MACHINE DESIGN

Volume 2

Design of Mechanical Elements

FANG HUA CAN
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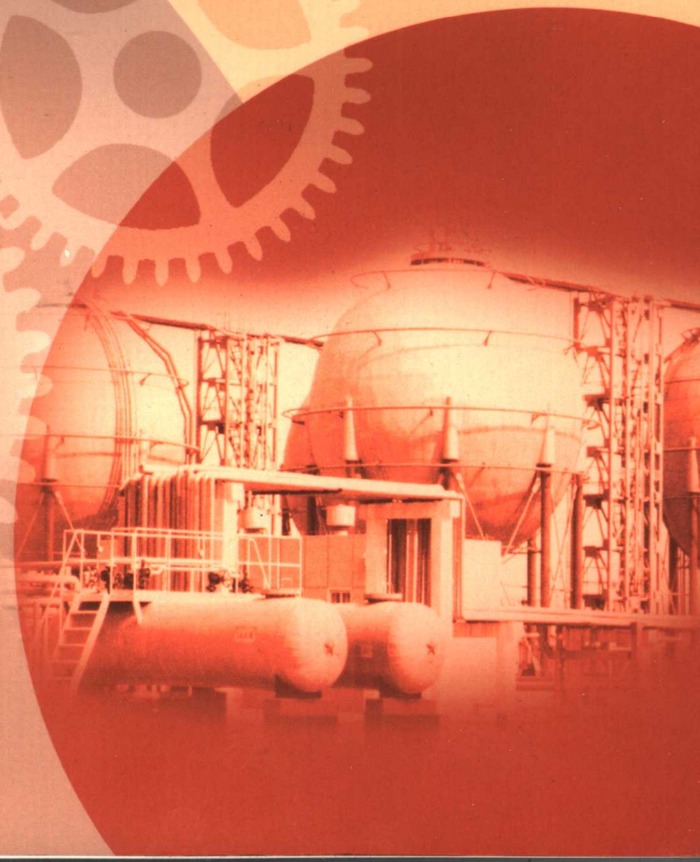
College of Mechanical and Electric Engineering
in China University of Petroleum, Beijing



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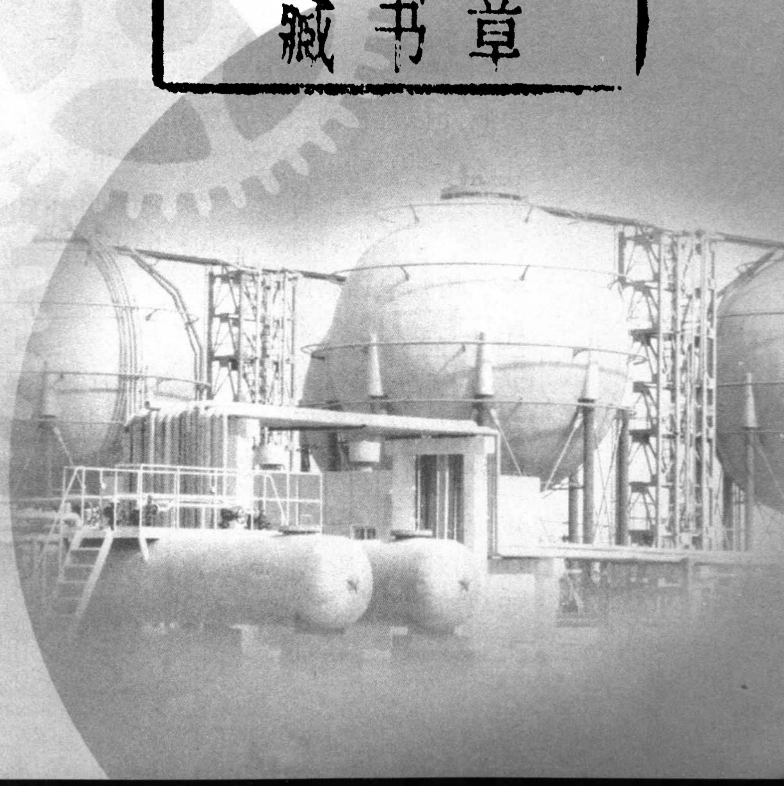

