of reference. For the convenience of delivery and understanding, we took in the essence of the reference textbooks written by foreign authors and revised it in plain and concise English.

The qualified undergraduates in mechanical engineering or other related specialties are the main readers. Some elements, the components and the description of their mechanisms in this book are believed sufficient for Chinese students. Those people with sufficient English competence and subjects understanding may finish these topics themselves if a general description of available material is given in class. Many references much appreciated by the authors for their contributing to the book can also provide readers with more advanced or detailed sources of information. For the same reason of time, only a limited number of case studies are included, while problems are omitted. The qualified students are expected to be able to solve related problems, whether in English or in Chinese, according to the given design procedure for each specific machine element.

The latest ISO standards for well-standardized elements applicable to Chinese situations, such as gears, rolling-element bearings, threaded fasteners, are included, while for those inapplicable ones, such as worm gears and V-belts, the Chinese standards are adopted.

Contents

Chapter 1 discusses design process and gives an overview of design considerations. General failure modes and design criteria of strength concerning stress and safety factor are covered in Chapter 2, in which some sections might be omitted if they are sufficiently covered in preceding courses. In fact, much mechanics knowledge is not included in this textbook since the students are believed to have grasped it through the foregoing courses. Moreover, in this book some derivations of important equations are omitted and emphases are given to their applications, e.g., derivation of the Hertz equations and Reynolds equation are omitted, but their applications to gear teeth and sliding bearings are included respectively. Chapter 3 is concerned with the basics of tribology, which may help students to extend their vision on machine design, i.e., not only must the design stress be less than the allowable stress and the deformation not exceed some maximum value, but lubrication, friction and wear (tribological considerations) also must be properly understood for machine elements to be successfully designed.

Chapters 4 to 13 relate the fundamentals to various machine elements. Each chapter is organized in such a consistent pattern that detailed discussion about analyzing, selecting, or designing the element under consideration is after a three-part introduction, which covers: (1) "Uses and characteristics"— What does it look like? What does it do? What variation is available? (2) "Probable failure modes"— based on practical experience; (3) "Typical materials used for the application"— based on common design practice.

Chapter 4 deals with shafting and associated parts, such as couplings and keys. A shaft design procedure is given for static loading with main attention paid to strength criterion. Chapter 5 presents the design of sliding bearings — both boundary lubricated and hydrodynamic lubricated journal bearings. The procedures describe many performance parameters, such as load-bearing capacity, minimum film thickness, temperature rise, coefficient of friction, lubrication flow through the bearing. Rolling element bearings are presented in Chapter 6, in which the bearing selection and associated calculation methods are emphasized. Chapter 7 covers power screws. Its mechanics analyses can also be simulated in threaded fasteners and the worm gears. Chapter 8 treats threaded joints from a perspective of practical strength design by considering joints under different loading conditions. Springs, especially helical springs, are covered in Chapter 9. After stress analysis and deflection analysis, the helical spring design procedure and general guidelines are summarized. Chapter 10 deals with the design of spur gears and briefly describes helical gears. The Hertz contact stress with modification factors is used to establish the design stress, which is then compared with an allowable stress to determine whether surface contact fatigue failure will occur. The bending strength analysis is also detailed following Lewis assumption. Design of worm gears are treated in Chapter 11 according to typical Chinese way of design to enhance comprehension, since our country' s worm gear standards and design/manufacturing methods are quite different from those western styles. Brakes and clutches are covered in Chapter 12. The band brake force analysis provides theoretical basis for belt drives discussed in Chapter 13, where the V-belts design procedure is also illuminated according to Chinese standards.

