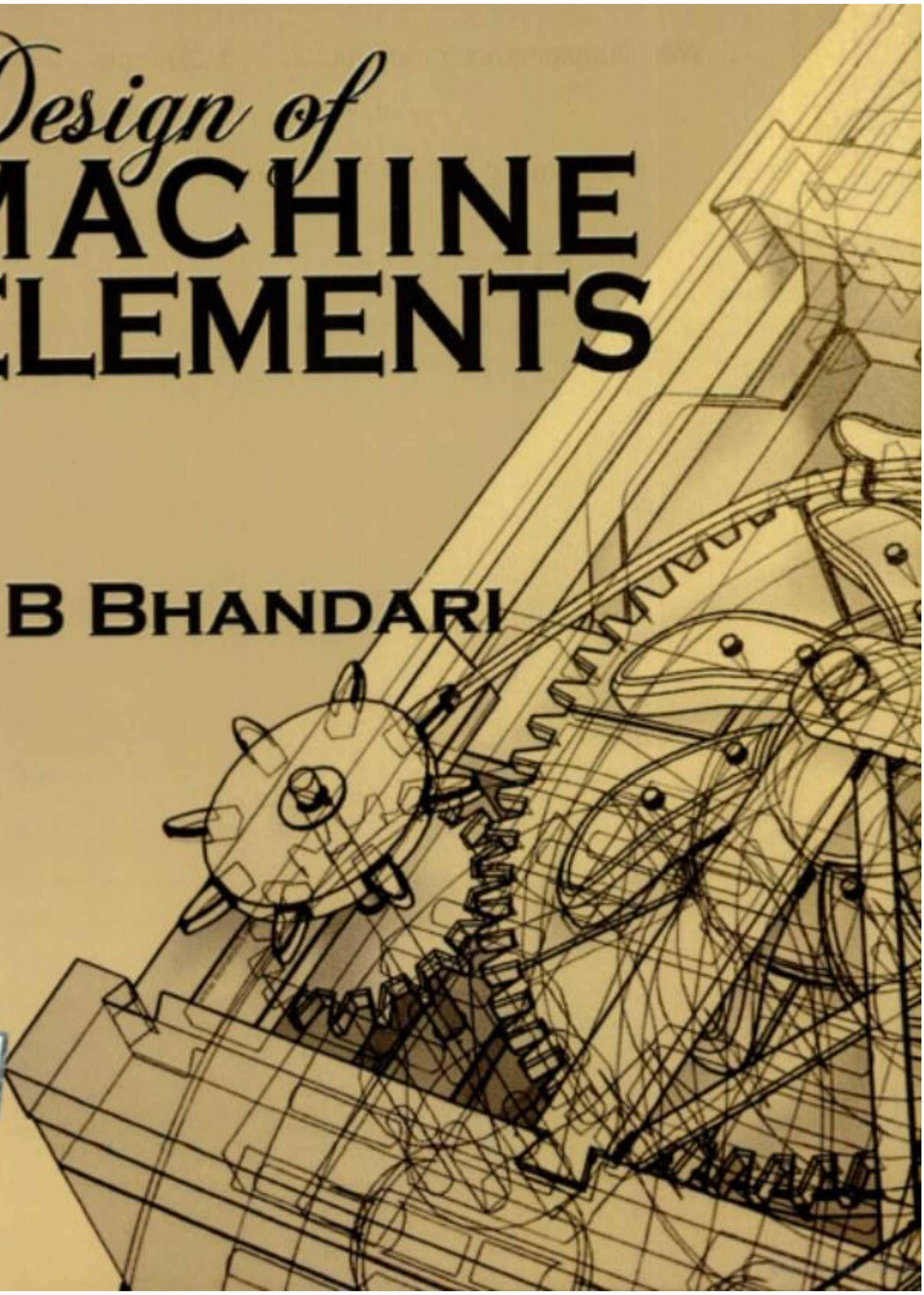
Design of MACHINE ELEMENTS

V B BHANDARI



Introduction

Chapter 1

If the point of contact between the product and people becomes a point of friction, then the industrial designer has failed. On the other hand, if people are made safer, more efficient, more comfortable—or just plain happier—by contact with the product, then the designer has succeeded.

