DESIGN OF
Machine Elements

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Features of

Learning Objectives

Each chapter of the book has a section on 'Learning Objectives', which lists the major topics discussed in the chapter.

Learning Objectives

A sincere study of the chapter will impart adequate knowledge for understanding the following topics:

1. Coupling construction, types, rigid and flexible couplings
2. Design criteria, muff and split muff couplings
3. Rigid flange couplings, pin and bush type flexible couplings
4. Splined and geared couplings
5. Design of turn buckle
6. Oldham's and Hooke's couplings

Figures and Images

The concepts are made easier to understand with the aid of numerous well-illustrated figures and actual images.

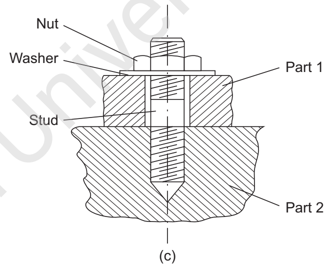

Fig. 11.4 Threaded fasteners (a) Screw (b) Bolt and nut (c) Stud and nut

Fig. 23.2 Link chain diagram and sample

Multiple-choice Questions

Each chapter contains a wealth of multiple-choice questions along with the answers to check the readers' understanding of concepts.

Multiple-choice Questions

1. A coupling is intended for connecting
   (a) a shaft and a gear
   (b) a shaft and a pulley
   (c) two shafts
   (d) a shaft and a flywheel
2. Which of the following is a flexible coupling?
   (a) Muff coupling
   (b) Split muff coupling
   (c) Pin and bush coupling
   (d) Oldham coupling
3. In rigid coupling with reamer bolts, torque transmission occurs by
   (a) bolt shear (c) bearing pressure
   (b) frictional force (d) none of these
4. In a rigid coupling using black bolts, torque is transmitted through the coupling by
   (a) compression
   (b) friction
   (c) shear resistance of bolts
   (d) crushing resistance of bolts
5. In an unprotected flange coupling the connecting bolts are subjected to
   (a) torsion (c) compression
   (b) bending moment (d) none of these

the Book

Solved Examples

Discussion on each topic is followed by solved numerical examples to enable application of the concepts learned.

Example 20.11 (LO 2) A hollow propeller shaft with outside diameter 1.5 times the inside diameter transmits 50 kW at 400 rpm. The permissible shear stress in the shaft material is 90 MPa. Find the outside and inside diameters of the propeller shaft.

Solution: Given: From Example 20.7

$P = 50$ kW

$N = 400$ rpm

$\tau = 90$ MPa

$d_0 = 1.5\, d_i$

Questions

1. What is a bearing and what are its functions?
2. Explain the difference between rolling bearings and roller bearings.
3. What is the meaning of anti-friction bearing?
4. Name the different types of anti-friction bearings in general use.
5. Differentiate between ball bearings and roller bearings.
6. Explain the concept of self-aligning in rolling bearings. Give examples.
7. How does a rolling element bearing differ from a sliding bearing?
8. Describe briefly the applications of sliding and rolling-contact bearings.
9. Mention the names of various types of ball bearings and roller bearings.
10. Explain the features of cylindrical roller bearings. In which applications are they preferred?
11. Explain the advantages of self-aligning ball bearings and spherical roller bearings.
12. Write note on the applications of taper roller bearings. Draw a line sketch to illustrate where they are typically used.
13. Explain the reason why taper roller bearings are used in pairs on a shaft.
14. Define the terms, static capacity and dynamic capacity, of a rolling-contact bearing.
15. Write down Stribeck's formula and explain the terms.
16. What is the significance of the static capacity of a rolling element bearing?
17. Define the dynamic capacity of a rolling-contact bearing.
18. What is rating life of a ball bearing?
19. Explain the terms, L_{10} life and L_{50} life for a ball bearing and a roller bearing.

Review Questions

Each chapter contains numerous questions to help students during exam preparation.

Exercises

Most of the chapters support a wealth of numerical problems for practice.

Exercises

1. A gear wheel is fixed on a 32 mm diameter shaft by means of a square key. The key material has a value of 480 MPa for its yield strength. If the transmitted power is 30 kW at a shaft speed of 720 rpm and the specified factor of safety is 3, find the dimensions of the key. **(LO 2)**

2. A square key with side 16 mm and length 100 mm is used on a shaft 60 mm diameter. The starting torque of the motor is 50 per cent more than the rated torque. Assume the permissible stresses in tension, crushing and shear of the key material are 120 MPa, 80 MPa, and 50 MPa respectively, estimate the minimum design rating of the coupling. Mention the mode of failure of the key. (Refer Gope, pr. 13.2, p. 686) **(LO 2)**

3. A square key is used on a shaft of the same material and strength. Calculate the length L of the key in terms

Preface

If engineering is applied science, design could be termed as 'applied engineering'. The objective of engineering design is to create a device or equipment with a specific purpose for enhancing the comfort or living standards in the society.

Design phase is considered to be extremely crucial in the engineering industry followed by production, procurement, and sales. A design transforms an idea or a need into a tangible reality through creativity and innovative skills. Study of engineering is incomplete without knowledge of at least the principles of design. A knowledge of the principles of design and the ability to study and understand an engineering drawing highly enhances the skillset of an engineer.

The idea behind writing this book on the design of machine elements is to educate mechanical engineering students on the principles of all important machine elements, components, and small devices. Though a prior knowledge of engineering mechanics and strength of materials is necessary, the initial chapters of the book cover the principles of design in brief. The students are gradually drawn into the intricacies of each topic in the chapters through an easy introduction, graded worked examples and practical examples, sketches, line diagrams, and even photographs where necessary.

About the Book

The book contains 34 chapters, beginning with the basic theoretical principles and then moves on to practical design of simple machine elements such as keys and oil seals and gaskets, and finally culminates in complex machine components such as crane and machine tool gear boxes, automobile transmission, and piping.

The language of the text is simple and lucid, while at the same time conveying all the concepts clearly. The theory is well balanced with a number of well-illustrated examples. Most of the diagrams have been drawn in a manner that helps a student to easily understand and redraw them during exams.

Key Features

- Each chapter contains a set of review questions and numerous exercises to be attempted by the student independently. More than 370 multiple-choice questions with answers have also been provided.
- Select example problems contain a *solution outline* that provides a quick snapshot of the steps to be used for solving the problem
- Includes photographs of various machine components that are directly relevant to the discussion
- Includes exclusive chapters on piping that assumes significance in transportation of fluids, and machine tool beds and slideways that provide a quick overview of machine tool design

Contents and Coverage

Each chapter commences with a list of learning objectives (LO's), which inform the student what he/she is going to learn in the chapter. After a brief introduction, the student is initiated into the topics in a graded way, avoiding unnecessary mathematical equations and derivations. The idea is to treat the subject in a practical way based on the standards and design factors that are used in industrial practice.

Chapter 1 is an introduction to machine design and all the terminology relevant to the development of a design useful for realization in the workshop and end use by the customer.

Chapter 2 deals with the analysis of loads, which is the starting point for determining the size of a machine element.

Chapter 3 discusses at length the properties of materials used in the construction of machines and their treatment for improving the original properties.

Chapters 4 and *5* deal with stresses, deflections, equilibrium, and stability of machine parts subjected to static loads.

Chapter 6 discusses combined loading of machine parts while *Chapter 7* handles the important topic of how machine components under loading undergo failure.

Chapter 8 details the situation when machine elements are subjected to variable loads.

Chapter 9 is devoted to a discussion on the damage to the surfaces of machine parts in contact and in relative motion.

Chapters 1–9 constitute the introduction and base for the practical design of specific machine elements and components discussed in Chapters 10–34.

Welding and welded joint design is given in *Chapter 10* while threaded fasteners (bolts, nuts, and washers) are discussed in *Chapter 11*.

Chapter 12 is devoted to power screws used for lifting and lowering loads and in industrial compactors.

Chapter 13 talks about mechanical springs and other springs that are indispensable in engineering practice.

Plain bearings, also known as bush or sleeve bearings are discussed in *Chapter 14*.

Chapters 15–18 discuss gears, without which engineering cannot be imagined. Spur, helical, bevel, and worm gears, are explained in these chapters respectively.

Chapter 19 deals with rolling bearings, otherwise called anti-friction bearings.

Shafts, keys, and couplings, which are always together in any assembly, are handled in *Chapters 20*, *21*, and *22* respectively.

Different types of power transmission like chain drives, wire ropes, drums, and pulleys, and belt drives are explained in *Chapters 23*, *24*, and *25* respectively.

Chapter 26 is devoted to IC engine components, which utilize all the principles discussed in the previous chapters.

Clutches, brakes, and flywheels find their place in *Chapters 27*, *28*, and *29*.

Chapter 30 gives brief details of oil seals and gaskets.

Chapters 31, *32*, *33*, and *34* can be deemed as special chapters giving additional information over and above that required for under-graduate studies.

Chapter 31 discusses the design details of rivetted joints and pressure vessel design with stress on riveted and welded joints.

Chapter 32 gives the theory and examples of multi-stage and multi-speed gear box design in machine tools and in automobiles—both manual and automatic.

Chapter 33 describes machine tool beds, slideways, spindles, and other structural parts.

Chapter 34 deals with the theory and principles of piping design, and is not found in many machine design books. It will be very useful for engineers to refresh fundamentals in the topics and gain confidence in dealing with piping design and site installation.

Online Resources

The following resources are available to support the faculty and students using this text.

For faculty:

- Solutions manual
- PowerPoint lecture slides

For faculty and students:

- Photographs of machines illustrated in the book
- Additional multiple-choice questions with answers

Acknowledgements

Firstly, I acknowledge the inquisitiveness of my students who honed my knowledge of the subject. This book is mainly based on my class notes that were prepared, keeping in view the needs and difficulties of the students in understanding the subject. Intelligent questions posed by students served as guidelines in drafting the text in this book. I specially thank four of my students of the 2012–2016 batch of Mechanical Engineering—K. Sourya Rakshit, N. Neeharika, B. Vijaya Narayana, and B. Moulika—for helping me with the solutions to some of the problems present in the book. I sincerely thank the editors at Oxford University Press India for getting the manuscript whetted by peers and shaping it so beautifully for the readers.

The enormous data I had collected during my industrial career spanning over twenty five years in design, engineering, and project management gave me a definite direction in drafting the manuscript.

I specially thank my colleagues in the teaching profession for encouraging me to take up this difficult project. My special thanks are to my friend who supplied the appropriate colour photographs with the help of his personal camera. I am grateful to my colleague, Prof. D. Varadaraju for his appreciation of my work, particularly the hand-drawn figures and diagrams.

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Kamaraju Ramakrishna

Brief Contents

Detailed Contents

1

CHAPTER

Design of Machine Elements—A Perspective

Words of wisdom from Sanskrit

Aachaaryaat paadamaadatte sishyah paadam swamedhaya
Paadam sabrahmachaaribhyah paadam kaalakramena cha

A disciple acquires only one-fourth of a subject from the teacher; another quarter by his own study; yet another quarter he imbibes by discussion with classmates; and the remaining one-fourth of knowledge on the subject, he continues to acquire throughout his life. (One's knowledge in any subject is never complete.)

The best way to predict the future is to design it.
–Buckminster Fuller

Learning Objectives

A sincere study of the chapter will impart adequate knowledge for understanding the following topics:

1. Meaning of design and machine design
2. Analysis, synthesis, and creativity
3. Uncertainty, factor of safety, and design constraints
4. Designer's responsiblity towards society, ecology, and ethics
5. Stages and procedure for design
6. Importance of design standards, codes and norms, aesthetics
7. Units, engineering parameters, conversion
8. Preferred numbers, standard series
9. Design for manufacture and assembly
10. Surface finish, limits, fits, and tolerances
11. Reliability, product range
12. Concurrent engineering and phases, ergonomic design

INTRODUCTION

The job of an engineer is, in general, to fulfil the desires of mankind for better comforts and benefits and elevate the standard of living in a society. In pursuit of this, the engineer has to utilize the natural resources available to him for conversion into useful and commercially viable products or devices. Laws of pure science are applied in developing the engineering processes suitable for the conversion of the natural resources. Mathematics and artistic perceptions of the product are involved in formulating the mathematical models of the product for analysis before its prototype can be developed and tested. Engineering is therefore called applied science imbued with artistic sense, drawing support from mathematical equations.

1.1 MEANING OF DESIGN

The word *design* in general English means a plan or a scheme for giving shape to something, for forming an idea about, or for conceiving something. Therefore, many things can be conceived or designed; for example, a simple rose garden or an amusement park, a skirt or a lady's handbag, or the landing gear of an aircraft, a ball point pen, or a TV tower. In all these examples, engineers and artists play more or less equal roles. Even if an artist cannot handle engineering design, and an engineer cannot be a full-fledged artist, an engineer should cultivate at least an artistic outlook for producing aesthetic engineering goods or products.

1.2 ENGINEERING DESIGN

Engineering design starts with a conceived idea for fulfilling a need, a want, or a desire of an individual, a society, or a nation. An individual may like to have a villa built on a hilltop or riverside or have a unique custom-built luxury car. A society or a city may wish to have its roads broadened and flyovers built for handling the ever-increasing traffic. A nation may plan to have its own design of a prestigious passenger airliner or a state-of-the-art fighter aircraft and combat vehicles to deter foreign aggressions.

Engineering design is, in particular, a specialized area other than areas such as production, procurement, or marketing. It relates to the definition of a problem or a need and the application of principles of science, mathematics, and a little bit of artistic perception to develop a sketch or a drawing for translating the idea into a full-fledged product to satisfy the specified need or to solve the stated problem.

Design of machine members, mechanical engineering design, or machine design is a very essential core subject for mechanical engineering students anywhere in the world. If a professional engineer is called upon to find a practical solution to a problem, a designer develops a plan for a new product or modifies an existing product for incorporating more quality or introducing more comfort.

An engineer's design analysis may not have scientific precision and the formulae used by him may give just approximate results. However, for all practical purposes the product or the equipment developed by him on the drawing board and manufactured in a proper workshop can perform well and give excellent service. With growing years a design engineer develops a capacity for correct judgement, supported by practical experience and feedback from the end-users.

All design engineers, whatever their specialization, do not develop products on the same lines. Even with the same specialization, the products developed by them may be the same but different in style, sophistication, quality, and utility. No two designs of a product are identical or even similar. For example, there is a limitless variety of models of luxury coaches for road travel around the world in different countries. This example enables the reader to imagine the immense scope available to the genius of an innovative design engineer.