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Epitome of Contents

The book—Machine Design is intended as a bilingual teaching (Chinese and English) textbook for students who take the course—Machine Design, including two volumes: Mechanisms Design (Vol. 1) and Design of Mechanical Elements (Vol. 2). This book is the Volume 2 and consists of six chapters. Chapter 1 is general introduction of machine design and design of mechanical elements. Chapter 2 is the design of fastenings including screw fastenings, keys and pins, force fit joints, riveted joints, welded joints, and adhesive bondings. Chapter 3 is the design of gear transmissions including spur gears, helical gears, bevel gears, worm gear and worms. Chapter 4 is the design of flexible mechanical elements including belt drives, chain drives, wire ropes, and flexible shafts. Chapter 5 is the design of shafts and bearings including shafts, rolling bearings, and sliding bearings. Chapter 6 is the design of miscellaneous elements and parts including clutches, brakes, couplings, mechanical springs, speed reducers, and stepless speed changing devices, etc.

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Preface

The bilingual teaching of professional courses has been advocated for many years and will become into a popular teaching practice in the universities over our country because of the advantages it brings in and the importance it will produce in future. First, it is helpful for students to consolidate their fundamental English. Second, it is an effective method to learn professional technology english. At last, it also provides a path for students to know the advanced science and technologies over the world.

The book—Machine Design is intended as a bilingual teaching (Chinese and English) textbook for the students who take the course—Machine Design, including two volumes: Mechanisms Design (Vol. 1) and Design of Mechanical Elements (Vol. 2). This book is the Volume 2 and consists of six chapters. The Volume 1 Mechanisms Design was published and printed by Petroleum Industry Press in August 2005.

The Volume 2 Design of Mechanical Elements consists of six chapters. Chapter 1 is general introduction of machine design and design of mechanical elements. Chapter 2 is the design of fastenings including screw fastenings, keys and pins, force fit joints, riveted joints, welded joints, and adhesive bondings. Chapter 3 is the design of gear transmissions including spur gears, helical gears, bevel gears, worm gears and worms. Chapter 4 is the design of flexible mechanical elements including belt drives, chain drives, wire ropes, and flexible shafts. Chapter 5 is the design of shafts and bearings including shafts, rolling bearings, and sliding bearings. Chapter 6 is the design of miscellaneous elements and parts including clutches, brakes, couplings, mechanical springs, speed reducers, and stepless speed changing devices, etc..

In the process of writing this volume, one of the difficulties is to combine chinese concrete mechanical design practice with the advanced theories and experience of foreign countries. In our country, there are many various standards, codes, and design methods of mechanical elements, which are different from those in North America and other countries. For instance, in the mechanical design practice of China, the international system of units is usually used. In many other countries, especially in the United Kingdom and North America, the imperial units are used. To solve this problem, the following measures were used. First, keep the following five aspects of contents in accordance with the chinese concrete conditions, including: 1) Commercial names of materials of mechanical elements, 2) Calculation methods of design of mechanical elements, 3) Procedures of design of mechanical elements, 4) Standards and codes of design of mechanical elements, 5) Selection of coefficients of calculation and design of mechanical elements. For example, in the rolling bearings, the identification codes and commercial names of materials of rolling bearings are all complied with the National Standard of PRC; the calculation methods of the life of rolling bearings follow the calculation formulas of China; the load coefficient (f_p) is selected using the table provided by PRC; the design procedure of composite design of rolling bearings is abode by chinese methods and steps. Second, introduce the related contents of advanced theories and experience of foreign countries into this book, including three aspects: 1) Methods of analysis of mechanics about mechanical elements, 2) Theories of design of mechanical elements, 3) New advanced constructions of mechanical elements and parts. For example, the analysis methods of pressure and torque of frictional clutches and brakes, the method of design of volute springs, the stress distribution of adhesive bondings and the new constructions of flexible shafts have been introduced in this book. As stated previously, this is only a new attempt. How it works will be identified and Evaluated in the teaching practice of the future.