Acknowledgements

This text has been worked on for nearly 3 years since the idea first emerged, and during this period many people have contributed comments, suggestions and advices. A number of faculty members from the Department of Machine Design and Its Theory at Harbin Institute of Technology (HIT) have commented on the text. In particular, the authors would like to thank Professor Wang Liqin for his review of the contents. We are grateful for his time and advice. The suggestions from Professor Deng Zongquan and Professor Wang Lianming were instrumental for shaping up the book. The authors would also like to recognize the Teaching Base for Machine Fundamentals and Teaching Office of HIT, which provided a grant last but not least, the authors acknowledge the use of tables and illustrations from References which made the compilation possible. One of the author, Ao Hongrui did much work on the figures preparation. Since it is our first attempt to compile a technical textbook in English, many inappropriate treatments may be found. Comments, suggestions, and corrections are sincerely appreciated, which can be addressed to Zhai Wenjie who has established the framework, revised and finalized the whole book. The email address: zhaiwenjie@hit.edu.cn.

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Chapter 1

Introduction

1.1 The Meaning of Design

Design means different things to different people, but all designs require significant creativity, practice, and vision to be done well. Design problems are, almost without exception, open-ended problems combining hard science and creativity. For the purpose of this textbook "design" is the transformation of concepts and ideas into useful machinery. A "machine" is a combination of mechanisms and other components that transforms, transmits, or uses energy, load, or motion for a specific purpose. "Engineering" is the art of directing the great sources of power in nature for the use and convenience of man. Design of machinery is the fundamental practice in engineering.

A machine comprises several different machine elements properly designed and arranged to work together as a whole. Fundamental decisions regarding loading, kinematics, and the choice of materials must be made during the design of a machine. Other factors, such as strength, reliability, deformation, tribology (friction, wear, and lubrication), cost, and space requirements, also need to be considered. The objective is to produce a machine that not only is sufficiently rugged to function properly for a reasonable time but is also economically feasible. Further, nonengineering decisions regarding marketability, product liability, ethics, politics, etc., must be integrated into the design process early. Since few people have the necessary tools to make all these decisions, machine design in practice is a gargantum discipline-blending human endeavor.

To "direct the great sources of power in nature" in machine design, the engineer must recognize the functions of the various machine elements and the types of load they transmit. A machine element may function as a normal load transmitter, a torque transmitter, an energy absorber, or a seal. Some normal load transmitters are rolling-element bearings, hydrodynamic bearings, and rubbing bearings. Some torque transmitters are gears, traction drives, chain drives, and belt drives. Brakes and dampers are energy absorbers. All the machine elements in this book can be grouped into one of these classifications.

Designing reasonably safe products involves many design challenges to ensure that components are large enough, strong enough, or tough enough to survive the loading environment. One subtle concept, but of huge importance, is that the engineer has a duty to protect the welfare of the general public. Welfare includes economic well-being, and it is well known that successful engineering innovations lead to wealth and job production. However, products that are too expensive are certain to fail in a competitive marketplace. Similarly, products that do not perform their function well will fail. Economics and functionality are always pressing concerns, and good design inherently means safe, economical, and functional design.

1.2 Design of Mechanical Systems

A mechanical system is a synergistic collection of machine elements. It is synergistic because as a design it represents an idea or concept greater than the sum of the individual parts. For example, a wristwatch, although merely a collection of gears, springs, and cams, also represents the physical realization of a time-measuring device. Mechanical system design requires considerable flexibility and creativity to obtain good solutions. Creativity seems to be aided by familiarity with known successful designs, and mechanical systems are often collections of well-designed components from a finite number of proven classes.

Designing a mechanical system is a different type of problem than selecting a component. Often, the demands of the system make evident the function requirements of a component. However, designing a large mechanical system, potentially comprising thousands or even millions of machine elements, is a much more open, unconstrained problem.