1.3 CREATIVITY

Creativity is a quality that enables one to generate novel ideas and develop new objects which are not routine but innovative. In this ever-changing world, people crave for new things or objects of pleasure and comfort. These would-be market products have to be conceived, developed, manufactured, and put in the market by engineers. The design engineer, whose task is the shaping or designing of an object, must first generate the new idea. For generation of new ideas, he has to be innovative and must possess the quality of creativity. The design engineer has to equip himself with creativity in one hand and an attention to detail in the other. For constantly developing a product in order that it stays in the market, a designer should work like an inventor who is always in quest of novelty in thinking and also in developing the ideas into competitive, marketable products.

In spite of the aforementioned arguments, it must be emphasized that not all design work is innovative and creative. Routine designs that are well established do not call for creativity on the part of the design personnel. A little risk is involved in well-proven products. Only in the case of new products, a lot of imagination and innovative thinking are required. Such projects should be entrusted to designers with creativity and an inventive bent of mind. Here again the need for creativity does not end with idea generation. It is required at every stage of design right up to the preparation of detailed drawings and even during manufacture.

Large organizations, which have long-range corporate planning for developing new products, usually engage two categories of design engineers. One group handles day-to-day design requirements of routine products. This group is not expected to be very innovative and creative. The other group which is teamed with the research wing is allowed freedom of independent thinking to generate new ideas and work on them, sometimes without binding targets of cost and completion. In such endeavours, the ambitions and the long-term goals, vision and mission of the organization are given priority rather than budgets and time limits.

Design engineers depend a lot on information. Information has to be collected by personal and professional efforts. It can be collected by reading professional journals, reference books, catalogues, technical manuals, and other related reports and through on-the-job-learning by attending conferences, symposia, and technical workshops. Another way of gathering information is by talking to scholars, customers, and end-users, and through questionnaires and pamphlets. The exercise does not end there. The collected information has to be sifted, understood, and interpreted in a proper way. The design engineer should have the discretion to understand his limits and constraints from standards, norms, and industrial regulations. For all these, the designer should have the proper attitude and aptitude. Over and above that, he must be an effective communicator, a good researcher, and a dispassionate interpreter.

Design engineering is not an easy discipline. In addition to the proper perception of the customer's needs, it calls for a deep technical knowledge of engineering mechanics, theory of machines, materials, metallurgy and heat treatment, production methods and facility in assembly and maintenance. If any of these prerequisites is lacking, the design may not be fully satisfactory, cost-effective, and may fail to give the desired performance in the short term and in the long term too.

1.4 ANALYSIS AND SYNTHESIS

Analysis and synthesis are very different in their meaning. Machine design as a subject deals with the most important machine elements such as shafts, couplings, springs, belts, gears, bearings, among others. These elements form a major portion of any equipment or device. The typical loading expected on these elements at any instant in the operation of the machine is considered for analysis and for determining the main dimensions of each element.

Design analysis consists of assuming a mechanism (readily available), material, and mode of failure. The dimensions and size of the machine and the individual component parts of the machine can be determined and finalized.

When design synthesis has to be undertaken, any predetermined mechanism is not readily available. A mechanism has to be selected for the machine from various alternatives. Then a suitable configuration for the desired output capacity or work has to be decided by the designer. The component parts have to be chosen. Alternative materials for the different parts have to be selected and each of them tried in different modes of failure. The best suitable and optimal solution has to be found and established.

Design synthesis involves starting from scratch, especially when it is an entirely new machine or equipment or device. It involves ingenuity and deeper knowledge of mechanisms, materials, theories of failure, and proper mathematical formulations on the part of the design engineer.

1.5 DESIGN CONSTRAINTS

An additional responsibility of the design engineer lies in identifying the constraints in his professional work. The real imagination of the design engineer comes into play in ascertaining and appreciating these constraints.

The major constraints or the overall design considerations may be listed as follows:

1. Availability of suitable materials and their cost
2. Manufacturing and inspection facilities for acceptable quality
3. Safety
4. Life expectancy of components and the equipment as a whole
5. Cranage for assembly in the workshops

6. Availability of space for assembly and subsequent storage
7. Major consignment dimensions for transport to the erection site or directly to the end-user

Other constraints are marketability, reliability, maintainability, aesthetics, ergonomics, ecological, and environmental acceptability in use and even after decommissioning. For example, when any equipment has served its life and has to be scrapped, it should be capable of being easily recycled or degraded without harming the environment.

Taking these constraints into account, the dimensions or materials of the individual elements or machine components may have to be modified to match other machine elements or components in the assembly of the whole machine. It is here that the design engineer has to use his expertise and real judgement in adapting to or overcoming the constraints for developing real wholesome equipment.

1.6 SAFETY FACTOR

Engineering goods and equipment, big or small, simple or complicated, are put to use for the good of the society. The equipment form a part of the social or the national life. Engineering is nowadays part and parcel of everyday life. As such the equipment must be safe to start, operate, and to lie still when not in use. Engineering goods should not become causes of concern and fear of any kind of hazard. It is the design engineer who has to ensure the safety of equipment or devices.

What is safety and how is it quantified? How can an engineering device be certified as safe? For knowing the answers to these questions, the concept of safety as applied to engineering design has to be understood.

An engineering product or a device is considered to have failed when it has failed to perform as per the stipulated specifications, showed up a defect or flaw while in operation, or came to a state of total breakdown. Things are therefore designed with 'sufficient' reserve strength to avoid failure and ensure safety. This reserve strength against failure is expected to ensure safety of the product.

Safety factors are ratios of two quantities with the same units. They are constants which are always more than one, the excess above unity denoting the amount of *reserve capacity or strength* built into the product. For example, a crane lifts loads by steel wire ropes. If the effective tensile load on a single rope is 4 kN and the safety specified is 6, the breaking load of the wire rope selected from the rope manufacturer's catalogue must not be less than 24 kN. Any suitable wire rope with a breaking load more than 24 kN will be considered safe for the application. In a similar fashion, if the ultimate tensile strength of medium carbon steel is 600 N/sq.mm and the actual tensile stress in the machine member designed with this steel is 200 N/sq.mm, the actual factor of safety is 600/200 or 3. Consider a pressure vessel designed for a factor of safety of 4, the actual pressure of the compressed fluid inside will be one-fourth of the design pressure.

1.7 UNCERTAINTY

What makes the factor of safety close to 1 or many more times than that like 10 or even 12? The answer is uncertainty. The design engineer is always confronted with uncertainties in his work. They can be enumerated as follows:

1. The loading (tensile or compressive loads or torsional moments or bending moments, thermal loads, and so on) on a machine member is neither completely known nor it can be exactly quantified. The loading is variable in many cases.
2. The point of application of the load is not always accurately known.
3. The direction of application of load cannot be defined or it is variable.
4. The frequency of loading may vary.
5. The properties of the material of construction may fall short of specifications.
6. The material may have some undetected defects or flaws.
7. There may be some manufacturing defects or flaws undetected during inspection, for example, minute tool marks or inadequate fillet radii on shafts, keyways, and gears.
8. The actual loading in operation of the machine may vary in a different pattern than assumed.
9. There may be unforeseen overloading, higher static loads or more of fluctuating loads and cyclic and reversing loads.
10. There may be assembly faults and misalignments.
11. There may be unforeseen imbalances and vibrations in the actual operations of the part or the machine.
12. Any other uncertainty pertaining to the particular equipment or structure may persist.

When the list of uncertainties is long, the design engineer has to play safe or introduce a safety factor much larger than unity into his design calculations. If the uncertainties could be eliminated one by one and the list becomes shorter, safety factor moves closer and closer to unity. This is the case with space vehicles where every vehicle is built after lots of research to ensure maximum possible safety or for rather *fail-proof* operation. However, for all practical purposes and particularly in general mechanical engineering design, safety factors cannot be taken as unity, which otherwise means that they are eliminated. They are always and will continue to be more than one or even two. The usual range of safety factors is 1.5 to 12. That is how safety can be quantified. The higher the safety factor, the greater is the safety pertaining to a product. The lower the confidence level of the designer, the larger is the safety factor, the heavier and costlier is the product. However, higher factors of safety are justifiable when hazards to human life are foreseen as in the case of a crane wire rope and a pressure vessel cited above.

1.8 IMPORTANCE OF FACTOR OF SAFETY

Factor of safety is essential for the following reasons:

1. Failure leading to loss of life or at least injury
2. Costly repairs in the machine and the surrounding equipment
3. Uncertainties in the loads in service
4. Uncertainty of material properties
5. Assumptions made for the analysis
6. Uncertainty in determining the stress-concentration factors, sudden and impact loads
7. Uncertainties about the conditions of the environment in which the components are intended for service
8. Uncertainty about the stresses which could be induced during manufacturing processes (welding, machining, heat treatment, etc.) and transport for assembly or shipping to erection site
9. Uncertainty regarding the extent to which the component would be damaged by exposure to the atmosphere (corrosion)
10. Reduction in dimensions due to corrosion and increase in stress levels, stress concentration, and fatigue levels

1.9 EXAMPLES OF FACTORS OF SAFETY

The choice of the factor of safety depends primarily on the material and the type of application that includes the loading pattern. Some typical examples are given in Table 1.1.

Table 1.1 Typical values of factors of safety

Aircraft against yield	1.0
Typical mechanical engineering applications	1.5–3.0
Hoisting equipment wire ropes	5–8
Passenger lift and mining lift steel wire ropes	10–12
Pressure vessels	8–10

These factors give us the allowable stresses for calculation. It is obvious that the greater the level of combined uncertainty, the higher will be the factor of safety. However, when it is known that the uncertainty is resulting in excessive weight of the component or machine, bulk, and consequently high initial cost, it is economical and worthwhile to resort to experimentation. Thus, uncertainties can be curtailed with confidence and the factor of safety lowered to make the component lighter and far less expensive.

A new entrant to design department is always at a loss for fixing the value of safety factor in his design. He has to take recourse to design codes or safety standards available in the particular area. Sometimes the design codes specify some modifying factors for reducing the basic permissible stresses or for increasing the actual loading on machine members. These factors serve indirectly as factors of safety. Examples are service factors, duty factors, velocity factors, dynamic factors, impact factors, stress concentration factors, fatigue factors, and so on. These factors are applied on the table stresses or the loads on the machine members. When nothing of the sort is available, the young design engineer has to depend on his peers and draw on their expertise till he accumulates his own experience and attains an adequate confidence level in the field. We shall discuss factor of safety again in the latter chapters of the text. The following oversimplified problems illustrate the meaning of factor of safety.

Example 1.1 (LO 2, 3) The draw bar used for connecting the trailer to the tractor has to be designed. The draw bar pull with full payload in the tractor is estimated to be 8 kN. Considering yield strength of 400 MPa for the material of the draw bar and a factor of safety of 4 and neglecting acceleration and retardation forces, calculate the diameter of the drawbar required for the purpose.

Solution: The draw bar is subjected to tension and the tensile load F is given as 8 kN or 8000 N.

If the diameter of the drawbar is denoted by d mm, the cross sectional area A of the draw resisting the tensile force is given by

$$A = (\pi/4)d^2 \text{ mm}^2$$

Permissible tensile stress in the drawbar

$$\sigma_{perm} = S_y/FS = 400/4 = 100 \text{ MPa}$$

The load capacity of the drawbar =

$$\sigma_{perm}\, A = 100 \times (\pi/4)d^2$$

We can equate the tensile force F to the load capacity of the draw bar.

$$F = \sigma_{perm}\, A$$

$$8000 = 100 \times (\pi/4)\, d^2$$

$$d = \sqrt{[(8000 \times 4)/(\pi \times 100)]} = \sqrt{(101.86)} = 10.1 \text{ mm}$$

In actual practice, there will be additional dynamic forces acting on the drawbar. Drawbars are also subjected to torsion when the tractor moves on uneven ground. When all these factors are considered in design, the draw bar for this application will be larger in diameter.

Example 1.2 (LO 3) For a load lifting application, a wire rope with a breaking load of 42 tonnes has been selected. If the actual estimated tensile force in the wire rope is 7 tonnes, what is the factor of safety used in the design for the application?

Solution: The breaking load of the wire rope from the catalogue = 42 tonnes

Actual tensile force in the rope = 7 tonnes

Factor of safety considered in the selection of the wire rope = Breaking load/Actual tensile force = 42/7 = 6

In view of the uncertainty about the complex stress patterns inside a wire rope and high risk involved in failure of a lifting wire rope, high factors of safety are considered for lifting appliances.

1.10 STAGES IN MACHINE DESIGN

Market conditions drive the design of a machine, a product, or a component in engineering. An organization engaged in the design and manufacture of a product must always be in touch with the end-users or the prospective buyers. The intention is for collecting information in the form of feedback from the users or at a vague description of a need or a desire of the prospective buyers or buyers-to-be. This is an organized effort put in by a key department in a progressive organization. It is the marketing department entirely different from the sales department. The marketing department conducts regular market surveys gathering information on the products and feeding positive criticism to the design department for constant improvement in the product. In fact there are group discussions, presentations, and seminars among all concerned in developing a better product or a new product altogether. Figure 1.1 shows the flow chart generally applicable for the development of an engineering product starting from the market survey.

Market survey
↓
Group discussion
↓
Product specifications
↓↑
Preliminary design
↓↑
Loading analysis and preliminary dimensioning
↓↑
Iteration
↓
Preparation of general assembly
↓
Engineering
report and approval
↓
Design of components for manufacture
↓
Release of production drawings to the workshops
↓
Prototype testing
↓
Final report

Fig. 1.1 Flow chart showing stages in the design and development process

Market survey Market survey serves to supply information on improvements required in the existing products and also information necessary to develop new products to satisfy customer needs. The marketing department plays a very important role in developing and innovating products and also in the overall growth and corporate development of an organization. Organizations without a strong and effective marketing department cannot face competition, show sustained growth, and over a period of time lose market share in that product.

Group discussion With the data collected from the market on the product or products on the desk, a meeting or group discussion should take place among all concerned. The group should consist of personnel from design and engineering, industrial and planning department, materials, costing and finance, production, quality and inspection, after-sales services, sales department, and in some special cases representatives from key customer groups. In this brain-storming session or sessions, conclusions are drawn on the product development and recorded for implementation. These conclusions are meant for immediate implementation at all levels in all the concerned departments.

Product specifications Now is the time for laying down specifications of the product for the engineering work to commence. The main specifications of the intended product are discussed and decided upon based on the conclusions drawn at the previous brain-storming sessions.

Preliminary design Simple line sketches are developed by the design engineers for approximately fixing the outer dimensions and to list out the major components in the product. The different mechanisms envisaged for the product and their relative disposition and operation are discussed and finalized for the preliminary force and loading analysis.

Loading analysis and preliminary dimensioning Analysis of the loading and critical sections in the components, mechanisms—individual and assembly—is done to arrive at the preliminary dimensions of the product and its component parts.