The book was written by Fang Huacan, a professor of the College of Mechanical and Electric Engineering in China University of Petroleum, Beijing.

I would like to express my sincere gratefulness to those authors whose books have been partly chosen and used in this book. A special thank should be given to Professor Huo Laijian, a professor of Department of Foreign Language of China University of Petroleum, Beijing, who checked the english manuscript of this book.

The author is grateful to the administration of China University of Petroleum, Beijing, the department of teaching affairs for their generous support. The author also expresses his thanks to these professors in the college of Mechanical and Electric Engineering for their valuable contribution to this book: Professor Zhang Laibin, Professor Wu Xiaolin, Professor Zhang Shicheng, Professor Hu Pinhui, Professor Zhang Hong, Professor Gao Wanfu, etc..

I thank associate Professor Yu Zhongshan, who teaches this course—Design of Mechanical Elements. He checked the contents of the whole book.

Finally, I thank the following individuals: graduate student Ye Zhongzhi; Lu Xiumei, Director of Office of College of Mechanical and Electric Engineering in China University of Petroleum, Beijing. They finished the typewriting of the manuscript of this book.

Any suggestion of the improvement and correction of this book will be appreciated very much. Please oblige me with your valuable opinions.

Fang Huacan

Beijing, PRC, July 1, 2005

Contents

Chapter 1 General Introduction

Design is an innovative and highly interactive process. Mechanical design is a complex technique to undertake, requiring many skills. A vocabulary that allows large relationships to be subdivided into a series of simple tasks is needed. To design is either to formulate a plan for the satisfaction of a specified need or to solve a problem. Hence, in this chapter the needs of machine design and mechanical elements design will be introduced, the steps of design of mechanical elements will also be introduced, besides, the fundamental methods of mechanical design are introduced too. Behind, the loads, stresses, and static, fatigue, surface contact fatigue strength will be given a simple introduction; the friction, wear, and lubrication are also simply introduced in this chapter.

1.1 Brief Introduction of Machine Design

1.1.1 Basic Needs of Machine to be Satisfied

The products of machine must be functional, safe, competitive, usable, manufacturable, and marketable. These need can be summarized as follows.

(1) Needs of Service

The products of machine must perform to fill its intended need and customer expectation. The machine should ensure to realize the specified function, specified motion, and specified productability index, should effectively operates during the service term. Reliability is the conditional probability, at a given confidence level, that the product will perform its intended function satisfactorily or without failure at a given age.

(2) Needs of Economics

The economics of machine run through the whole process of design, manufacturing, and service. For example, during designing process the advanced designing methods, the standard elements, the series products, etc. should be adopted; during manufacturing process the first is manufacturable, it means that the product of machine has been reduced to a "minimum" number of parts, suited to mass production, with dimensions, distortion and strength under control. Secondly, the new and advanced technology should be adopted; and during the service term the cost of installation, maintenance, repair, and management should be decreased as possible. All of these are aimed at achieving the following targets:

1) Competitiveness—The product of machine is competitive in its market.

2) Marketability—The product of machine can be bought, and service (repair) is available.

(3) Needs of Society

First, it must satisfy the needs of human engineering, which means that the product is "user friendly", accommodating to human size, strength, posture, reach, force, power, and control. Second , it is the safety, which means that the product is not hazardous to the user, bystanders, or surrounding property. Hazards that cannot be "designed out" are eliminated by guarding (a protective enclosure); if that is not possible, appropriate directions or warnings are provided. Besides, the aesthetics requirements are also considered, for example, the beautiful mould-making, the simple shape, the harmonious colour, etc..

(4) Miscellaneous Special Needs

For example, the machine tools require to keep the accuracy at a long-term; the airplane requires having small mass, having small resistance on the fly; the heavy machine requires the convenience of transportation, etc.. In short, besides satisfying the above general needs, in some special cases the special requirements must also be satisfied.