Henry Dreyfuss[1]

1.1 MACHINE DESIGN

Machine design is defined as the use of scientific principles, technical information and imagination in the description of a machine or a mechanical system to perform specific functions with maximum economy and efficiency. This definition of machine design contains the following important features:

(i) A designer uses principles of basic and engineering sciences such as physics, mathematics, statics and dynamics, thermodynamics and heat transfer, vibrations and fluid mechanics. Some of the examples of these principles are

- (a) Newton's laws of motion,
- (b) D' Alembert's principle,
- (c) Boyle's and Charles' laws of gases,
- (d) Carnot cycle, and
- (e) Bernoulli's principle.

(ii) The designer has technical information of the basic elements of a machine. These elements include fastening devices, chain, belt and gear drives, bearings, oil seals and gaskets, springs, shafts, keys, couplings, and so on. A machine is a combination of these basic elements. The designer knows the relative advantages and disadvantages of these basic elements and their suitability in different applications.

(iii) The designer uses his skill and imagination to produce a configuration, which is a combination of these basic elements. However, this combination is unique and different in different situations. The intellectual part of constructing a proper configuration is creative in nature.

(iv) The final outcome of the design process consists of the description of the machine. The description is in the form of drawings of assembly and individual components.

(v) A design is created to satisfy a recognised need of customer. The need may be to perform a specific function with maximum economy and efficiency.

[1] Henry Dreyfuss–*The Profile of Industrial Designer*—Machine Design, July 22, 1967.

Machine design is the creation of plans for a machine to perform the desired functions. The machine may be entirely new in concept, performing a new type of work, or it may more economically perform the work that can be done by an existing machine. It may be an improvement or enlargement of an existing machine for better economy and capability.

1.2 BASIC PROCEDURE OF MACHINE DESIGN

The basic procedure of machine design consists of a step-by-step approach from given specifications about the functional requirements of a product to the complete description in the form of drawings of the final product. A logical sequence of steps, usually common to all design projects, is illustrated in Fig. 1.1. These steps are interrelated and interdependent, each reflecting and affecting all other steps. The following steps are involved in the process of machine design.

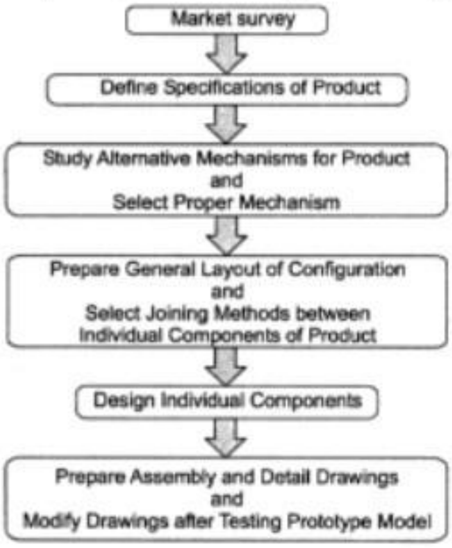


Fig. 1.1 *The Design Process*

Step 1: Product Specifications

The first step consists of preparing a complete list of the requirements of the product. The requirements include the output capacity of the machine, and its service life, cost and reliability. In some cases, the overall dimensions and weight of the product are specified. For example, while designing a scooter, the list of specifications will be as follows:

(i) Fuel consumption = 40 km/l
(ii) Maximum speed = 85 km/hr
(iii) Carrying capacity = two persons with 10 kg luggage
(iv) Overall dimensions
Width = 700 mm
Length = 1750 mm
Height = 1000 mm
(v) Weight = 95 kg
(vi) Cost = Rs 40000 to Rs 45000

In consumer products, external appearance, noiseless performance and simplicity in operation of controls are important requirements. Depending upon the type of product, various requirements are given weightages and a priority list of specifications is prepared.

Step 2: Selection of Mechanism

After careful study of the requirements, the designer prepares rough sketches of different possible mechanisms for the product. For example, while designing a blanking or piercing press, the following mechanisms are possible:

(i) a mechanism involving the crank and connecting rod, converting the rotary motion of the electric motor into the reciprocating motion of the punch;
(ii) a mechanism involving nut and screw, which is a simple and cheap configuration but having poor efficiency; and
(iii) a mechanism consisting of a hydraulic cylinder, piston and valves which is a costly configuration but highly efficient.