Iteration The process of iteration is used for changing any unsuitable parameters or dimensions and the previous steps are repeated for obtaining better or more suitable results.

Preparation of general assembly With the dimensions obtained after the iteration process, a general assembly or a layout drawing of the desired product is prepared.

Engineering report and approval The engineering report is meant for presentation to the core group assigned for the development of the product. The design and engineering group will make the presentation by way of drawings, sketches, calculations to convince the people from the other departments about the improvements made in the design.

Design of components for manufacture After the final approval or approval with comments, the designer is free to develop individual component drawings with adequate tolerances for assembly. However, he has to bear in mind all the constraints for translating the drawings into machine components suitable for flawless assembly and prototype testing. This subject is called design for manufacture.

Release of production drawings to the workshops The design engineer can now release the manufacturing or production drawings to the workshops for production. Before release, he may have last minute consultation with his production colleagues on the intricacies and the finer details of design, production, process, assembly, testing, dispatch, and maintainability of the equipment.

Prototype testing A prototype is a full scale model of the equipment or the product. It is subjected to all relevant and prescribed tests to establish its load capacity or throughput and reliability at a slight overload under static conditions. For example, a 40 tonne crane is tested for an overload of 25%, which means that the crane should be capable of lifting 50 tonnes under static conditions. This stage in design offers excellent opportunity for on-the-spot study of the prototype from various angles and making modifications for the better.

Final report At this stage, a final report is made to unveil the success of the design project. The report is presented before all the concerned personnel, perhaps including the prospective customer(s). After this the prototype is deemed fit for going into mass production on a scale matching the existing demand or orders already placed in advance.

It must be pointed out here that for equipment with some variations from the previous ones, the whole procedure given above need not to be followed. In such cases the starting point is the design specifications and the end point is release of drawings to the workshops. Prototype is not needed.

1.11 SOCIETAL CONSIDERATIONS

It has to be understood by every designer that his work must be for the benefit of the society and for elevating the quality of life. He should always endeavour by dint of his work to develop products and build machines for adding comfort to human life. To attain his goals, a designer must have properly a formulated, precise definition of the problem that he has to solve. If the definition of a problem is vague and ambiguous the solution to the problem would be erratic and wasteful.

Suppose a problem is mentioned as 'pollution is very high'. This cannot be taken as a statement of the problem. It should be specific. Say the air pollution levels in downtown city are much higher than normal where the normal levels are already available in detail. Now the first stage in the solution to the problem is to note down the normal permissible levels of all the constituents of downtown air. At heavy traffic levels, samples of air can be collected and all the constituents and their percent content in the air sample can be measured in a lab. Then the methods of reducing these high levels of pollutants to the permissible levels can be devised.

The next step would be to assess the benefit or benefits accruing to the society or a community or a nation by finding a solution to a specific problem. The areas where a society can benefit are many but in general there are some key areas like health, education, social safety, employment. If these areas are taken care of, other areas can also be fostered. The major areas are

1. Health
2. Education (schools, colleges, universities, research institutions)
3. Social security
4. Safety in travel
5. Employment opportunities
6. Protection to the environment
7. Conservation of natural resources
8. Control on population growth
9. Concessions to the physically and mentally challenged
10. Special privileges to the senior citizens
11. Equal opportunities (irrespective of caste, creed, language, nationality, region or religion)
12. Freedom within the constraints of the society

It is easily understood that when a major portion of these requirements of a society are fulfilled a state of well-being prevails. The quality of life is said to be good. The job of an engineer or, for that matter, a design engineer is to work out appropriate solutions to well-defined problems in the areas listed for translation into viable products with the technologies available to him at any point of time. To be effective in his profession, the design engineer should have the following attributes:

1. Proper qualification
2. Adequate experience in the domain
3. Comprehensive knowledge of design standards and codes in his domain
4. Goodwill and support of his peers
5. Positive attitude to all situations
6. Constructive approach to all attendant problems
7. Cool temperament
8. Empathy
9. Open-mindedness
10. High level of receptivity

A human being, in general, is on the quest for change, a change in his environment, a change in his belongings, a change even in the midst of prosperity. Changes like this can be brought about by engineers and before a change can materialize, a concept, an idea, and a design are absolutely necessary. Such is the importance of the design engineer. It is only the design engineers who can bring about changes in the material world.

1.12 MASLOW'S CONTENT THEORY

Abraham Maslow was an American psychologist with very humble beginnings. He grew up in social isolation and became a famous psychologist with many contributions to humanistic psychology. According to him, human needs can be arranged in a hierarchical form ranging from basic needs up to self-actualization at the highest level. The *hierarchy of needs* as postulated by Maslow is shown in Fig. 1.2, which is self-explanatory. The ascent on these steps changes human life greatly and can transform the present world into a peaceful place. Engineers can help people in realizing these noble goals and can themselves reach stages of self-realization in doing so.

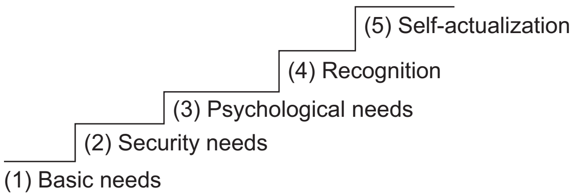


Fig. 1.2 Hierarchy of needs (Abraham Maslow)

1.13 ECOLOGICAL CONSIDERATIONS

During the manufacture of goods, products, and equipment for the good of the society, as it were, there are always waste products or by-products that are unwanted and thrown away or disposed of as garbage. These waste products can be recycled, if technically feasible, or should be such that they are bio-degradable without causing any temporary or permanent damage to the environment. Though this is a statutory requirement in many advanced countries, adherence to the standards is partially or totally lacking in many countries. This is owing to the lack of awareness about the hazards or lack of implementation mechanism or sheer connivance by the concerned authorities for reasons best known to them.

Environmental protection is a social responsibility. By throwing our garbage in the neighbour's courtyard, we are not getting rid of the evil. By letting off toxic waste waters from a processing plant in to a river close by, we are polluting our own environment.

The main reason for reluctance to adherence of environmental standards is the additional first cost and operating cost of the equipment. The plant designer should be dutiful and the enforcement authorities should be accountable to the society as a whole. Only then this planet would be safe from depletion, damage, degradation, and decay.

Some of the measures a design engineer should take for protecting the environment in his own capacity are as follows:

1. To the extent possible, a design engineer should show preference to materials which will be amenable to *recycling*. The advantages of this measure are less damage to the environment and conservation of materials. Pollution of air, water, soil can be protected in this way.
2. He should strive to design any equipment that consumes relatively low power in operation. In other words, the equipment must be *fuel-efficient* or *energy-efficient*. This method will reduce thermal pollution and conserve fuels available to us from Nature.
3. He should ensure operation of the designed equipment with the lowest possible noise levels. This would *lower noise pollution*.
4. The designer should always try to keep the designs as simple as possible. He should avoid complex shapes and fanciful contours that may create problems in manufacture, assembly, and maintenance.
5. The design engineer should bear in mind the manufacturing process or processes that will transform his designs into end products. The point is that a process which generates less amount of scrap is preferable to one in which scrap quantity and its disposal may create problems. Castings and their subsequent machining generates large amount of metallic and non-metallic scrap whereas with forgings the case is different. Forged components, where feasible, should be preferred to cast and machined components.
6. The design engineer should also take into consideration disposal of other 'auxiliary' materials like packing wood or cardboard for ecological reasons.
7. Last but not the least, a design engineer should always follow the relevant engineering norms and standards in his domain.

1.14 ETHICS FOR DESIGN ENGINEERS

The science of ethics defines the standards of uprightness and personal integrity. In their practice of the design engineering profession, designers should be aware of their bounden duty and their accountability in protecting the quality and well-being of the society he lives in. For that matter ethical behaviour and conduct is mandatory for any individual for a healthy growth and safety of the society and the nation. In an environment of globalization, these precepts relate to the international context. Ethics teaches what is good and what is bad and tells us whether our conduct or behaviour in professional and personal life is beneficial or detrimental to the human society.

More often than not, situations arise in the professional life of a design engineer in which he might be called up on to dilute the standards and compromise the design. It is strongly expected of the designer to stand firm and stick to the norms, standards, and the stipulated specifications in his design assignments. This is all the more important because design happens to be the starting point in any manufacturing endeavour.

To assist the employees in maintaining standards, the organizations can help by forming special vigilance committees to prevent unethical conduct and uphold high standards of quality and product excellence.

NSPE Code of Ethics for Engineers National Society of Professional Engineers (NSPE), USA, has formulated some fundamental canons for the professional conduct of engineers. They are reproduced here for ready reference of the readers and students.

Engineers, in the fulfilment of their professional duties, shall:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.
6. Conduct themselves honourably, responsibly, ethically and lawfully so as to enhance the honour, reputation and usefulness of the profession.

It is very clear from the above that an engineer is held in high esteem in the society and his moral and ethical responsibilities are ponderous.

1.15 DESIGN STANDARDS AND CODES

Design standards and codes are great supplements to the knowledge and expertise of the design engineer. In every domain of engineering, there are standards which supply data and information on what is best and safe for a given situation. For example, what should be the dynamic load factor for design of spur gears in a particular application? The design engineer derives guided assistance from the standard instead of relying on his own empirical knowledge. Standards introduce uniformity in engineering practice. Standards are based on the collective opinion and efforts of a group of highly knowledgeable professionals or even organizations in the particular field or domain. Standards not only cater to uniformity but also interchangeability and acceptable quality. Standards serve the purpose of cutting down on the variety of items or goods or at least spare parts and thereby impose a limit on the number of such items or components. This is true of a particular organization, a country, or a group of countries, giving rise to *company standards, national standards,* or *international standards*.

Codes, on the other hand, are legally tenable and are obligatory and rank higher than standards in stature. Codes deal with and are intended more for safety than for uniformity of design. They are statutory in nature and have to be followed per force. In case of noncompliance with a code, the designer or his employer organization can be called in question in the court of law. Non-adherence to codes can be a subject of public litigation. It may be mentioned here that the word, code, is sometimes used in place of standard. Standards for testing of equipment like a pressure vessel, a crane, or a steel structure like a bridge are acceptably called codes of practice for relevant equipment.

Norms may pertain to a particular situation or an organization. Norms may not be binding. Obligatory norms can be called standards, which are not necessarily universal. Organizations can have their own norms and standards.

1.16 BENEFITS OF STANDARDIZATION

Many benefits accrue from standardization. The main advantages of standardization are follows:

1. As described above, standards can set a limit on the variety and number of items of similar function. This type of rationalization facilitates mass production and reduces the cost of production due to reduction in the initial cost of machine and cutting tools and manufacturing cost.
2. Standard components can be outsourced to or procured from specialist manufacturers by the main machine-building organizations. This

measure will greatly reduce the initial cost of the main plant facility and make the equipment more cost-effective and competitive. Examples of standard and proprietary items are bearings, wire ropes, chains, oil seals, wheels, forgings, rubber tyres, fasteners, brackets, door handles, knobs, gear boxes, couplings, and many more.

3. When standard components are used in design and construction, their replacement is done in case of wear and tear or unexpected damage. Moreover, standard components can be stored as ready spares and greatly reduce the downtime due to instant procurement. Of course this argument does not hold good if the organization is fully geared up for just-in-time (JIT) procurement and an efficient supply chain management.
4. Complete units like pumps and speed reducers and even engines can be procured as they are and the need for designing them from scratch does not arise. This introduces lot of economy at the micro- and also macro-level by elimination of work duplication by several firms.
5. Standards and accepted codes of practice in the industry improve the quality of products from various vendors and make them safe and acceptable and, at the same time, competitive in the market.

After being assigned a job or a project, the first thing a design engineer should do is to collect all relevant design standards, norms, and codes pertaining to the project on hand and keep them handy during the course of the design process. Sometimes specific standards are mentioned in the customer's tender documents and they have to be followed without fail. Any deviations, intentional or unintentional, may lead to rejection of the product and create legal complications. Many customers, consultants, and inspection agencies insist on approval of the design drawings as per standards and codes before they can be released for manufacture or execution at site. This would be a much better procedure than leaving the approval till the end.

1.17 CATEGORIES OF DESIGN STANDARDS

Design standards decide the characteristics of a product to be released into the market. The characteristics of a product relate to the materials of construction, its overall dimensions, shape, testing procedures adopted, size after packing as consignment for dispatch, conformity to standard store house, and so on. What follows is an attempt to give a list of categories of standards used in practical mechanical engineering.

1.17.1 Material Standards

These standards, national or international, list out standard materials with their chemical compositions, mechanical properties, and other suitable processing methods to improve properties like heat treatment. Examples are cast irons, alloy steels, stainless steels, composite materials, and other non-ferrous metals and alloys.

1.17.2 Dimension Standards

These standards ensure interchangeability, reduction in numerous non-standard sizes, and savings in inventory and storage costs. Fasteners, transmission belts, gear modules, anti-friction bearings, wire ropes, oil seals, keys and keyways, and splines are good examples of machine elements covered by dimension standards.

1.17.3 Surface Finish Standards

All fits depend on the relative surface finish provided on the matching components. Limits and tolerances are universally standardized and provide excellent guidelines to the design engineer on the type of fit to be provided in a particular situation. These topics are covered under 'Limits, fits and tolerances' in mechanical engineering design literature.

1.17.4 Testing Standards

Starting with the dimensions of a test specimen of steel and procedure for tensile test on a universal tensile testing machine, these standards lay down guidelines and formal test procedures for small components and even large machines including aircraft. Stringent test procedures have to be followed without exemption for boilers, pressure vessels, oil tankers where there is a risk of explosion and loss of human life.

1.17.5 Engineering Drawing Standards

These are standards for representing engineering components, subassemblies, assemblies with relative dispositions, instructions on materials, manufacturing methods, machining tolerances, test procedures, etc.

on engineering drawing which have to be released to shop floor for manufacture. The standards lay down rules and guidelines in furnishing all the information on the drawing that can be easily understood without ambiguity.

1.17.6 Individual Company Standards

In addition to these national and international standards that are binding on the manufacturer when they are mentioned in the original specifications, the manufacturers themselves have their standards—for quality and manufacturing practices—though within the framework of the specified standards.

As an example, we can talk about speed reducers (gear boxes) for use on cranes. The gear boxes can be standardized based on power input, output torque, and reduction ratio. The crane designer simply selects the most suitable gear box required for the purpose from the store.

Company standards should always try to fine-tune the specified national or international standards. The manufacturers' standards are binding on all sister concerns of the parent company.