1.1.2 Main Contents and General Procedures of Machine Design

(1) Contents of Design

Design (subject to certain problem-solving constraints) means that a component, system or process will perform a specified task (subject to certain solution constraints) optimally.

It is important that the designer begins by identifying exactly how he will recognize a satisfactory alternative, and how to distinguish between two satisfactory alternatives in order to identify the better. From this kernel, optimization strategies can be formed or selected.

A *design imperative* can be expressed as follows:

1) Invent alternative solutions.

2) Establish key performance metrics.

3) Through analysis and test, simulate and predict the performance of each alternative, retain satisfactory alternatives, and discard unsatisfactory ones.

4) Choose the best satisfactory alternative discovered as an approximation to optimality.

5) Implement the design.

Design is an innovative and highly iterative process. It is also a decision-making process.

Design is a communication-intensive activity in which both words and pictures are used, and written and oral forms are employed.

A designer' s personal resource of creativeness, communicative ability, and problem-solving skill are interlined with knowledge of technology and first principles.

(2) Rational Design Making

Designers have to make decisions, few or many, some a priority. Rational design making is a systematic design process involving the following key elements:

1) Key 1: Suitability, Feasibility, and Acceptability.

a. Suitability—A contemplated action is *suitable* if its adoption will indeed accomplish the intended purpose.

b. Feasibility—A contemplated action is *feasible* if the action can be carried out with the knowledge, personnel, money, and material at hand, or if it can be assembled in time.

c. Acceptability—A contemplated action is *acceptable* if the probable results are worth the anticipated costs.

2) Key 2: Satisfactory alternative.

If a contemplated action is suitable, feasible, and acceptable, it becomes a *satisfactory alternative*, and it is set aside to be compared with other satisfactory alternatives. If one can compare two satisfactory alternatives and choose the better, an *optimization strategy* can be crafted or selected to deal with a large number of satisfactory alternatives.

3) Key 3: specification set.

A specification set is the ensemble of drawings, texts, bills of materials, and directions that constitutes the decision record in a form that enables the builder or user to realize function safely, reliably, competitively, and usably, the product of machine has been fabricated and serviced to the customer's satisfaction.

4) Key 4: Decision set.

A decision set is a list of decisions required to establish the specification set. The decision set is equivalent to the specification set. The decision set is expressed in terms of the designer's thinking parameters, and it easily focuses on function, safety, reliability and so on. For example, the specification set for a helical coil spring for static services can be displayed as follows:

a. Material and condition.

b. End treatment.

c. Coil inner or outer diameter and tolerance.

d. Total turns and tolerance.

e. Free length and tolerance.

f. Wire size and tolerance.

However, the designer does and therefore organizes the equivalent decision set as follows:

a. Materials and condition.

b. End treatment.

c. Force F_1 and end contraction y_1 or F_1 and length L_1 (function).

d. Work over a rod: d_{rod} (function).

e. Fractional overrun to coil closure ξ: $\xi = 0.15$ (safety, reliability, and spring linearity (robustness of the mathematical)).

f. Wire diameter d (competitiveness through optimality) .

5) Key 5: A prior decisions versus design variables.

The first five decisions in the previous decision set example can be made a priority (they are called a *prior decisions*) . The last decision, that of wire size d, is called a *design variable* before we make the decision and the *design decision* after we have made the decision.

6) Key 6: The adequacy assessment (skill 1).

An adequacy assessment consists of the cerebral, empirical, and related mathematical modeling steps the designer takes to ensure that a given specification set is satisfactory (suitable, feasible, and acceptable) . An adequacy assessment is the primal skill of the designer. It is so important that it is called skill 1. Most of a first course in design of machine elements focuses on building and refining this skill in many applications. It′s centrality is seen in Fig. 1. 1.