The alternative mechanisms are compared with each other and also with the mechanism of the products that are available in the market. An approximate estimation of the cost of each alternative configuration is made and compared with the cost of existing products. This will reveal the competitiveness of the product. While selecting the final configuration, the designer should consider whether the raw materials and standard parts required for making the product are available in the market. He should also consider whether the manufacturing processes required to fabricate the non-standard components are available in the factory. Depending upon the cost-competitiveness, availability of raw materials and manufacturing facility, the best possible mechanism is selected for the product.

Step 3: Layout of Configuration

The next step in a design procedure is to prepare a block diagram showing the general layout of the selected configuration. For example, the layout of an Electrically-operated Overhead Travelling (EOT) crane will consist of the following components:

(i) electric motor for power supply;
(ii) flexible coupling to connect the motor shaft to the clutch shaft;
(iii) clutch to connect or disconnect the electric motor at the will of the operator;
(iv) gear box to reduce the speed from 1440 rpm to about 15 rpm;
(v) rope drum to convert the rotary motion of the shaft to the linear motion of the wire rope;
(vi) wire rope and pulley with the crane hook to attach the load; and
(vii) brake to stop the motion.

In this step, the designer specifies the joining methods, such as riveting, bolting or welding to connect the individual components. Rough sketches of shapes of the individual parts are prepared.

Step 4: Design of Individual Components

The design of individual components or machine elements is an important step in a design process. It consists of the following stages:

(i) Determine the forces acting on the component.
(ii) Select proper material for the component depending upon the functional requirements such as strength, rigidity, hardness and wear resistance.
(iii) Determine the likely mode of failure for the component and depending upon it, select the criterion of failure, such as yield strength, ultimate tensile strength, endurance limit or permissible deflection.
(iv) Determine the geometric dimensions of the component using a suitable factor of safety and modify the dimensions from assembly and manufacturing considerations.

This stage involves detailed stress and deflection analysis. The subjects 'Machine Design' or 'Elements of Machine Design' cover mainly the design of machine elements or individual components of the machine. Section 1.4 on Design of Machine Elements, elaborates the details of this important step in design procedure.

Step 5: Preparation of Drawings

The last stage in a design process is to prepare drawings of the assembly and the individual components. On these drawings, the material of the component, its dimensions, tolerances, surface finish grades and machining symbols are specified. The designer prepares two separate lists of components—standard components to be purchased directly from the market and special components to be machined in the factory. In many cases, a prototype model is prepared for the product and thoroughly tested before finalising the assembly drawings.

It is seen that the process of machine design involves systematic approach from known specifications to unknown solutions. Quite often, problems arise on the shop floor during the production stage and design may require modifications. In such circumstances, the designer has to consult the manufacturing engineer and find out the suitable modification.

1.3 BASIC REQUIREMENTS OF MACHINE ELEMENTS

A machine consists of machine elements. Each part of a machine, which has motion with respect to some other part, is called a machine element. It is important to note that each machine element may consist of several parts, which are manufactured separately. For example, a rolling contact bearing is a machine element and it consists of an inner race, outer race, cage and rolling elements like balls. Machine elements can be classified into two groups—*general-purpose* and *special-purpose* machine elements. General-purpose machine elements include shafts, couplings, clutches, bearings, springs, gears and machine frames Special-purpose machine elements include pistons, valves or spindles. Special-purpose machine elements are used only in certain types of applications. On the contrary, general-purpose machine elements are used in a large number of machines.

The broad objective of designing a machine element is to ensure that it preserves its operating capacity during the stipulated service life with minimum manufacturing and operating costs. In order to achieve this objective, the machine element should satisfy the following basic requirements:

(i) Strength: A machine part should not fail under the effect of the forces that act on it. It should have sufficient strength to avoid failure either due to fracture or due to general yielding.

(ii) Rigidity: A machine component should be rigid, that is, it should not deflect or bend too much due to forces or moments that act on it. A transmission shaft in many times designed on the basis of lateral and torsional rigidities. In these cases, maximum permissible deflection and permissible angle of twist are the criteria for design.

(iii) Wear Resistance: Wear is the main reason for putting the machine part out of order. It reduces useful life of the component. Wear also leads to the loss of accuracy of machine tools. There are different types of wear such as abrasive wear, corrosive wear and pitting. Surface hardening can increase the wear resistance of the machine components, such as gears and cams.