1.17.7 International Standards

A design engineer should always try to add as many standard components as possible in the machine he has been asked to design. When these parts conform to international standards the products become even more competitive. Standard parts like anti-friction bearings, V-belts, catalytic converters are available in the market from reputed manufacturers, indigenous, and foreign. These components need not be redesigned by the designer for use on his machine. In these days of globalization, use of standard components reduces the cost of equipment and at the same time ensures quality of product and its performance.

1.18 SYSTEMS OF UNITS

Quite often mistakes are made in engineering calculations by choosing wrong units for the variables involved in the design. The dimensional unit of a variable should not only be correct but should also be consistent with the units of the other related variables. One variable cannot be in meters and the other variables in sq. cm and N/sq.mm. Similarly in the same set of calculations, units in inches, pounds cannot be used together with units in mm, Newtons, and so on. Consistency of units is essential for design calculations.

The so-called base units constitute a system. In the United States of America, the inch-pound-second (IPS) system and the foot-pound-second (FPS) system are the two systems prevalent. Sometimes, the SI system of units is also adopted. In India though the Metric system is used it is the SI system that is now predominantly adopted for engineering calculations.

1.18.1 Base Units

In any system there are three base units and one derived unit. The four units are (a) force, (b) mass, (c) length, and (d) time. If force, length, and time are chosen as base units, mass becomes the derived unit. On the other hand, force becomes the derived unit when mass, length, and time are chosen as the base units.

Derived units are those which are derived from and which depend on the base units. For example, area is a derived unit depending on units of length, and pressure is a derived unit depending on units of force and area.

In SI system, force is in Newtons, length is in meters, time in seconds, and mass in kgs. All other engineering design variables and their respective units are given in Table 1.2.

Table 1.2 Engineering design variables and units

Variable	Symbol	fps Units	SI Units
Force	F	lb	N (Newton)
Length	l	ft(feet)	m (Meter)
Time	t	sec	s
Mass	m	slugs (lb-sec^2/ft)	kg (kilogram)
Weight	W	lb	N
Pressure	p	psf	Pa (Pascal)
Stress	σ, T	—	MPa
Velocity	v	ft/sec	m/sec
Acceleration	a	ft/sec^2	m/sec^2
Angle	θ	rad	rad
Angular velocity	$\dot{\omega}$	rad/sec	rad/sec
Angular acceleration	α	rad/sec^2	rad/sec^2

(*Contd*)

Table 1.2 (*Contd*)

Variable	Symbol	fps Units	SI Units
Moment	M	ft-lb	N-m
Torque	T	ft-lb	N-m
Bending Area	A	ft^2	m^3
Volume	V	ft^3	m^4
Area moment of inertia	I	in^4	m^4
Specific weight	w	ft-lb-sec^2	N/m^{3+}
Energy	E	lb/ft^3	N-m = J (Joule)
Power	K	ft-lb	N-m/sec (watt)
Spring rate	k	lb/ft	N/m

Table 1.3 shows the conversion relationships between units of the IPS and the SI systems.

Table 1.3 Conversion relationships

Quantity	Conversion
Force	1 lb = 4.448 N
Length	1 in = 25.4 mm
Area	1 in^2 = 645.16 mm^2
Volume	1 in^3 = 16387.2 mm^2
Mass	1 slug = 32.17 lb
	1 kg = 2.21 lb
	1 kg = 9.81 N
Pressure	1 psi = 6895 Pa
	1 Pa = 1 N/m^2
Stress	1 psi = 6.895×10^{-3} MPa
	1 ksi = 6.895 MPa
Modulus of elasticity	10^6 psi = 6.895 GPA
Spring rate	1 lb/in = 175.126 N/m
Velocity	1 in/sec = 0.0254 m/sec
Acceleration	1 in/sec^2 = 0.0254 m/sec
Work, energy	1 in-lb = 0.1138 N-m
Power	1 hp = 74537 W (watts)
Moment torque	1 in-lb = 0.1138 N-m
Area/Moment of inertia	1 in^4 = 4.162×10^{-7} m^4

Table 1.4 shows a short list of prefixes for SI units.

Table 1.4 Some prefixes for SI units

Name	Symbol	Factor
Giga	G	10^9
Mega	M	10^6
Kilo	k	10^3
Centi	c	10^{-2}
Milli	m	10^{-3}
Micro	μ	10^{-6}
Nano	n	10^{-9}

Example 1.3 (LO 7) A circular rod is subjected to a tensile load of 10 kN. If the permissible tensile stress in the material of the rod is 150 MPa, calculate the diameter of the rod.

Solution: The cross-sectional area of the rod can be calculated in mm or m.

The area of cross section A of a member subjected to a static tensile load F equals the tensile load divided by the permissible tensile stress σ_t in the member.

$$A = F/\sigma_t = 10 \times 1000 \text{ (N)}/150 \text{ (N/mm}^2)$$
$$= 66.67 \text{ mm}^2$$
$$= (\pi/4) \times d^2$$
$$d = 9.21 \text{ mm}$$

In FPS units:

$F = 10 \times 1000/4.448 = 2248.2$ lbs

$\sigma_t = 150 \text{ MPa} = 150/(6.895 \times 10^{-3}) = 21754.9$ psi

$A = F/\sigma_t = 2248.2/(21754.9) = 0.103 \text{ in}^2$

$d = 0.36274 \text{ in} = 9.21$ mm

Example 1.4 (LO 2, 7) A pulley is mounted centrally on a circular pin of 20-mm diameter and 200-mm length and supported on bearings 150 mm apart. A man passes a rope over the pulley for pulling a weight of 5 kN attached at one end of the rope. He holds the other end of the rope for pulling the weight upward. Calculate the maximum bending stress in the pin.

Solution: Here we have to calculate the end reactions of the pin due to the central load F and then the bending moment M_b on the pin at mid-point where it is the maximum.

The end reaction at each end is $F/2$. If the length of the pin between the supports is denoted by L and the diameter of pin by d,

M_b (maximum) at the centre of the pin = $(F/2) \times (L/2) = (FL)/4$

Moment of inertia (area) I_{xx} of the pin about the X-axis = $(\pi d^4)/64$

Maximum bending stress σ_{bmax} in the pin = $(M_b\, y)/I$ where $y = d/2$

$\sigma_{bmax} = [(FL/4) \times (d/2)]/[(\pi d^4)/64] = (8FL)/(\pi d^3)$. On substituting with proper units,

$\sigma_{bmax} = (5 \times 1000 \times 150)/(\pi \times 20^3) = 29.84$ N/mm^2 (or MPa)

When expressed in FPS units, the maximum stress equals 4327.77 psi by referring to the conversion Table 1.2.

1.19 METHODOLOGY FOR DESIGN PROBLEMS

Machines and equipment are expected to be manufactured and put to use for flawless operation as per the given specifications showing the desired performance. To realize this, an organized and systematic approach and procedures are absolutely essential at every stage. In the making of a machine, the designer is the first architect. His work is of paramount importance in giving a shape to the desired product. He has to put in concerted effort for realizing this objective. We shall now discuss some general guidelines which will apply to any design work and mechanical design in particular.

1.19.1 Systematic Design Procedure

The *following steps* should be followed by a design engineer who likes to execute his work systematically to avoid confusion and controversies at later stages of detail design, preparations of drawings, approvals, production, selection of alternative materials, inspection and dispatch of the product, and its performance in the field or market.

1. Open a separate design calculation pad exclusively for the design project in hand.
2. Define the problem clearly after understanding the need or the improvement required.
3. Chart out all given data concerning the problems, in figures and in remarks.
4. Prepare simple sketches useful in understanding the rough physical appearance of the product.
5. Note down all the assumptions required to simplify the problem definition and the subsequent solution.
6. Write down problem in a mathematical form, if possible.
7. Collect the relevant formulae or texts which will be useful for a better understanding of the problem.
8. Collect relevant standards and codes and keep them handy on the design table.
9. Check the effect of the present design on the surroundings.
10. Prepare an outline sketch of the assembly, sub-assemblies, and various mechanisms in the design.
11. Develop free-body-diagrams of the components and analyse the loading.
12. Apply the relevant physical laws and predict the behaviour of the whole system.
13. Make use of the fundamental relationships developed in engineering mechanics, mechanics of materials, engineering materials and metallurgy.
14. Record all changes made to the specifications, later date suggestions, and iterations made in the design. Important and crucial points should be marked in red.

All the data collected, calculated, derived, and noted during the course of the design work should be available clearly and legibly in the design note pad mentioned above. The design pad should serve as a ready reference for any clarifications sought by any party even after completion of the project. By following the aforementioned steps a good deal of valuable time can be saved for the designer and the organizations by avoiding search for any slips and mutual accusations and incriminations.

1.20 WORK AND ENERGY

All machines are designed to do some useful work converting some form of energy supplied to them. Work and energy have the same units. When forces or loads acting on machine members make them move through distances work is done. If work done by a force F on a body is represented by W and distance by s,

$W = F \times s$ or expressed in general terms,

$W = \int F \cdot ds$ (between limits s_1 and s_2). The two limits, s_1 and s_2 indicate the distances traversed up to position 1 and position 2, respectively.

The distance travelled under the action of a force need not be linear. It is the cumulative product of the force and the distances travelled that is required to arrive at the work done.

We can take the example of a centrally mounted wheel or a disc that can rotate under the action of a tangential force F at a radius R as shown in Fig. 1.3.

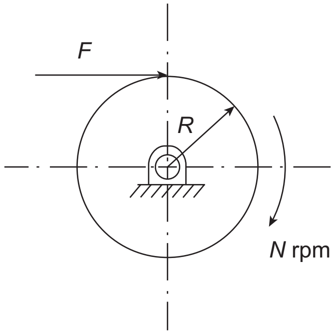


Fig. 1.3 Rotating disc

When the disc makes N revolutions under the action of the force, the work done will be the product of the force and the distance travelled:

$$W = F \times S$$

$$\text{Here } S = (2 \times \pi \times R) \times N$$

Instead of a tangential force, we imagine a turning moment T turning the disc through an angle, θ, expressed in radians,

$$W = F \times R \times \theta = T \times \theta$$

When we say that work has been done on a component by a force or a turning moment or torque, it is understood that energy has been transferred to the member to be stored as another form of energy.

Energy has the same units as work. It is expressed in N·m or joule (J).

Example 1.5 (LO 7) A cam on a camshaft has to exert an upward force of 2 N to lift the follower against spring force in the valve operation of an IC engine. Eight degrees of ration of the cam produces a lift of 1.5 mm of the follower. Estimate the average torque on the camshaft.

Solution: The cam and the follower are represented in Fig. 1.4.

We assume that the torque required on the camshaft is constant and friction between the cam and the follower and in the follower guides is negligible. These assumptions simplify the computations for now before a finer analysis could be taken up in the final design.

In the analysis we take the following steps:

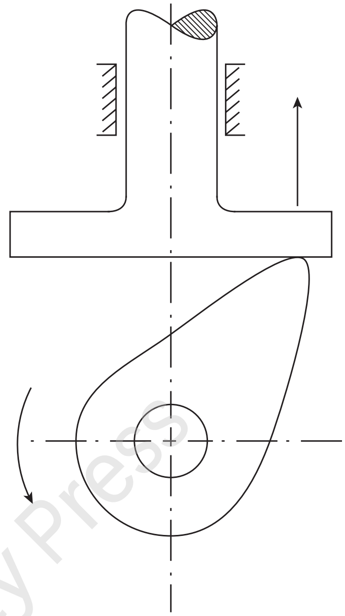


Fig. 1.4 Cam and follower

From the principle of conservation of energy, we can say that the work done on the camshaft is equal to the work done on the follower (with friction neglected).

Force on the follower $F = 2\ N$

Upward displacement of follower $S = 1.5$ mm

Work done on the follower is equal to Force × distance = $F \times S$ N·mm= 2 × 1.5 = 3 N·mm

Let T (N × mm) be the torque on the camshaft.

Work done on the camshaft = Torque × Rotational displacement

$T \times \theta$ (in radians) = $(T \times 2 \times \pi \times 8)/360 = 0.1396$ T N × mm

Since output work is equal to input work,

$$0.1396\ T = 3$$

$$T = 21.49 \text{ N·mm}$$

1.21 POWER

Power is different from work and energy. Work is defined as the rate of doing work or rate of transfer of energy. If distance is considered in the calculation of work, rate of travel, or speed or velocity at the point of application of force has to be considered to determine the power required to move a body under the action of the force or torque. Expressed mathematically,

$$\text{Rate of work} = F \times V = (T/R) \times R \times \omega = T \times \omega$$

In rotation the rate of travel or speed is the angular velocity expressed as radians per second. The work done by the force on the body or member will be equal to the integral of the product of force and the speed with reference to time. The power or energy transfer can be considered during a period of time starting at t_1 and ending at t_2.

$$W = \int F \cdot V\, dt \text{ (between limits } t_1 \text{ and } t_2)$$

The unit of power in SI units is J/sec or Nm/sec or popularly known as watt. A larger unit of power used to express the power of electrical motors and other appliances is kW equal to one thousand watts. The other unit of power, horsepower (hp) is a fraction of kW.

$$1 \text{ hp} = 0.746 \text{ kW or } 1 \text{ kW} = 1.34 \text{ hp}$$

Other relationships among parameters and their units:

Power in kW = $(2 \times \pi \times N \times T)/(60 \times 10^6)$ where

T = torque in N-mm

N = speed in revolutions per minute (rpm)

Alternatively,

$$T = [60 \times 10^6 \times (\text{kW})]/(2 \times \pi \times N)$$

Example 1.6 (LO 7) The torque required on a motor shaft for driving a machine is 300 N·m. The motor shaft rotates at 1000 rpm. Calculate the power required from the motor.

Solution: Power required in kW = $(2 \times \pi \times N \times T)/60 \times 10^6$ where, T = torque in N·mm; N = motor speed in revolutions per minute;

By substitution in the above formula, we obtain

Power in kW = $(2 \times \pi \times 1000 \times 3000 \times 1000)/(60 \times 10^6) = 31.416$ (kW)

Example 1.7 (LO 7) An electric motor shaft rotates at 1500 rpm and transmits a power of 40 kW to the input shaft of a speed reducer. The efficiency of the single stage gear box is 95% and the speed ratio is 5:1. Calculate the torque on the two shafts of the gear box. Also, calculate the torque ratio.

Solution: The torque T_m produced by the electric motor output shaft,

$T_m = [60 \times 10^6 \times (\text{kW})]/[2 \times \pi \times N]$ where $N_1 = 1500$ rpm

$T_m = [60 \times 10^6 \times 40]/[2 \times \pi \times 1500] = 254.647$ N·m

Gear box output power will be less owing to friction losses given in the efficiency as 95%.