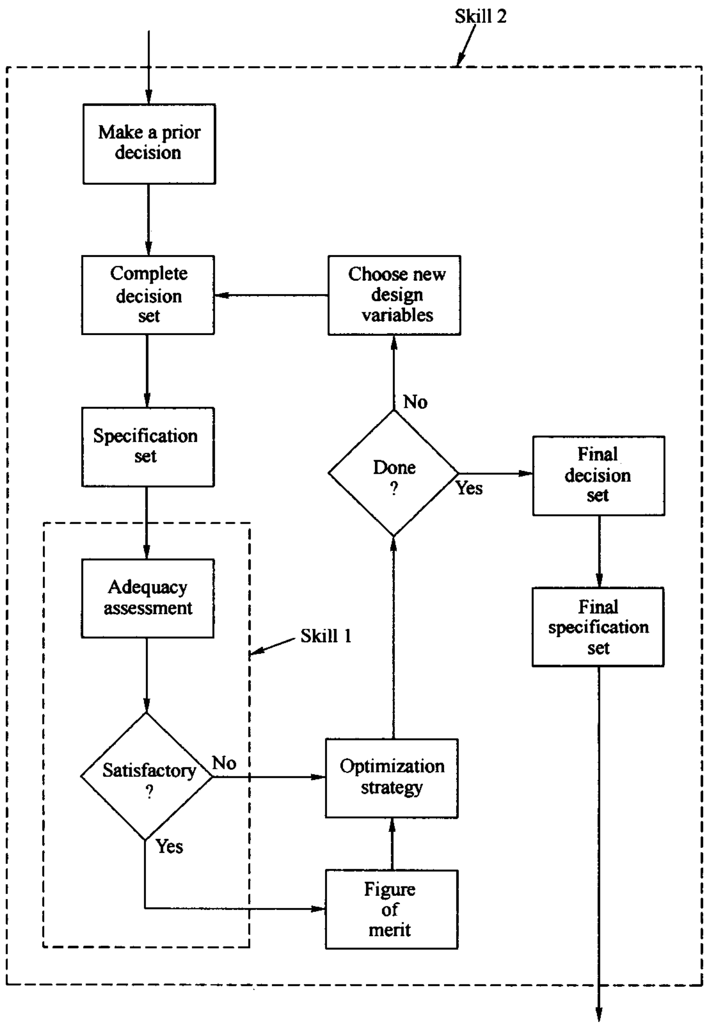

Fig. 1. 1 A Logic Flowchart of Designer's Skill 1 and Skill 2

7) Key 7: Figure of merit.

If in the coil spring example, the designer finds several wire sizes that pass the adequacy assessment, he or she uses a figure of merit (f_{om}) to help identify the best. The volume of material used to form the spring is an index to cost. Quantitatively, it can be expressed in the case of the helical coil compression spring as:

$$f_{om} = -\frac{\pi d^2 n_t D}{4} \quad (1-1)$$

where d is the wire diameter, n_t are the total turns, and D is the average coil diameter.

The minus sign allows the figure of merit to increase with decreasing volume. A figure of merit is a number whose magnitude is a monotonic index to the merit, or desirability, of the spring. A figure of merit permits rapid choice among several satisfactory designs.

8) Key 8: A skill of synthesis (skill 2).

The skill of synthesis involves an optimization strategy, a figure of merit, and skill 1. A flowchart of skill 1 and skill 2 is seen in Fig. 1. 1. Note that skill 1 is embedded in skill 2, and it needs to be mastered first.

(3) Process of Design

The complete design process, from start to finish, is often outlined as shown in Fig. 1. 2. The process begins with recognition of a need and a decision to do something about it. After much iteration, the process ends with the presentation of the plans for satisfying the need.

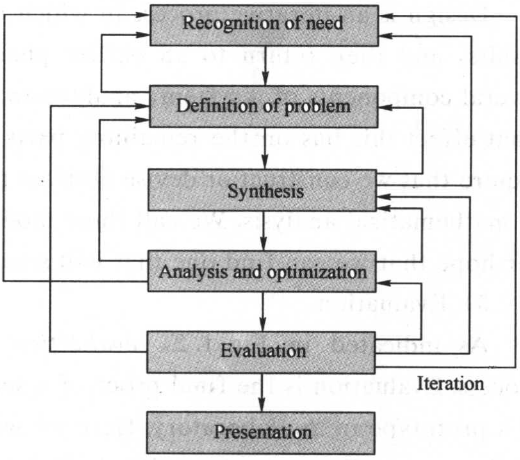

Fig. 1. 2 The Complete Design Process

1) Recognition of need.