(iv) Minimum Dimensions and Weight: A machine part should be sufficiently strong, rigid and wear-resistant and at the same time, with minimum possible dimensions and weight. This will result in minimum material cost.

(v) Manufacturability: Manufacturability is the ease of fabrication and assembly. The shape and material of the machine part should be selected in such a way that it can be produced with minimum labour cost.

(vi) Safety: The shape and dimensions of the machine parts should ensure safety to the operator of the machine. The designer should assume the worst possible conditions and apply 'fail-safe' or 'redundancy' principles in such cases.

(vii) Conformance to Standards: A machine part should conform to the national or international standard covering its profile, dimensions, grade and material.

(viii) Reliability: Reliability is the probability that a machine part will perform its intended functions under desired operating conditions over a specified period of time. A machine part should be reliable, that is, it should perform its function satisfactorily over its lifetime.

(ix) Maintainability: A machine part should be maintainable. Maintainability is the ease with which a machine part can be serviced or repaired.

(x) Minimum Life-cycle Cost: Life-cycle cost of the machine part is the total cost to be paid by the purchaser for purchasing the part and operating and maintaining it over its life span.

It will be observed that the above mentioned requirements serve as the basis for design projects in many cases.

1.4 DESIGN OF MACHINE ELEMENTS

Design of machine elements is the most important step in the complete procedure of machine design. In order to ensure the basic requirements of machine elements, calculations are carried out to find out the dimensions of the machine elements. These calculations form an integral part of the design of machine elements. The basic procedure of the design of machine elements is illustrated in Fig. 1.2. It consists of the following steps:

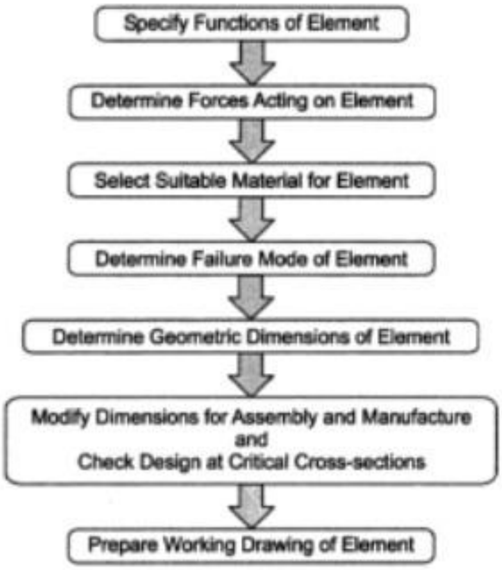


Fig. 1.2 *Basic Procedure of Design of Machine Element*

Step 1: Specification of Function

The design of machine elements begins with the specification of the functions of the element. The functions of some machine elements are as follows:

(i) ***Bearing*** To support the rotating shaft and confine its motion

(ii) ***Key*** To transmit the torque between the shaft and the adjoining machine part like gear, pulley or sprocket

(iii) ***Spring in Clock*** To store and release the energy

(iv) ***Spring in Spring Balance*** To measure the force

(v) ***Screw Fastening*** To hold two or more machine parts together

(vi) ***Power Screw*** To produce uniform and slow motion and to transmit the force

Step 2: Determination of Forces

In many cases, a free-body diagram of forces is constructed to determine the forces acting on different parts of the machine. The external and internal forces that act on a machine element are as follows:

(i) The external force due to energy, power or torque transmitted by the machine part, often called 'useful' load

(ii) Static force due to deadweight of the machine part

(iii) Force due to frictional resistance

(iv) Inertia force due to change in linear or angular velocity

(v) Centrifugal force due to change in direction of velocity

(vi) Force due to thermal gradient or variation in temperature

(vii) Force set up during manufacturing the part resulting in residual stresses

(viii) Force due to particular shape of the part such as stress concentration due to abrupt change in cross-section

For every machine element, all forces in this list may not be applicable. They vary depending on the application. There is one more important consideration. The force acting on the machine part is either assumed to be concentrated at some point in the machine part or distributed over a particular area. Experience is essential to make such assumptions in the analysis of forces.