Gear box output power = $40 \times (95/100) = 38$ kW

Speed of the gear box output shaft, $N_2 = 1500/(5:1) = 294$ rpm

Torque T_g of the gear box output shaft

$$[60 \times 10^6 \times (\text{kW})]/[2 \times \pi \times N_2] \Rightarrow [60 \times 10^6 \times 38]/[2 \times \pi \times 294] = 1234.260 \text{ N·m}$$

Increase in torque = 1234.260/254.647 = 4.85 (times)

Example 1.8 (LO 7) For cranking a wheel, a force of 500 N is required on a handle 400-mm long. If the cranking has to be done by an electric motor with a synchronous speed of 1000 rpm, find the power the motor has to develop for doing the job.

Solution: Torque produced on the handle = Force × arm length = 500 N × 400 mm = 200 N·m

The same torque can be produced by an electric motor running at 1000 rpm.

Power in kW to be developed by the motor is equal to $(2 \times \pi \times N \times T)/(60 \times 10^6)$ =

$$(2 \times \pi \times 1000 \times 200 \times 10^3)/(60 \times 10^6) = 20.95 \text{ kW}$$

1.22 CONSERVATION OF ENERGY

Consider a system with no transfer of mass across its boundaries. Conservation of energy for such a system requires that the change in the total energy contained in the system must be equal to the sum of heat transferred to the system and the mechanical work done on the system. The same statement can be expressed as follows with the following notation:

Q = heat or thermal energy transferred into the system
W = work performed on the system
ΔU = change in the internal energy of the system
ΔE = change in the total energy of the system
ΔKE = change in the kinetic energy of the system = $(1/2)\, m\, (v^2 - v_0^2)$
ΔPE = change in the potential energy due to gravity of the system = $mg\, (\Delta h)$

$$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE} = Q + W$$

This equation represents the total energy balance in a system. One form of energy is converted into another form but the total energy is conserved. The total energy also includes the energy irretrievably lost due to friction and heat dissipation. It is called the law of conservation of energy which states that energy in whatever form cannot be created nor destroyed.

Rate of energy balance in a system with respect to time is obtained by differentiating the total energy in a system with respect to time. Hence,

$$dE/dt = dU/dt + d(\mathrm{KE})/dt + d(\mathrm{PE})/dt = dQ/dt + dW/dt$$

The two terms on the RHS of the equation represent the rate of heat transfer into the system and the rate of work done on the system, respectively.

Work, power, and energy are concepts that are very essential in the design of machines which consume energy in one form or the other and give mechanical work or energy as output. Similarly, mechanical energy can be converted into other forms of energy. In both the cases, the law of conservation of energy (including all irretrievable losses) applies.

1.23 PREFERRED NUMBERS

In engineering, the size of an end product has to be laid down or specified even before the design is made. In fact the design is based on specifications that will ultimately decide the size of the product. Basic specifications of some products are well known to even laymen. Examples are the horse power rating of an electric motor, the diameter of a car wheel, diameters of steel wires. Length, weight, load capacity, and capacity of containers are other examples. For the sake of standardization and reduction of inventory, products are designed with 'preferred sizes'. Preferred sizes also contribute to saving in initial cost, reduction in tooling, facility in manufacturing procedures, and saving in manufacturing time and cost. Preferred sizes also offer an overall benefit to the manufacturer in manufacturing cost and the end user or customer by way of competitive pricing.

The concept of preferred sizes is based on the theory of preferred numbers of Charles Renard, a French engineer. There are series of numbers like R5, R10, R20, R40, R80—a total of five. The series and the series factors are given in Table 1.5.

Table 1.5 Basic Renard series and series factors

Series	Series factor
R5	5^{th} root of 10 = 1.58
R10	10^{th} root of 10 = 1.26
R20	20^{th} root of 10 = 1.12
R40	40^{th} root of 10 = 1.06
R80	80^{th} root of 10 = 1.03

In each series, say R10 or R20 we get a series of secondary numbers by multiplying any base number say 1 by the series factor. For example, taking one and multiplying it by 1.12 we obtain 1.12. Again multiplying 1.12 by the series factor (in R20 series) we get 1.2544. By following this procedure we can build a series of numbers in all the R-series (see Table 1.6). The resultant numbers are rounded off on practical considerations. 1.2544 is rounded off to 1.25 and similarly (1.2544 × 1.12 = 1.40492) is rounded off to 1.4.

Table 1.6 Secondary (preferred) numbers in design

R5	R10	R20	R40
1.00	1.00	1.00	1.00
			1.06
		1.12	1.12
			1.18
	1.25	1.25	1.25
			1.32
		1.40	1.40
			1.50
1.60	1.60	1.60	1.60
			1.70
		1.80	1.80
			1.90
	2.00	2.00	2.00
			2.12
		2.24	2.24
			2.36
2.50	2.50	2.50	2.50
			2.65
		2.80	2.80
			3.00
	3.15	3.15	3.15
			3.35
		3.55	3.55
			3.75
4.00	4.00	4.00	4.00
			4.25

(*Contd*)

Table 1.6 (*Contd*)

R5	R10	R20	R40
		4.50	4.50
			4.75
	5.00	5.00	5.00
			5.30
		5.60	5.60
			6.00
6.30	6.30	6.30	6.30
			6.70
		7.10	7.10
			7.50
	8.00	8.00	8.00
			8.50
		9.00	9.00
			9.50
10.00	10.00	10.00	10.00

The practical use of these preferred numbers can be understood from the Example 1.10. Crane wheels are standardized based on the size, mainly diameter. This makes spares inventory comfortable and less expensive. If we have to fix standard sixes between diameters of 200 mm and 800 mm, the aforementioned tables will help us very much. We choose R10 series and start with 200 mm as the smallest diameter for any wheel. The next higher size will be 2.5. All the sizes of the wheels falling in the range 200 mm and 800 mm are 250 mm, 315 mm, 400 mm, 500 mm, and 630 mm. In the R20 series, the additional sizes will be 225 mm, 280 mm, 355 mm, 450 mm, 560 mm, and 710 mm. Table 1.6 shows the preferred numbers based on the R-Series and series factors.

Example 1.9 (LO 8) Find the numbers in R10/4 derived series. The numbers range from 1 to 10.

Solution: The series factor for R10 series is 10^{th} root of 10 equal to 1.26. Let us find every third term in the derived series. If we want to find every third number in the derived series, the ratio factor is given by:

$$\text{Ratio factor } \varphi = (1.26)^3 = 2.000$$

Now if the first number is 1 the other higher numbers are in R10/3 derived series are 1, 4, 8 and so on.

To find the intermediate numbers, we have to derive R20 or R40 series. R20/4 derived series will give 1, 1.6, 2.5, 4, 6.3, 8, 10. This discussion helps us in determining the intermediate sizes in a series of products already in production. For example, a company making products of sizes 1, 4, and 8 sizes can expand the product range to include intermediate sizes of 1.6, 2.5, and 6.3.

Example 1.10 (LO 11) A manufacturer of front end loaders wants to develop a product range with capacities ranging from 25 kN to 800 kN. Initially the company wants to have 5 models and then extend to nine models within the same capacity range. Find the capacities of the front-end loaders.

Solution: Let the ratio factor be φ. The capacities of the five models will be

$$25\,(\varphi)^0,\ 25\,(\varphi)^1,\ 25\,(\varphi)^2,\ 25\,(\varphi)^3,\ 25\,(\varphi)^4$$

Since the maximum capacity of the front-end loader is 800 kN,

$$25\,(\varphi)^4 = 800$$

$$(\varphi)^4 = 800/25 = 32$$

$$\varphi = (32)^{1/4} = 2.3784$$

Now using the ratio factor, the following product range can be finalized.

Load capacities:

First model: 25 kN
Second model: $25 \times 2.3784 = 59.46 = 60$ kN (approx.)
Third model: $25 \times (2.3784)^2 = 141.42 = 140$ kN (approx.)
Fourth model: $25 \times (2.3784)^3 = 336.35 = 340$ kN (approx.)
Fifth model: $25 \times (2.3784)^4 = 799.99 = 800$ kN (approx.)
For extending the range to nine models, the following procedure can be used.

For nine models the load capacities will be

$$25\,(\varphi)^0,\ 25\,(\varphi)^1,\ 25\,(\varphi)^2,\ 25\,(\varphi)^3,\ 25\,(\varphi)^4,\ \ldots,\ 25\,(\varphi)^8$$

Maximum capacity = $25\,(\varphi)^8 = 800$ kN

$$(\varphi)^8 = 800/25 = 32$$

$$\varphi = (32)^{1/8} = 1.5422$$

The extended range of the product can now be listed as

First model: 25 kN
Second model: 38.55 kN = 40 kN (appr.)
Third model: 59.46 kN = 60 kN
Fourth model: 91.65 kN = 90 kN
Fifth model: 141.42 kN = 140 kN
Sixth model: 218.1 kN = 220 kN
Seventh model: 336.34 kN = 340 kN
Eighth model: 518.71 kN = 520 kN
Ninth model: 799.96 kN = 800 kN

Depending on the need, the company can develop any number of models in this manner. In conclusion, it may be mentioned that the method of preferred numbers may not always be suitable for fixing a product range. There is no hard and fast rule that the principle of preferred numbers has to be adopted all the time. The manufacturing organization is free to choose the product range based on market conditions and the prevailing competition. Examples are speeds in metal-cutting machine tools and modules of gears.

1.24 DESIGN FOR MANUFACTURE AND ASSEMBLY

Design for manufacture is a full-fledged subject taught at the post-graduate level. An attempt will be made here to introduce the concept of design for manufacture. Especially in these days of international marketing, design for manufacture assumes an important role in promoting business by introducing interchangeability, low processing and manufacturing cost, easy maintenance access, and reduction of overall inventory of spare parts.

In engineering, design is one thing and manufacture or transforming the design drawing into tangible components or products is quite another mammoth task. The individual machine elements have to be made, assembled, inspected, and tested before a decision for despatch can be taken. If proper care is taken at the design stage for ensuring easy manufacture, the organization can reap rich dividends.

Some important guidelines are given in the following list to help the student and the young designer in grasping the practical meaning of design for manufacture:

1. Any machine or device should contain the minimum number of individual parts.
2. Standards and codes should be followed wherever possible.
3. Modular design should be preferred. This means elements should be combined to form modules which fit or assemble easily with other modules. Assembly and dismantling during maintenance and repair become easy with modular design.
4. The design sizes should conform to the manufacturing facilities and tooling available.
5. Rerouting and transfer of material on the same paths for processing should be avoided by specifying the sequence of operations at the design stage.
6. Suitable chamfers, locating lugs or pins, spigots and recesses, guide ways, and marking lines should be amply provided to ensure unobstructed view, easy accessibility, and self-location of parts during assembly. This arrangement will greatly help in dismantling of assembled parts for subsequent repair, maintenance, and trouble-shooting.
7. Finally, the number of standard parts used in an assembly or a machine should be minimized to cut down on inventory cost and storage documentation and cost.

A machine component has to be manufactured by adopting different processes and methods like casting, forming, machining, welding or fabrication, bolting, welding, rivetting, among others. The method or methods adopted depend on the materials, quality, cost, and so on. The shape, surface finish, tolerances, and quality also influence the decision regarding the selection of the manufacturing methods to be applied for the manufacture of the component. Each one of these methods has its own facility and complexity. The endeavour of the designer is to base his design on the best methods for optimum cost and maximum benefit by way of quality and performance. In the following sub-sections, the various manufacturing methods are discussed in brief pinpointing their merits and demerits. The young designer should bear these points in mind while deciding the type of manufacturing or process for the component under consideration.

1.24.1 Casting

Machine components that do not conform to any geometrical shape, or in other words, machine parts of articulate shape with intricate sections, are best made by casting, which is a metal-forming process. The engine block of a multi-cylinder IC engine is a good example. Engine blocks are castings, either cast iron or aluminium alloy. Casting technology has advanced a lot and machining of intricate castings is also possible with special-purpose machines. Castings are preferred where rigidity and negligible deflections are desired as in the case of machine tool beds and columns, gear box casings, pump housings, generator and motor casings, engine blocks, etc. A few important points that the designer has to consider during casting design are mentioned here.

Cast iron parts are much stronger in compression than in tension. To the maximum extent possible, cast components are used for withstanding compressive forces. Sections in a casting should not not have abrupt changes. Thin sections should be avoided for facility in pouring and spreading of molten metal through intricate sections. All corners in castings should be smooth and rounded with generous fillet radii. This measure greatly reduces stress concentration at corners and prevents formation of blowholes and slag inclusions. Pockets of metal shrinkage can be avoided by providing cored holes at critical points and proper location of stiffeners and ribs inside or outside the castings.

Casting requires a full-fledged establishment like a foundry including a pattern shop, melting shop with furnace(s), a fettling shop, and heat treatment facility among others.

1.24.2 Welding or Fabrication

The equipment required for welding is less expensive than in the case of casting. Unlike casting, some portions of welding or fabrication work can be undertaken at the construction site also.

Welding, which is a metal-joining process, is versatile, provided the metals to be joined have good weldability. Compared to an equivalent casting, a weldment or the welded component is lighter. An example is a rope pulley used at the free end of a crane jib. Where possible, castings should be replaced by welded (fabricated) parts. Welded parts can have thinner sections and they do not suffer from defects like slag inclusions and blow holes.

An important point to be borne in mind with welding is the accessibility of the weld location. Overhead welding should be avoided as much as possible. Welded components are liable to develop internal stresses due to the thermal effects during the welding process. Warping of welded parts could be a possibility. To minimize these effects, a proper sequence of welding should be followed. The design drawing must show the welding details including the sequence of welding. The production or the process engineer is always consulted in preparing the welding sequence of complicated structures or components to be made by fabrication.

1.24.3 Forging

Forged components when properly manufactured are expected to contain near-zero defects as in castings like blowholes, slag inclusions, pinholes, and cracks. They are strong against severe fluctuating and completely reversed loads as in rotating shafts, crakshafts in IC engines, and components subjected to vibrations like aircraft structure, automotive parts, and rolling stock. Forgings are reliable and ensure safety in operation. Moreover a properly designed forged component does not require large compressive and impact forces during the forging operation. This reduces the forces on the dies and the civil foundation, thus reducing the first cost and extending the service life of the dies.

Like in castings and welded components there are a few important points to be considered in the design of forged components. The design should be such that the force flow lines in the loaded component should be along the grains in the metal structure and not across it. A forging is weaker in the latter case. When forging dies are used, the parting line between the two opposing dies should be kept in one plane, as much as possible. A forging should have rounded (not sharp) corners and should be provided with proper fillet radii where necessary. As in castings, thin sections should be avoided in forgings. As a general guideline, the thinnest section in a steel forging should be about 5 mm.