Recognition of the need and phrasing the need often constitute a highly creative act, because the need may be only a vaguer discontent, a feeling of uneasiness, or a sense that something is not right. The need is often not evident at all; recognition is usually triggered by a particular adverse circumstance or a set of random circumstances that arise almost simultaneously.

There is a distinct difference between the statement of the need and the identification of the problem that follows this statement (as shown in Fig. 1. 2) . The problem is more specific. For example, if the need is for clean air, the problem might be that of reducing the dust discharge from power-plant stacks, etc. .

2) Definition of the problem.

Definition of the problem must include all the specifications for the object that is to be designed. The specifications are the input and output quantities, the characteristics and dimensions of the space the object must occupy, and all the limitations on these quantities. The specifications define the cost, the number to be manufactured, the expected life, the range, the operating temperature, and the reliability. Specified characteristics can include the speed, feeds, temperature limitations, maximum rang, expected variation in the variables, and dimensional and weight limitations.

3) Synthesis.

The synthesis of a scheme connecting possible system elements is sometimes called the *invention of the concept*. This is the first step in the synthesis task.

4) Analysis and optimization.

As the fleshing out of the scheme progresses, *analysis* must be performed to assess whether the system performance is satisfactory or better and, if satisfactory, just how well it will perform. This is an analysis task. System schemes that do not survive analysis are revised, improved, or discarded. Those with potential are optimized to determine the best performance of which the scheme is capable. Fig. 1. 2 shows that *synthesis* and *analysis* and *optimization* are intimately and iteratively related. Synthesis draws heavily on talent. In this iteration the specification set is formed.

Design is an iterative process in which we proceed through several steps, evaluate the results, and then return to an earlier phase of the procedure. Thus we may synthesize several components of a system, analyze and optimize them, and return to synthesis to see what effect this has on the remaining parts of the system. Both analysis and optimization require that we construct or devise abstract models of the system that will admit some form of mathematical analysis. We call these models mathematical models. In creating them it is our hope that we can find one that will simulate the real physical system very well.

5) Evaluation.

As indicated in Fig. 1. 2, *evaluation* is a significant phase of the total design process. Evaluation is the final proof of a successful design and usually involves the testing of a prototype in the laboratory. Here we wish to discover if the design really satisfies the need or needs. For example, is it reliable? Is it economical to manufacture and to use? Is it easily maintained and adjusted? Is it likely that recalls will be needed to replace defective parts or systems? and so on.

6) Presentation.

Communicating the design to others is the final, vital *presentation* step in the design process. Presentation is a selling job. The engineer, when presenting a new solution to administrative, management, or supervisory persons, is attempting to sell or to prove to them that this solution is a better one.

(4) Design Considerations

Sometimes the strength required of an element in a system is an important factor in the determination of the geometry and the dimensions of the element. In such a situation we say that *strength* is an important design consideration. When we use the expression *design consideration*, we are referring to some characteristics that influence the design of the element or, perhaps, the entire system. Usually quite a number of such characteristics must be considered in a given design situation. Many of the important ones are as follows (not necessarily in the order of importance):

1) Functionality
2) Strength/Stress
3) Distortion/Deflection/Stiffness
4) Wear
5) Corrosion
6) Safety
7) Reliability
8) Manufacturability

9) Utility
10) Cost
11) Friction
12) Weight
13) Life
14) Noise
15) Styling
16) Shape
17) Size
18) Control
19) Thermal properties
20) Surface
21) Lubrication
22) Marketability
23) Maintenance
24) Volume
25) Liability
26) Remanufacturing/Resource Recovery

Some of these have to do directly with the dimensions, the material, the processing, and the joining of the elements of the system. Other considerations affect the configuration of the total system.

(5) General Steps of Machine Design

The whole process of machine design may be divided into five steps as shown in Fig. 1. 3.