Step 3: Selection of Material

Four basic factors, which are considered in selecting the material, are availability, cost, mechanical properties and manufacturing considerations.

For example, flywheel, housing of gearbox or engine block have complex shapes. These components are made of cast iron because the casting process produces complicated shapes without involving machining operations. Transmission shafts are made of plain carbon steels, because they are available in the form of rods, besides their higher strength. The automobile body and hood are made of low carbon steels because their cold formability is essential to press the parts. Free cutting steels have excellent machinability due to addition of sulphur. They are ideally suitable for bolts and studs because of the ease with which the thread profiles can be machined. The crankshaft and connecting rod are subjected to fluctuating forces and nickel–chromium steel is used for these components due to its higher fatigue strength.

Step 4: Failure Criterion

Before finding out the dimensions of the component, it is necessary to know the type of failure that the component may fail when put into service. The machine component is said to have 'failed' when it is unable to perform its functions satisfactorily. The three basic types of failure are as follows:

(i) failure by elastic deflection;
(ii) failure by general yielding; and
(iii) failure by fracture.

In applications like transmission shaft, which is used to support gears, the maximum force acting on the shaft is limited by the permissible deflection. When this deflection exceeds a particular value (usually, 0.001 to 0.003 times of span length between two bearings), the meshing between teeth of gears is affected and the shaft cannot perform its function properly. In this case, the shaft is said to have 'failed' due to elastic deflection. Components made of ductile materials like steel lose their engineering usefulness due to large amount of plastic deformation. This type of failure is called failure by yielding. Components made of brittle materials like cast iron fail because of sudden fracture without any plastic deformation. There are two basic modes of gear-tooth failure—breakage of tooth due to static and dynamic load and surface pitting. The surface of the gear tooth is covered with small 'pits' resulting in rapid wear. Pitting is a surface fatigue failure. The components of ball bearings such as rolling elements, inner and outer races fail due to fatigue cracks after certain number of revolutions. Sliding contact bearings fail due to corrosion and abrasive wear by foreign particles.

Step 5: Determination of Dimensions

The shape of the machine element depends on two factors, viz., the operating conditions and the shape of the adjoining machine element. For example, involute profile is used for gear teeth because it satisfies the fundamental law of gearing. A V-belt has a trapezoidal cross-section because it results in wedge action and increases the force of friction between the surfaces of the belt and the pulley. On the other hand, the pulley of a V-belt should have a shape which will match with the adjoining belt. The profile of the teeth of sprocket wheel should match the roller, bushing, inner and outer link plates of the roller chain. Depending on the operating conditions and shape of the adjoining element, the shape of the machine element is decided and a rough sketch is prepared.

The geometric dimensions of the component are determined on the basis of failure criterion. In simple cases, the dimensions are determined on the basis of allowable stress or deflection. For example, a tension rod, illustrated in Fig. 1.3, is subjected to a force of 5 kN. The rod is made of plain carbon

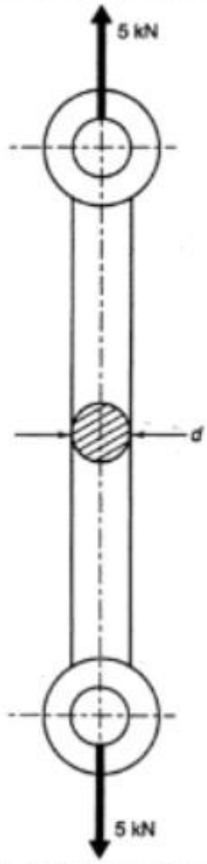


Fig. 1.3 *Tension Rod*

steel and the permissible tensile stress is 80 N/mm^2. The diameter of the rod is determined on the basis of allowable stress using the following expression:

$$\text{stress} = \frac{\text{force}}{\text{area}} \quad \text{or} \quad 80 = \frac{(5 \times 10^3)}{\left(\frac{\pi d^2}{4}\right)}$$

Therefore,

$$d = 8.92 \text{ or } 10 \text{ mm}$$

As a second example, consider a transmission shaft, shown in Fig. 1.4, which is used to support a gear. The shaft is made of steel and the modulus