1.24.4 Machining

It can be said without hesitation that there is hardly any mechanical engineering component that does not require some kind of machining operation before it can be used in a machine. Machining extends from rough machining to expensive operations such as drilling, reaming, milling, planing, grinding, honing, lapping, reboring, polishing, burnishing, and superfinishing. The equipment required for machining are also extensive and varied and can be generally divided in to two categories—general-purpose machine tools (lathes, drilling machines, shaping machines, grinding machines) and special-purpose machines (SPMs). The field of machine tools is vast and drafting the guidelines for machining design is a difficult task. However, a few points that apply to almost all machining operations are discussed here.

Machining adds to the cost of a component. As such it is generally recommended that where not necessary or required, machining should be avoided.

The number of machining operations on a component increases the machining time. In addition to the actual machining time, transfer time (from machine to machine), mounting time, and dismantling time add to the total cycle time. The design of a machined component should be such that the idle time in the total cycle time should be as short as possible. This increases the productivity of the machine shop as a whole, enhancing the overall turnover of the machining facility.

Expensive machining operations like grinding should be avoided to cut down machining cost. Close tolerances, where not required, should not be provided. Of course, the designer is the best judge in this regard. The raw stock used for machining should preferably be round bars, square bars, and hexagonal bars in standard sizes as available in the market. Shaft surfaces that do not carry any components like gears, pulleys, or rotors should be left unfinished. Even on the machined portions, stretches of fine machining like grinding should be provided, for example, in bearing seats. Grooves on shafts for circlips should be properly made based on manufacturers' recommendations. A machined component should have adequate rigidity to (a) withstand the cutting forces on a machine tool, (b) avoid vibrations and tool chatter and (c) introduce dimensional inaccuracies in the job. Sharp corners and abrupt changes in cross section should be strictly avoided on machined components. The machinability of a material should be checked before using it in the design. Hard materials take longer machining time, add to the cost, and adversely affect the overall productivity.

1.24.5 Design for Assembly

Design for assembly takes into account the difficulties faced by the workshop personnel during the assembly of the machines designed by him/her. At the design stage itself, while preparing the assembly drawings, care should be taken to check the accessibility of places or points on the machines, especially where joints are involved with bolts, rivets and assembly welds. Handling of components for assembly is another factor which has to be considered. The cost of handling the components, sub-assemblies, and other machine parts or panels should be minimized during assembly. Moreover, the designer should not design whole components that cannot be handled by the in-house handling facilities.

Therefore, design for manufacture and design for assembly are two subjects with which the designer should be familiar, if not conversant. The designer can always draw on the expertise available from the shop floor in such matters so that the designs are fine-tuned before release for manufacture.

1.25 SURFACE FINISH, LIMITS, FITS, AND TOLERANCES

The overall dimensions of a machine, a device or equipment, or the sizes determined by design and analysis for the component parts of a machine cannot be called by any means complete design. Take for example, the diameter of the cylinder bore which is specified the same as that of the piston in an IC engine. A flywheel has to be fitted on a shaft without a key so that it does not rotate relative to the shaft.

There are two things that are important here, namely surface finish and the type of fit. These are interrelated and greatly affect the performance of the component and the machine.

1.25.1 Surface Finish

Surface finish, which defines the condition of a surface, machined or unmachined, is also termed as surface roughness. Appropriate surface finish is required on machine components from the viewpoint of performance and aesthetic appearane. Surface finishing involves cost and should be avoided where not required.

The surface of a blacksmith's anvil need not be machined or given a finishing. However, the the surface of a car's body has to be finished for obtaining the gloss and elegance it is required to present.

A good surface finish on exposed areas reduces the tendency to atmospheric corrosion. A fine-finished surface on a component posseses better endurance strength. Based on the operational requirement, the designer has to specify an optimum surface finish on the machine components, bearing in mind that the major factor to be considered in this regard is cost.

A very popular concept for surface roughness is the root mean square (RMS) value. On a given length L of a surface of a component, the highs and lows are marked and a mean straight line parallel to the longitudinal axis of the component is drawn. If the highs (positive) and lows (negative) along the Y-axis are denoted by y and the length is measured as x, the RMS value of the surface roughness is given by

$$\text{RMS} = [(1/L)\int y^2 dx]^{1/2}$$

The limits of integration are 0 and L since the investigation is along the length of the given surface.

For ready reference the RMS values of surface finish obtained by various machining processes are given in Table 1.7.

Table 1.7 RMS values

Machining process	RMS (microns)
Turning-milling-shaping	12.0 to 1.0
Drilling	6.5 to 2.5
Reaming	2.5 to 0.5
Grinding	6.0 to 0.5
Honing, lapping, polishing	0.5 to 0.05

Surface finish charts and conversion charts from the FPS system to metric system are available in appropriate literature. The numerical value required surface finish has to be indicated in the design drawing on the surface of the component. Surface finish details are as important as the dimensions on a design drawing and are subjected to strict shop inspection.

Electropolishing is an extremely effective method for improving surface finish. It can be said that electropolishing is the opposite of electroplating where an additional coating is formed on the rough surface. Mechanical polishing leaves numerous scratches on the surface with varying electrical potential increasing the possibility of the formation of local corrosive cells. Electropolishing is an electrical method that uses electrical current and some specified cleaning chemicals to reduce the asperities (high points) on a given surface. The method is much more effective than the mechanical methods mentioned so far. Since the peaks on the surface are removed, the total area to be cleaned and sterilized is very much reduced. Surface defects and smears like dirt, oil, or grease are removed and the surface assumes a lustre. Surface friction is greatly reduced and corrosion resistance is improved.

1.25.2 Limits, Fits, and Tolerances

When two surfaces are in contact and they are in relative motion, there is something called a *type of fit* between the two components at the interface.

A piston should be free to reciprocate inside the cylinder in its bore with very little clearance. This is called a *clearance fit*. A similar fit can also be provided between a rotating shaft and a fixed bush bearing. In both cases, the moving part has a slightly smaller dimension than the stationary part, although in macroscopic terms the two dimensions are the same. Between the flywheel bore and the crankshaft there should be an *interference fit*. That means the shaft diameter should be slightly larger than the bore in the flywheel hub.

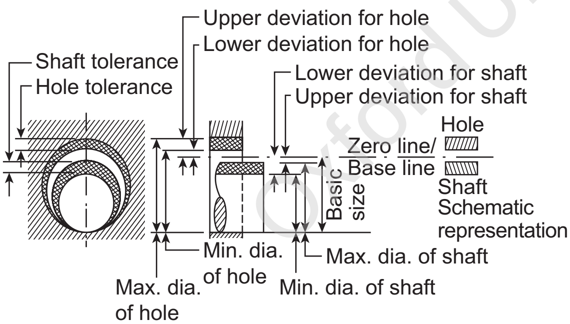
These are the two extremes between which are what are called *fits like transition fit, light push fit, force fit, press fit*. These are required in mechanical engineering for various applications. For achieving these fits the *macro-dimensions* of machine parts are provided with *limits*—upper limit and lower limit—and when they match with the other part with suitable limits give us the desired fit as per design. These smaller dimensions, giving the limits can be called the *micro-dimensions*.

When a part is manufactured, its dimension has to be maintained. The allowable variation in the dimension is called the *tolerance*, which can otherwise be called the permissible deviation from the macro-dimension. When this tolerance is tight meaning that the difference is narrow and the two limits are close, the tolerance is called close and the part is said to have close tolerance. Obviously parts manufactured to close tolerance are more expensive. Closer tolerances ensure quality, and smooth and stable operation of a machine. High-end cars are manufactured with better materials for parts with close manufacturing tolerances. A surface machined with close tolerances will have a much better finish, which becomes quite evident in automobiles.

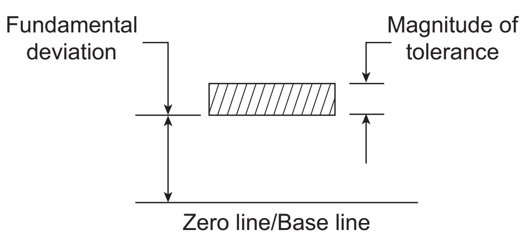
The detail drawings and assembly drawings of machines should clearly mention the data on limits, fits and tolerances, and surface finish symbols (rough machining, fine machining, grinding, polishing, honing, lapping, super-finishing, etc.) must be available on the drawings to the shop floor personnel. Production costs are directly proportional to the number and closeness of tolerances given on the drawing(s).

The basic dimension for example, the diameter of a shaft, say 40 mm, is the normal size or the basic size. The two permissible upper and the lower sizes or in other words, the maximum size and the minimum size are called the upper and the lower limits, respectively. The difference between the upper and the lower limits is the (permissible) tolerance. It is also called the permissible variation from the normal or basic dimension of the machine part.

When a journal rotates inside a sleeve bearing, there should be enough clearance between the journal and the sleeve for free movement and for retention of lubricating oil in the clearance. For the nomenclature of tolerances, see Figs 1.5(a) and (b), which show graphically the meaning of tolerance in design engineering practice.



(a)



(b)

Fig. 1.5 (a) Nomenclature in tolerance (b) Tolerance

1.26 Unilateral and Bilateral Tolerances

In engineering practice, tolerances are specified by two systems, unilateral and bilateral tolerance systems. In the unilateral system, one of the limits—upper or lower—is set at zero and all the permissible variation is included in the other limit. As an example, we can specify a 60-mm dimension as $60^{+0.05/+0.00}$ or $60^{+0.00/-0.05}$.

In the bilateral system, there are variations in both directions, upper and lower. As an example we can write $80^{\pm 0.4}$ or $80^{+0.4/-0.2}$. Though not always, in bilateral tolerance system, the two limits are equal.

Example 1.11 (LO 10) A light press fit, H7/p6 is provided for a brass sleeve inside a gear hub. Using the tolerance tables, find the micro-dimensions for the hub and the sleeve. The macro-dimension for the gear hub bore and the sleeve is 40 mm.

Solution: For the bore in the hub, 40H7 denotes $40^{+0.025/0.00}$ or 40.025/40.000 mm

For the sleeve 40p6 denotes $40^{+0.042/0.026}$ or 40.042/40.026 mm

Maximum interference = 40.042 – 40.000 = 0.042 mm

Minimum interference = 40.026 – 40.025 = 0.001 mm

Example 1.12 (LO 10) The gudgeon pin bush in the small end of a connecting rod has an outside diameter of 50 mm and an inner diameter of 30 mm. It is provided with an interference fit in the eye of the connecting rod and a clearance fit on the gudgeon pin. Determine the micro-dimensions and the maximum and minimum interference and clearance in the respective cases.

Solution:

Interference fit between the sleeve and the eye of small end:

Let the interference fit provided be H7r6.

For the eye, 50H7 denotes $50^{+0.025/0.000}$ or 50.025/50.000 mm

For the sleeve on the outer diameter, 50r6 denotes $50^{+0.045/0.034}$ or 50.045/50.034 mm

Maximum interference = 50.045 – 50.000 = 0.045 mm

Minimum interference = 50.034 – 50.025 = 0.009 mm

Clearance fit between the bush and the gudgeon pin:

Let the clearance fit be H8g7.

For the bush, 30H8 denotes $30^{+0.039/0.000}$ or 30.039/30.000 mm
For the piston pin, 30g7 denotes $30^{-0.025/-0.034}$ or 29.075/29.066 mm
Maximum clearance = 30.039 – 29.066 = 0.073 mm
Minimum clearance = 30.000 – 29.075 = 0.025 mm

1.27 FITS

Let us say that we are assembling a journal in a sleeve bearing. The relation that results between their sizes due to the difference in individual actual size is called fit. If the shaft size is smaller than that of the sleeve, it is called a *clearance fit*. Now consider a wrought wheel tyre or rim is heated and shrunk on to a steel wheel. After cooling, the tyre fits on the wheel without any clearance. It would rather be an *interference fit* where the actual size of the wheel tyre (its inner diameter) is less than the actual diameter of the wheel (it outer diameter). By varying the upper and lower limits, a series of fits are obtained between two mating components, namely clearance fits, transition fit, light press fit, force fit, and interference fit. In transition fits, the tolerance zones of the two mating components overlap. The resulting fit can be a clearance fit or interference fit depending on the actual values of tolerances. Figure 1.6 illustrates the types of fits explained in this paragraph.

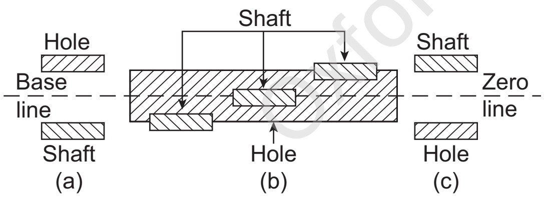


Fig. 1.6 Types of fits (a) Clearance (b) Transition (c) Interference

The tolerance systems fall into two categories, hole-basis and shaft-basis systems. A single hole is the basis for the hole-basis system. Here the lower deviation is zero. It is also called the *H-system*. The different fits are obtained by assembling various shafts with the single H-hole. In the same fashion we have a hole-basis also which is based on single hole whose upper deviation is zero. The system is called the *h-system*. Figures 1.7 and 1.8 show the two systems separately.

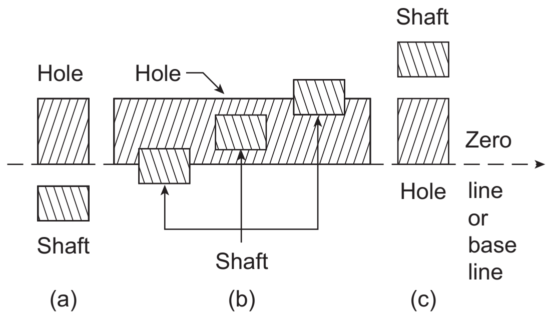


Fig. 1.7 Fits on the hole-basis (a) Clearance (b) Transition (c) Interference

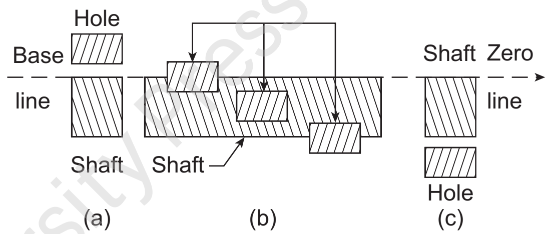


Fig. 1.8 Shifts on shaft basis (a) Clearance (b) Transition (c) Interference

Experience has shown that different types of fit are required for different applications. Table 1.8 gives general guidelines for selecting fits for some applications. Specific experience and field data available with manufacturers must be used in actual practice for better performance equipment. Table 1.8 gives recommended fits for general engineering applications.