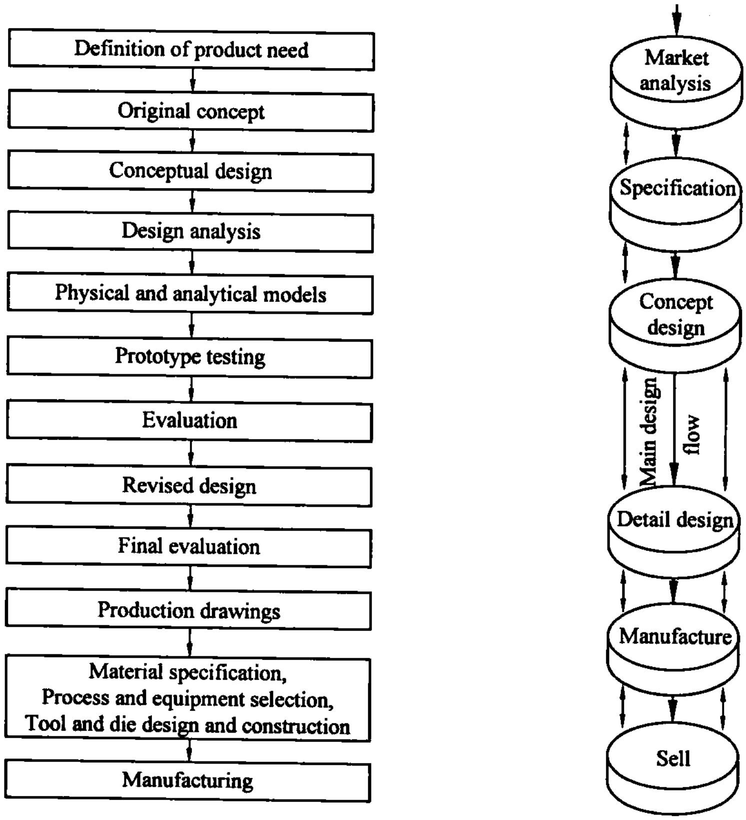
To design superior mechanical systems, an engineer must have a certain sophistication and experience regarding machine elements. Studying the design and selection of machine elements affords an appreciation for the strengths and limitations of classes of components. They can then be more easily and appropriately incorporated into a system. For example, a mechanical system cannot incorporate a worm gear or a Belleville spring if the designer does not realize that these devices exist.

A toolbox analogy of problem solving can be succinctly stated as, "If your only tool is a hammer, then every problem is a nail." The purpose of studying machine element design is to fill the toolbox so that problem solving and design synthesis activities can be flexible and unconstrained.

1.3 Design as a Multi-Disciplinary Endeavor

A typical design process [Figure 1.1(a)] shows that the skills involved in machine element design play an essential role in the process. This approach was commonly used in the United States in the postwar era. However, major problems with this approach became apparent in the 1970s and 1980s—some market driven, others product driven.

The term "over-the-wall engineering" has been used to describe this design approach. Basically, someone would apply a particular skill and then send the product "over the wall" to the next step in development. A product design could sometimes flow smoothly from one step to the next and into the marketplace within weeks or months. This was rarely the case, however, as usually a problem would be discovered. For example, a manufacturing engineer might ask that workpieces be more easily clamped into a milling machine fixture. The design engineer would then alter the design and send the product back downstream. A materials scientist might then point out that the material chosen had drawbacks and suggest a different choice. The design engineer would make the alteration and resubmit the design. So the product would take a long time to develop by this approach.



(a) Over-the - wall engineering approach

(b) Concurrent engineering approach

Figure 1.1 Approaches to product development

Figure 1.1(b) shows a more modern design approach. Here, there is still the recognized general flow of information from product conception through introduction into the market place, but there is immediate involvement of many disciplines in the design stage. Different disciplines are involved simultaneously instead of sequentially as with the over-the-wall approach. Some tasks are extremely technical, such as design analysis (the main focus of this book) or manufacturing. Others are nontechnical, such as market analysis. Concurrent engineering is the philosophy of involving many disciplines from the beginning of a design effort and keeping them involved throughout product development. Thus, redundant efforts are minimized and higher quality products are developed more quickly. Although design iterations still occur, the iteration loops are smaller and incur much less wasted time, effort, and expense. Saving development time through concurrent engineering made companies much more competitive in the international marketplace. Also, design shortcomings can be corrected before they are incorporated. For example, service personnel can inform design engineers of excessive component failures during the conceptual design stage. No such mechanism for correcting design shortcoming ever existed in conventional design approaches or management structures.

Concurrent engineering has profoundly affected design engineers. They can no longer work alone and must participate in group discussions and design reviews. They need good communication skills. Designing machinery has become a cooperative endeavor.