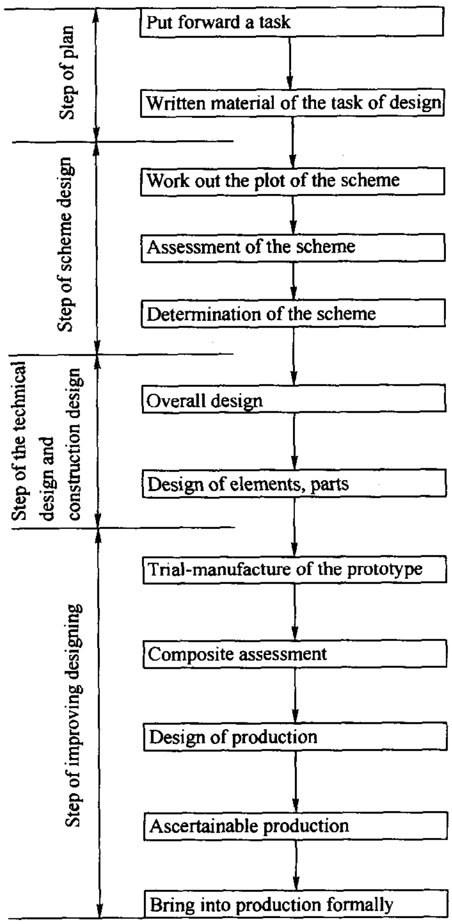

Fig. 1. 3 The General Steps of Machine Design

1. 1. 3 Fundamental Requirements and Steps of Design of Mechanical Elements

(1) Fundamental Requirements

1) Reliability—Reliability can mean that there is not various failures occur in the specified service life. It is very important for the designer and manufacturer to know the reliability of their products. The reliability method of design is one in which we obtain the probability distribution of stress and probability distribution of strength and then relate these two in order to achieve an acceptable success rate. Hence, the designer should use the advanced designing method to ensure the reliability of strength, rigidity, service life, and stability of the mechanical elements.

2) Manufacturability—It means that under a given condition of production can conveniently and economically produce the mechanical elements, which not only satisfy the requirements of characteristics, but also can be convenient to assemble for machine. Hence we should comprehensively consider the manufacturability from all of the links in the production chain, such as the blank making, heat-treatment, machining and assembling, etc..

3) Economy—When we design the mechanical elements, we correctly select the material of elements, rationally determine the dimensions and constructions of elements, adopt the standardized elements to the full. When producing the mechanical elements, we rationally determine the accuracy class and technical conditions, etc.. All of these should be considered in order to achieve a better economy.

4) Lightening mass—Because if the mass of the elements are lightened, not only the material of elements is saved, but also the inertia and dynamic load of elements will be decreased, and hence the dynamic character of elements can be improved.

(2) General Steps of Design of Mechanical Elements

In general, the steps of design of mechanical elements are shown as in Fig. 1. 4.

The above steps are not fixed, which may be changed with respect to the variety of types and designing methods of the elements.

1. 1. 4 Main Failure Modes and Calculation Criteria of Mechanical Elements

(1) Main Failure Modes of Mechanical Elements

Under specified conditions at a specified time interval if the mechanical elements cannot perform specified functions, it is called the failure of mechanical elements. Hence it can mean that a part has separated into two or more pieces; it has become permanently distorted; thus running is geometry; it has had its reliability downgraded, whatever the reason. A designer speaking of failure can mean any or all of these possibilities.

The main failure modes of mechanical elements are as follows:

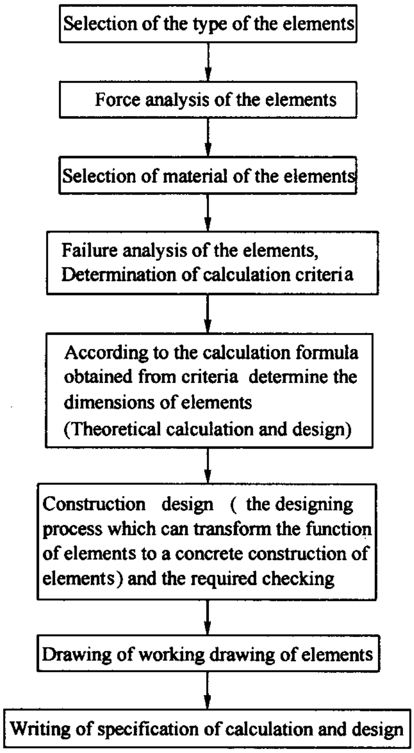

Fig. 1.4 General Steps of Design of Mechanical Elements

- Failures of overall elements
  - Strength
    - Failures resulting from static loading (such as producing of plastic deformation)
    - Fatigue failures
    - Impact failures of fracture
  - Rigidity — Failures due to too great elastic deformation
  - Vibration — Failures of resonance. The noise exceeds the limit of standard
  - Stability — Loss in stability (for example, the buckling of column)
- Failures of surface of the elements
  - Surface applied force
    - No relative motion
      - Failures of crushing strength
      - Failures of slip (such as the belt drive) or loosing (such as screw fastenings)
    - With relative motion
      - Failures of wear
      - Fatigue failures
      - Failures of overheating
  - Surface does not act force — Failures of corrosion

(2) Calculating Criteria of Mechanical Elements

The fundamental principle to calculate the working ability of mechanical elements in order to prevent the occurrence of failures is called *calculating criteria*. According to the above classifications of failure mode selecting a few essential modes we illustrate their calculating criteria as follows.

1) Criteria of strength—Whose calculating formulas can be expressed by stresses as follows:

$$\sigma \leqslant [\sigma] = \frac{\sigma_{lim}}{S_\sigma} \qquad (1-2)$$

$$\tau \leqslant [\tau] = \frac{\tau_{lim}}{S_\tau} \qquad (1-3)$$

where σ, τ are the normal and shear stresses of elements respectively (MPa); $[\sigma]$, $[\tau]$ are the allowable normal and shear stresses of elements respectively (MPa); S_σ and S_τ are the safety factors of normal and shear stresses respectively; σ_{lim} and τ_{lim} are the ultimate normal and shear stresses of material of the elements respectively.

2) Criteria of rigidity—The ability of elements under a specified loading to resist the elastic deformation is called *rigidity*. The calculating criteria of rigidity is

$$y \leqslant [y] \qquad (1-4)$$

where y is the deflection of elements during operating; $[y]$ is the allowable deflection of the mechanical elements.

3) Criteria of wearlessness—The ability of working surface of both elements making relative motion to resist the wear is called *wearlessness*. At present, there are not reliable and quantitative methods to calculate the wear. In general, the conditional calculations are adopted, for example, the limited pressure p and the product (pv) of limited pressure p and speed v are generally used, in order to ensure that there is one layer of boundary film of high strength on the surface of elements, and the over-wear of surfaces of elements does not occur.

4) Criteria of vibration and noise—If the natural frequency (f) of machine or mechanical elements is equal or approach to the frequency (f_p) of forced vibration due to disturbing source, the resonance will occur, which is also the source of noise. Hence, the dynamic characteristics of a high-speed machine should be analyzed and the following conditions must be satisfied:

$$f < 0.87 f_p \quad \text{or} \quad f > 1.18 f_p \qquad (1-5)$$

5) Criteria of thermal equilibrium—The elements having severe friction during operation will produce a great amount of heat at the location of friction, and hence the temperature of mechanical elements will be raised, the normal lubrication condition will be destroyed. Thus, the thermal equilibrium calculation according to the following condition must be carried out:

$$H_1 \leqslant H_2 \qquad (1-6)$$

where H_1 is the quantities sum of heat produced by friction; H_2 is the quantities sum of heat dissipation.

6) Criteria of reliability—If the working stress (s) and strength of material (r) of mechanical elements are considered as random variables, under a specified working condition, during a specified service term, the probability of the mechanical elements to perform a specified function is called *reliability*.

Let y represent the failure function of the random variables s and r, we get

$$y = r - s \qquad (1-7)$$