1.28 TOLERANCE GRADES

The Bureau of Indian Standards stipulates that the tolerance is specified by a letter (alphabet), which can be a capital letter or a small letter and the grade of tolerance by a number, for example, H8 or p6. A fit is specified as a combination of the tolerances on the two mating parts, say a shaft and sleeve, for example 60 H8/h7, 50 H7-g8 or 40_{h9}^{H8}.

The number denoting the grade of tolerance includes a group of tolerances with the same level of accuracy. There are a total of 18 grades of tolerances like *IT1, 1T2, ..., IT18*.

After deciding on the proper fit to be used in an application, the micro-dimensions can be calculated. However, ready-made tables are available in standards

Table 1.8 Recommended fits

Type of FU	Shaft Tol.	Hole Tol.				Brief description	Examples
		H7	H8	H9	H11		
Clearance	c11					Loose clearance	Some farm equipment
	d10					Loose running	Gland seals
	e9					Easy running	Several bearing in line
	f7					Normal running	Pump or gear box shaft bearings
	g6					Precision location	Light precision bearings
	h6					Average location	Non-running assemblies
Transition	k6					Easy keying	Couplings keyed to shafts
	n6					Push	Fitted bolts
Interference	p6					Press	Gears, nuts
	s6					Heavy press	Bearing bushes in alloy housings

that give the fundamental deviation, magnitude of tolerance of various grades mentioned above. In this text, Tables 1.9, 1.10, and 1.11 show the tolerances for hole-sizes, and shaft-sizes up to 100 mm are given for reference and for a better understanding of the topics discussed so far.

Table 1.9 Tolerances for holes

Diameter steps in mm		H							
Over	To	5	6	7	8 es	9	10	1	5.11 ei
0	3	+4	+6	+10	+14	+25	+40	+60	0
3	6	+5	+8	+12	+18	+30	+48	+75	0
6	10	+6	+9	+15	+22	+36	+58	+90	0
10	18	+8	+11	+18	+27	+43	+70	+110	0
18	30	+9	+13	+21	+33	+52	+84	+130	0
30	50	+11	+16	+25	+39	+62	+100	+160	0
50	80	+13	+19	+30	+46	+74	+120	+190	0
80	100	+15	+22	+35	+54	+87	+140	+220	0

The following examples are useful in understanding the concepts discussed so far on limits, fits, and tolerances and using the tolerance tables for different sizes and grades.

Example 1.13 (LO 10) A light press fit, H7/p6 is provided for a brass sleeve inside a gear hub. Using the tolerance tables, find the micro-dimensions for the hub and the sleeve. The macro dimension for the gear hub bore and the sleeve is 40 mm.

Solution: For the bore in the hub, 40H7 denotes $40+^{0.025/0.00}$ or 40.025/40.000 mm

For the sleeve 40p6 denotes $40+^{0.042/0.026}$ or 40.042/40.026 mm

Maximum interference = 40.042 – 40.000 = 0.042 mm

Minimum interference = 40.026 – 40.025 = 0.001 mm

Example 1.14 (LO 10) The gudgeon pin bush in the small end of a connecting rod has an outside diameter of 50 mm and an inner diameter of 30 mm. It is provided with an interference fit in the eye of the connecting rod and a clearance fit on the gudgeon pin. Determine the micro-dimensions and the maximum and minimum interference and clearance in the respective cases.

Solution:

Interference fit between the sleeve and the eye of small end:

Let the interference fit provided be H7r6.

For the eye, 50H7 denotes $50^{+0.025/0.000}$ or 50.025/50.000 mm

For the sleeve on the outer diameter, 50r6 denotes $50^{+0.045/0.034}$ or 50.045/50.034 mm

Maximum interference = 50.045 – 50.000 = 0.045 mm

Minimum interference = 50.034 – 50.025 = 0.009 mm

Clearance fit between the bush and the gudgeon pin:

Let the clearance fit be H8g7.

For the bush, 30H8 denotes $30^{+0.039/0.000}$ or 30.039/30.000 mm

For the piston pin, 30g7 denotes $30^{-0.025/-0.034}$ or 29.075/29.066 mm

Table 1.10 Tolerances for shafts of sizes up to 100 mm (from d to h)

Diameter steps in mm		d					e					f				g			h						
		S11	8	9	10	11	6–9	6	7	8	9	6–8	6	7	8	6–7	6	7	5–10	5	6	7	8	9	10
Over	to	es	ei				es	ei				es	ei			es	ei		es	ei					
0	3	–20	–34	–45	–60	–80	–14	–20	–24	–28	–39	–6	–12	–16	–20	–2	–8	–12	0	–4	–6	–10	–14	–25	–40
3	6	–30	–48	–60	–78	–105	–20	–28	–32	–38	–50	–10	–18	–22	–28	–4	–12	–16	0	–5	–8	–12	–18	–30	–48
6	10	–40	–62	–76	–98	–130	–25	–34	–40	–47	–61	–13	–22	–28	–35	–5	–14	–20	0	–6	–9	–15	–22	–36	–58
10	18	–50	–77	–93	–120	–160	–32	–43	–50	–59	–75	–16	–27	–34	–43	–6	–17	–24	0	–8	–11	–18	–27	–43	–70
18	30	–65	–98	–117	–149	–195	–40	–53	–61	–73	–92	–20	–33	–41	–53	–7	–20	–28	0	–9	–13	–21	–33	–52	–84
30	50	–80	–19	–142	–180	–240	–50	–66	–75	–89	–112	–25	–41	–50	–64	–9	–25	–34	0	–11	–16	–25	–39	–62	–100
50	80	–100	–146	–174	–220	–290	–60	–79	–90	–106	–134	–30	–49	–60	–76	–10	–29	–40	0	–13	–19	–30	–46	–74	–120
80	100	–120	–174	–207	–260	–340	–72	–94	–107	–126	–159	–36	–58	–71	–90	–12	–34	–47	0	–15	–22	–35	–54	–84	–140

Table 1.11 Tolerances for shafts of sizes up to 100 mm (from j to s)

Diameter steps in mm	j							k			m			n			p			r			s			
		5		6		7		5	6	5–6	6	7	6–7	6	7	6–7	6	7	6–7	5	6	5–6	5	6	7	5–7
Over	to	es	ei	es	ei	es	ei	es		ei	es		ei	es	ei	es	ei	es	ei	es		es	es			ei
0	3	+2	–2	+4	–2	+6	-4	+4	+6	0	+8	–	+2	+10	+14	+4	+12	+16	+6	+14	+16	+10	+18	+20	+24	+14
3	6	+3	–2	+6	–2	+8	–4	+6	+9	+1	+12	+16	+4	+16	+20	+8	+20	+24	+12	+20	+23	+15	+24	+27	+31	+19
6	10	+4	–2	+7	–2	+10	–5	+7	+10	+1	+15	+21	+6	+19	+25	+10	+4	+30	+15	+25	+28	+19	+29	+32	+38	+23
10	18	+5	–3	+8	–3	+12	–6	+9	+12	+1	+18	+25	+7	+23	+30	+12	+9	+36	+18	+31	+34	+23	+36	+39	+46	+28
18	30	+5	–4	+9	–4	+13	–8	+11	+15	+2	+21	+29	+8	+28	+36	+15	+35	+43	+22	+37	+41	+28	+44	+48	+56	+35
30	50	+6	–5	+11	–5	+15	–10	+13	+18	+2	+25	+34	+9	+33	+42	+17	+42	+51	+26	+45	+50	+34	+54	+59	+68	+43
50	80	+6	–7	+12	–7	+18	–12	+15	+21	+2	+30	+41	+11	+39	+50	+20	+51	+62	+32	+55	+61	+42	+69	+75	+86	+56
80	100	+6	–9	+13	–9	+20	–15	+18	+25	+3	+35	+48	+13	+45	+58	+23	+59	+72	+37	+66	+73	+54	+86	+93	+106	+71

Maximum clearance = 30.039 – 29.066 = 0.073 mm
Minimum clearance = 30.000 – 29.075 = 0.025 mm

Example 1.15 (LO 10) A journal and a sleeve with a nominal diameter of 40 mm are given provided with tolerances of H8-g7. Find the maximum and minimum clearances between the two mating parts.

Solution: The sleeve has a H8 tolerance (hole basis will have the lower limit zero and the upper limit from the table) of +39. The two limits can be shown as 40.039/40.000 mm.

For the journal the limits are −0.009 and −0.034 (taken from *Tolerance Tables*). The size of the journal will be 39.991/39.968 mm. Maximum and the minimum clearances between the journal and the sleeve will be

$$40.039 - 39.968 = 0.071 \text{ mm}$$

$$40.000 - 39.991 = 0.009 \text{ mm}$$

1.29 MACHINING COST AND TOLERANCES

It has been found that the rate of increase of machining cost, in general, is not significant up to semi-finishing operations. But beyond semi-finishing to super-finishing operations like grinding, honing, polishing, there will be a steep rise in the machining costs. That is the reason manufacturing processes, machining in particular, should be selected very carefully. Non-essential fine machining should be avoided wherever possible.

Experience is required in deciding these factors regarding process and tolerances. Design engineers should always refer to the standards available on the subject to make their designs more authentic and at the same time cost-effective.

The topic of limits, fits, and tolerances is vast and can be studied from literature available on the subject. The designer must be aware of the vital point that where close tolerances are not necessary, they have to be avoided, unless they are required for better performance or just for the sake of individual fancy and luxury.

1.30 RELIABILITY IN DESIGN

Another word for reliability is dependability. When we embark on a long overnight journey in a car, we must be sure of reaching our destination without any failure or breakdown on the way. We rely on the fitness of our vehicle. In a similar way, any engineering product must be reliable. *It should be clearly understood that reliability cannot be ensured by adopting a high factor of safety*. This is because failure is related to many other areas rather than just design. In this competitive world, products vie with each other in reliability rather than any other property. If reliability is such a highly desired property, how do we define it and quantify it?

The *reliability features* of a machine or a device can be listed as:

1. Durability
2. Dependability
3. Stability of operation
4. Low maintenance and repair
5. Low frequency of failure
6. Long periods between consecutive failures
7. Ease in maintenance and repair
8. Negligible trouble in operation
9. Ease in upkeep, clean-up, and lubrication
10. Resistance to ageing and environmental effects like sunshine, snow, and rain
11. Need for little supervision
12. Overload capacity or endurance
13. Low fatigue level of operator

This list contains some terms which appear to be synonymous with others and some others overlap in meaning. That goes to show that reliability is not easy to define unless we take into account so many features that make a product dependable and acceptable to the customer.

Reliability is defined as a measure of the probability that a product will not fail in its function. The probability can be measured or quantified by statistical methods. For any component, the stresses involved during operation and the strength of the materials of construction can be tabulated and their statistical distribution can be studied. The success rate can be determined by drawing a comparison between the two distribution curves. Instead of going into the theory of probability at this juncture we can understand reliability in simple terms as explained in the following paragraph.

If R is the reliability of a product, R will be unity when the product could be 100% reliable—which is not the case in general mechanical practice. The value of R will lie within the limits of zero and unity. This means that in engineering products there is some amount of 'unreliability' which is why the value of R always less than one. To make the point more clear, if the reliability of a product is 90% (which is generally the case), there is 10% chance that it will fail in its function and the reliability is therefore 90%.

Let us look at it in a different way. We take a batch of identical components. If the batch quantity is 100 and the failure of 3 components is established in each such test batches, the failure rate is 3% and the reliability is given by

$$R = (1 - 3/100) = 0.97 \text{ or } 97\%$$

The reliability of a product depends on the design, materials of construction, process, precision in manufacture, proper inspection, and any other crucial factors characteristic of the organization. The design engineer is therefore advised to use his expertise and exercise his best judgement and discretion in choosing his reliability factors which are not necessarily the same for all components in machine.

Reliability is best understood and quantified by conducting experiments and field tests on machine components in actual operation in cases where the degree of uncertainty is high. The value of reliability factor depends primarily on the criticality of the component involved in the investigation or the design. For example, the wings of an aircraft should theoretically have a reliability of unity or 99.99%. The antifriction bearings in a general machine are usually designed with a reliability factor of 90%.

1.31 AESTHETICS IN DESIGN

In engineering design, functional requirements of a product, device, or equipment are of paramount importance. Any device has to give the desired output or performance for a reasonably long service period and ensure a good value to the price which the customer pays for it. So far so good! In the globalized market of the present day, there is a large number of competitive products from which the customer has to choose. They all have almost the same quality, durability, reliability, comparable service life, and so on. Above all these characteristics, the one product that attracts the buyer is its external appeal, a streamlined shape, and a soothing colour or colour combination. All these additional features are summed up in one word—aesthetic appeal to the purchaser. Just like architecture in building design and construction, aesthetics in machine design and manufacture plays a vital role in making the product easily marketable, all other things being equal and on par with others.

Consumer products, automobiles, furniture are examples of products which have to be necessarily developed based on aesthetic aspects. A harmonious combination of technical specifications of performance, quality, surface finish, and aesthetic features goes a long way in developing an excellent piece of equipment that could have an immediate appeal to the discerning customer.

1.32 PRODUCT RANGE

Product range can be understood by imagining pair of shoes from size 4 to size 12. Sizes 4−12 constitute the product range for a particular shoe model or design. The same concept can be applied to automobile engines, the smallest being say 39 hp and gradually increasing, 50 hp, 70 hp, 90 hp, 120 hp, 150 hp, 180 hp, and so on. This is just a random example and the figures given are approximate. The range of capacities of an automobile engine is now from 39 hp to 180 hp.

It is easily seen that if the range is wide, the designs should be different for each of the sizes in the range. Many of the components may not be interchangeable and have to be manufactured separately for each engine size. This increases the initial cost of machinery, tooling, processing, and inventory costs. Therefore, any manufacturer always tries to optimize the product sizes and minimize the product range. This is called reduction of product range. The width of the product range is influenced by market conditions, manufacturing facilities, and other commercial and financial considerations. The product range can be narrowed down by the following methods:

1. Rationally selecting design parameters such as capacity, rating, and overall dimensions.
2. Making each machine more versatile
3. Keeping reserve capacities in the present designs for future development and demand

1.32.1 Unified Series and Parametric Series

Multi-cylinder engines present an excellent example here. Cylinders with standardized diameters can be used in engines with more than one cylinder for increasing the power rating. Even the arrangement of the cylinders can be varied depending on the requirement. That means the number of cylinders and their arrangement are varied with the cylinder size remaining same. These are called *unified series*. In another way, the number of cylinders and their arrangement can be retained and the cylinder size can be varied to obtain a range of capacities. This is called the *parametric series*.