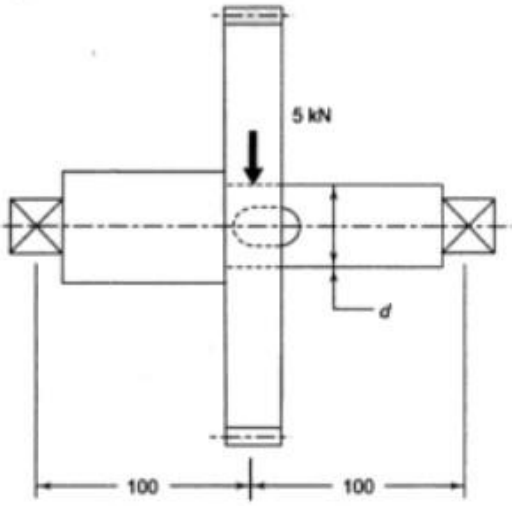


Fig. 1.4 *Transmission Shaft*

of elasticity is 207 000 N/mm^2. For proper meshing between gear teeth, the permissible deflection at the gear is limited to 0.05 mm. The deflection of the shaft at the centre is given by,

$$\delta = \frac{Pl^3}{48EI} \text{ or } 0.05 = \frac{(5 \times 10^3)(200)^3}{48(207\,000)\left(\frac{\pi d^4}{64}\right)}$$

Therefore,

$$d = 35.79 \text{ or } 40 \text{ mm}$$

The following observations are made from the above two examples:

(i) Failure mode for the tension rod is general yielding while elastic deflection is the failure criterion for the transmission shaft.

(ii) The permissible tensile stress for tension rod is obtained by dividing the yield strength by the factor of safety. Therefore, yield strength is the criterion of design. In case of a transmission shaft, lateral deflection or rigidity is the criterion of design. Therefore, modulus of elasticity is an important property for finding out the dimensions of the shaft.

Determination of geometric dimensions is an important step while designing machine elements. Various criteria such as yield strength, ultimate tensile strength, torsional or lateral deflection and permissible bearing pressure are used to find out these dimensions.

Step 6: Design Modifications

The geometric dimensions of the machine element are modified from assembly and manufacturing considerations. For example, the transmission shaft illustrated in Fig. 1.4 is provided with steps and shoulders for proper mounting of gear and bearings. Revised calculations are carried out for operating capacity, margin of safety at critical cross-sections and resultant stresses taking into consideration the effect of stress concentration. When these values differ from desired values, the dimensions of the component are modified. The process is continued till the desired values of operating capacity, factor of safety and stresses at critical cross-sections are obtained.

Step 7: Working Drawing

The last step in the design of machine elements is to prepare a working drawing of the machine element showing dimensions, tolerances, surface finish grades, geometric tolerances and special production requirements like heat treatment. The working drawing must be clear, concise and complete. It must have enough views and cross-sections to show all details. The main view of the machine element should show it in a position, it is required to occupy in service. Every dimension must be given. There should not be scope for guesswork and a necessity for scaling the drawing. All dimensions that are important for proper assembly and interchangeability must be provided with tolerances.

1.5 TRADITIONAL DESIGN METHODS

There are two traditional methods of design—*design by craft evolution* and *design by drawing*. Bullock cart, rowing boat, plow and musical instruments are some of the products, which are produced by the craft-evolution process. The salient features of this age-old technique are as follows:

(i) The craftsmen do not prepare dimensioned drawings of their products. They cannot offer adequate justification for the designs they make.

(ii) These products are developed by trial and error over many centuries. Any modification in the product is costly, because the craftsman has to experiment with the product itself. Moreover, only one change at a time can be attempted and complete reorganization of the product is difficult.

(iii) The essential information of the product such as materials, dimensions of parts, manufacturing methods and assembly techniques is transmitted from place to place and time to time by two ways. First, the product, which basically remains unchanged, is the main source of information. The exact memory of the sequence of operations required to make the product is second source of information. There is no symbolic medium to record the design information of the product.

With all these weaknesses, the craft-evolution process has successfully developed some of the complex structures. The craft-evolution method has become obsolete due to two reasons. This method cannot adapt to sudden changes in requirement. Secondly, the product cannot be manufactured on a mass scale.

The essential features of design by drawing method are as follows:

(i) The dimensions of the product are specified in advance of its manufacture.