1.33 CONCURRENT APPROACH IN ENGINEERING

A product is developed or an existing product is improved based on feedback from the field or the market. The information collected is used in the design of the product to the complete satisfaction of the customer or the end-user. The product life cycle commences with market survey and with shipment or despatch from the manufacturer's premises. The information has to flow through all the departments concerned namely, marketing, design, materials, production, quality control, and despatch. Instead of connecting these departments in series, one after the other, for the sake of information flow, a *concurrent approach* should be adopted. Product development can also be followed in parallel operations. In other words, the departments should share the available information concurrently and react in advance so that valuable time in the product life cycle is saved. *Simultaneous engineering* is a lesser known name of *concurrent engineering*.

As a definition, concurrent engineering can be called the design process that brings all concerned with product development together even at the early stages for saving time in the production life cycle. The point is clearly illustrated in Figs 1.9 and 1.10.

Figure 1.9 shows the conventional approach in which the various stages come one after the other. In concurrent approach, the various steps or stages in product development can be made to overlap each other as shown in Fig. 1.10. A team approach is essential at all stages of product development, especially in mass production. Team members from the later stages of product life cycle should interact with members of the earlier stages like design, material selection, and process with valuable suggestions during decision-making. Frequent reviews among the members across the concerned departments are part of the concurrent engineering as it is called.

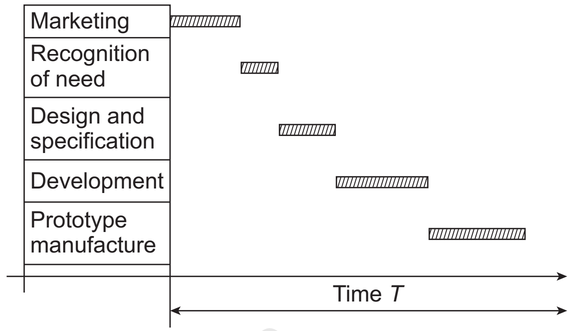


Fig. 1.9 Conventional approach

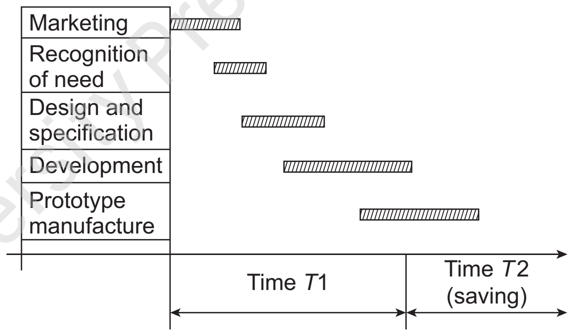


Fig. 1.10 Phases in concurrent engineering

Concurrent engineering aims at making all concerned understand a problem or an issue in the right perspective and agree to a binding decision to preclude expensive modifications during the latter stages. Even vendors and clients are requested to participate in the meetings and discussions. Concurrent approach breaks the rigid walls of the conventional departments and introduces walk-through compartments with vestibule connections as in an express train.

In spite of all the advantages mentioned in the previous paragraphs, concurrent approach may eventually slow down the decision-making process due to the large number of stakeholders involved. Meetings may be postponed due to thin attendance or decisions cannot be taken fast owing to a large number of participants. However, concurrent engineering can be successful if the stakeholders have zeal for a better product and the higher management accords importance to this new approach and lends its whole-hearted support.

1.34 ERGONOMIC DESIGN

Ergonomics is a science that studies and offers solutions to problems relating to man and machine. Ergonomics originates in the two Greek words, ergos (work) and nomos (laws or rules). This science lays down some laws and rules which, when followed, facilitate a smooth running of the machine by minimizing the fatigue of the operator.

Take the example of a car and the driver. The driver has to operate the steering wheel, activate brake and clutch with his feet, and manage the gear change lever. The driver's seat has to be designed in such a way that he is able to reach out to all these points of control without having to bend forward or lean backward. He should be able to drive for a reasonably long time without undue fatigue due to too many physical movements during driving. The same concept applies to the much more complicated design of a cockpit in an aircraft to provide the maximum possible ergonomic comfort to the pilot. A pilot under fatigue jeopardizes the lives of the passengers. A machine operator, for example, a crane operator, when unduly tired, puts the machines and shop floor personnel in jeopardy.

Ergonomics is not just concerned with the physical fatigue of a machine operator. It has to take into account the anatomical, physiological, and psychological aspects of work, which can then be applied properly in the design of the equipment. The most important aspects of ergonomic design are as follows:

1. The operator should have a comfortable seat with minimum flexing or strain of his body muscles. Fundamental knowledge of human anatomy is needed for this.
2. The operating levers and handles, actuating pedals, the instrumental panels should be laid out in such a way that the operator is able to operate the machine with minimum movement of hands and feet and minimum head and eye movement. This calls for a basic knowledge of physiology.
3. The levers, handles, pedals should be designed for minimum physical effort in operating them. That is the reason why clutch and brake pedals and the steering mechanism are provided with power-assist to reduce the effort required in operating them.
4. The approach to point 3 should be scientific as it involves determination of the energy requirements in terms of body calories for the overall operation of the machine. These figures should be as low as possible.
5. A cool and comfortable ambience is also a requisite to reduce operator strain and fatigue. The work stations should be well ventilated with proper lighting and climatic conditions like cooling or heating as the case may be. Knowledge of worker and operator psychology is a prerequisite for a study of these conditions.
6. Proper care should be taken to prevent incidence of claustrophobia in compact and cooped-up places of work.

It is the duty of the ergonomist to study the features of the machine to be designed and then conduct an ergonomic analysis of the whole machine and not just the operating levers and instrument panels. There should be an integrated approach by both the designer and the ergonomist. They should work hand-in-hand to bring out a good ergonomic design.

Questions

1. What is meant by design from the engineering perspective?
2. Write a note on need-based design.
3. What is a product and how is it developed?
4. Explain the terms, element, part, component, mechanism, assembly in relation to a machine, and machine design.
5. What is meant by design synthesis? Explain how it differs from design analysis.
6. Describe the various stages in engineering design.
7. What is meant by a tentative design procedure?
8. Discuss the difference between initial design and final design.
9. Explain the difference between fool-proof design and fail-safe design.
10. Explain the difference between preliminary design and detail design.

11. Explain the terms, empirical design and rational design.
12. Explain the meaning of product life cycle. How does it differ from production cycle?
13. Why are standards required in design? How do they differ from codes and norms?
14. Name some international standards organizations.
15. Discuss the importance of creativity in engineering design.
16. Name the major constraints within which a design has to work. Discuss the overall considerations which have to be taken in to account.
17. What do you understand by factor of safety? Give examples in its relation to failure of a machine member.
18. Why is factor of safety called uncertainty factor?
19. Experience is essential for developing proper design. Discuss.
20. What is meant by a fit?
21. Explain the term dimensional tolerances.
22. What in meant by upper limit and lower limit of a dimension?
23. What are the two systems of giving tolerances?
24. Explain the meaning of clearance, transition, and interference fits. Give examples of application of each fit.
25. What is prototype design? How does it differ from modelling?
26. Explain Maslow's content theory. How is it relevant in a design engineer's life?
27. Compare a designer and an artiste.
28. Discuss the impact of ecology on engineering design.
29. Design affects society. Discuss.
30. What is the role of ethics in engineering design?
31. Explain the importance of aesthetics in design engineering. What is meant by styling?
32. What is the scope of ergonomics? Why is it important in engineering design?
33. What are preferred numbers?
34. Explain the terms, basic Renard series, series factor, ratio factor, and derived series. Give simple examples.
35. Discuss the importance of preferred numbers in standardization. Give examples.
36. Discuss the difference between durability and reliability.

Exercises

1. Convert the following into SI units:
(a) Length of 35.8 feet
(b) Area of cross section of 48.9 sq.in
(c) Volume of 3400 cft
(d) Force of 487 lbs.
(e) Moment of 237 lb.in
(f) Pressure of 398 psi
(g) Volume of 945 cub.in **(LO 7)**

2. Convert the following into SI units:
(a) Stress of 500 psi
(b) Area of 1950 sq.ft.
(c) Modulus of elasticity of 32 Mpsi
(d) Velocity of 10 ft/s
(e) Deflection of 0.0012 in
(f) Acceleration of 4.3 ft/s^2
(g) Volume of 876 ft^3 **(LO 7)**

Note: For Questions 1 and 2, take the help of Tables 1.2 and 1.3.

3. A particular steel has an ultimate tensile strength of 700 N/mm^2. The designer wants to consider a factor of safety of 3.5 over the ultimate strength. Specify the permissible tensile stress. **(LO 3)**

4. The yield strength of a material is 360 MPa. The factor of safety is given as 3. The area resisting a tensile force on a machine component is 150 mm^2. Find the magnitude of the tensile load. **(LO 2, 3)**

5. A round steel bar, 20 mm in diameter, is subjected to an axial tensile load of 50 kN. If the yield strength of steel is 400 MPa, find the actual factor of safety in the design. **(LO 2, 3)**

6. A square block of grey CI (FG300) has to withstand a compressive load of 80 kN. The compressive stress should not exceed 150 MPa. Find the size of the block. **(LO 2, 7)**

7. In Question 6, the square block is replaced by a round block with a diameter of 30 mm, find the actual stress in the block. Also, find the revised factor of safety. **(LO 2, 3)**

8. A round pin with a diameter of 12 mm is in single shear. The shear stress is not expected to go beyond 150 N/mm^2. If the transverse load is 25 kN, verify the adequacy of the bolt size. If the answer is no, revise the size of the pin. **(LO 2, 7)**

9. Calculate Questions 4, 6, and 8 in FPS units. **(LO 2, 3)**

10. An electric motor develops 60 kW at 1000 rpm. Calculate the rated torque of the motor. It is connected to a two-stage gear box with reduction ratios of 4.2 and 4.7 in the first stage and the second stage, respectively.

(a) Tabulate the torque values on all the shafts assuming no power loss in the reduction.

(b) If the efficiency of transmission is as low as 90% per stage due to lack of proper lubrication and poor maintenance, recheck the torque values. **(LO 7)**

11. A torque of 24 kN-m is required to run a machine at 500 rpm. Find the electric motor power required to run the machine. The rated speed of the motor is 1000 rpm. **(LO 7)**

12. There is a speed reduction of 2.8 between two parallel shafts. The first shaft is driven by a 40-hp motor running at 1440 rpm. Calculate the torque on the slower shaft. Find the ratio of the diameters of the two shafts if they are made of the same material. Assume no power loss in the transmission of power. **(LO 7)**

13. The speed of rotation of a gear box input shaft is 1500 rpm. The power transmitted by the gear box is 30 kW. Power at the output shaft which rotates at 300 rpm is 28 kW. Calculate the torque on each of the two shafts. **(LO 7)**

14. A load of 20 kN is lifted by a rope wound on a drum at a speed of 30 m/min. Find the power required in kW. If the diameter of the drum is 630 mm, find the torque on the drum shaft and the tangential force at the periphery of the drum. **(LO 7)**

15. A man uses an effort of 600 N to turn a wheel with a handle holding it at a radius of 400 mm. Calculate the power required of an electric motor rotating at 750 rpm. **(LO 7)**

16. A 10-hp motor with a synchronous speed of 1500 rpm turns a mechanism. Find the manual effort required to turn the mechanism with a handle at a radius of 500 mm. **(LO 7)**

17. The stroke length of a punch press is 60 mm with an average force of 2400 N. The shaft operating the press runs at 400 rpm. The estimated over-all efficiency of the press is 85%. Calculate the power passing through the shaft and the average torque that acts on the press shaft. **(LO 7)**

18. Write the numbers of R20 basic series from 10 to 100. **(LO 8)**

19. A product range for electric motors has to be developed. The smallest and the largest capacities of the motors are 5 kW and 100 kW. The initial plans are to have 5 motors in the product range and subsequently to increase it 10. Find the motor ratings in both cases. **(LO 11)**

20. A packaging company wants to develop cardboard cartons for a particular product. Initially it plans to make cartons in seven sizes from 500 cc to 5000 cc. In future the size range of the cartons will be extended to 12. Find the sizes in both cases in round figures. **(LO 11)**

21. A bush and a bearing housing are provided with a fit designated as 30 H6/r5. Use the tables of fits and tolerances; write down the maximum and the minimum diameters of the bush and the bearing housing. Find the maximum and the minimum interference between the bush and the bearing house. **(LO 10)**

22. A 50-mm diameter journal and its bearing housing have a fit denoted by H8/h9. Find the maximum and minimum clearance possible with this fit. **(LO 10)**

23. A shrink fit is required on 80-mm diameter shaft. Suggest a suitable fit for the bore and the shaft and write down the limits of diameters of both. **(LO 10)**

24. A coupling half is fixed on a gearbox input shaft of diameter of 100 mm with H7/p6 fit. Find the correct dimensions of the coupling bore and the shaft. **(LO 10)**

25. A 60-mm diameter shaft is fitted in the hub of a pulley with an interference fit, H7-s6. Find the maximum and the minimum diameters of the shaft and the hub. Write down the maximum and the minimum interference between the shaft and the hub. **(LO 10)**

Multiple-choice Questions

1. Factor of safety in passenger lifts is
   (a) 6
   (b) 2–4
   (c) More than 10
   (d) 1.5
2. Design of components for manufacture is taken up
   (a) after preliminary design
   (b) before preparation of general assembly drawing
   (c) after technical report and approval
   (d) after prototype testing
3. Standards and codes apply to
   (a) materials
   (b) surface finish
   (c) dimensions
   (d) all of these
4. One Pascal is equal to
   (a) 1 N/m^2
   (b) 1000 N/m^2
   (c) 100 N/m^2
   (d) 106 N/m^2
5. One psi is equal to
   (a) 6.895×10^2 Pa
   (b) 6895 Pa
   (c) 6895×10^3 Pa
   (d) 68950 Pa
6. 1000 hp is approximately equal to
   (a) 7500 kW
   (b) 75 kW
   (c) 750 kW
   (d) none of these
7. A 10 kW motor 1000 rpm can produce a torque approximately equal to
   (a) 95 N-m
   (b) 950 N-m
   (c) 9500 N-mm
   (d) none of these
8. 5 motor capacities have been found to be between 10 kW and 100 kW. The second model in the product range will have an approximate kW rating of
   (a) 18 kW
   (b) 32 kW
   (c) 15 kW
   (d) 55 kW
9. H7/n6 is a
   (a) clearance fit
   (b) transition fit
   (c) interference fit
   (d) difficult to say
10. Ergonomic design is another name for
    (a) Aesthetic design
    (b) Economic design
    (c) Product design
    (d) None of these

Answers

1. (c); 2. (c); 3. (d); 4. (a); 5. (b); 6. (c); 7. (a); 8. (a); 9. (b); 10. (d)