(ii) The complete manufacturing of the product can be subdivided into separate pieces, which can be made by different people. This division of work is not possible with craft-evolution.

(iii) When the product is to be developed by trial and error, the process is carried out on a drawing board instead of shop floor. The drawings of the product are modified and developed prior to manufacture.

In this method, much of the intellectual activity is taken away from the shop floor and assigned to design engineers.

1.6 DESIGN SYNTHESIS

Design synthesis is defined as the process of creating or selecting configurations, materials, shapes and dimensions for a product. It is a decision making process with the main objective of optimisation. There is a basic difference between design analysis and design synthesis. In design analysis, the designer assumes a particular mechanism, a particular material and mode of failure for the component. With the help of this information, he determines the dimensions of the product. However, design synthesis does not permit such assumptions. Here, the designer selects the optimum configuration from a number of alternative solutions. He decides the material for the component from a number of alternative materials. He determines the optimum shape and dimensions of the component on the basis of mathematical analysis.

In design synthesis, the designer has to fix the objective. The objective can be minimum cost, minimum weight or volume, maximum reliability or maximum life. The second step is mathematical formulation of these objectives and requirements. The final step is mathematical analysis for optimisation and interpretation of the results. In order to illustrate the process of design synthesis, let us consider a problem of designing cylindrical cans. The requirements are as follows:

(i) The cylindrical can is completely enclosed and the cost of its material should be minimum.

(ii) The cans are to be stored on a shelf and the dimensions of the shelf are such that the radius of the can should not exceed R_{max}.

The following notations are used in the analysis:

$$r = \text{radius of can}$$
$$h = \text{height of can}$$
$$A = \text{surface area of can}$$
$$V = \text{volume of can}$$

Therefore,

$$A = 2\pi r^2 + 2\pi rh \qquad \text{(a)}$$
$$V = \pi r^2 h \qquad \text{(b)}$$

Substituting Eq. (b) in Eq. (a),

$$A = 2\pi r^2 + \frac{2V}{r} \qquad \text{(c)}$$

For minimum cost of material of the can,

$$\frac{dA}{dr} = 0 \quad \text{or} \quad 4\pi r - \frac{2V}{r^2} = 0$$

$$\text{or} \quad r = \left(\frac{V}{2\pi}\right)^{1/3}.$$

Let us call this radius as r_1 giving the condition of minimum material. Therefore,

$$r_1 = \left(\frac{V}{2\pi}\right)^{1/3} \qquad \text{(d)}$$

In order to satisfy the second requirement,

$$0 < r < R_{max.} \qquad \text{(e)}$$

In Eqs (d) and (e), r_1 and $R_{max.}$ are two independent variables and there will be two separate cases as shown in Fig. 1.5.

Case (a)

$$r_1 > R_{max.}$$

The optimum radius will be,

$$r = R_{max.} \qquad \text{(i)}$$

Case (b)

$$r_1 < R_{max.}$$

The optimum radius will be

$$r = r_1 \qquad \text{(ii)}$$

It is seen from the above example, that design synthesis begins with the statement of requirements, which are then converted into mathematical expressions and finally, equations are solved for optimisation.

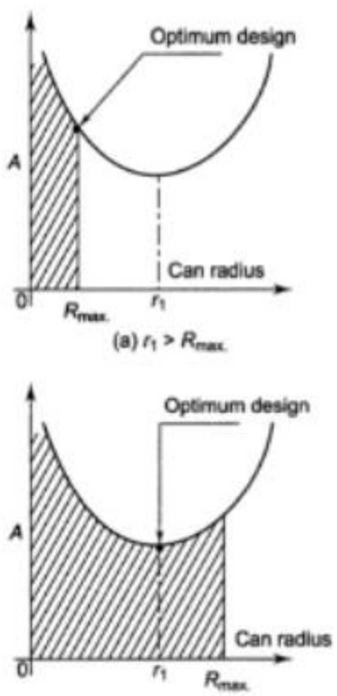


Fig. 1.5 *Optimum Solution to Can Radius*

1.7 USE OF STANDARDS IN DESIGN

Standardization is defined as obligatory norms, to which various characteristics of a product should conform. The characteristics include materials, dimensions and shape of the component, method of testing and method of marking, packing and storing of the product. The following standards are used in mechanical engineering design:

(i) Standards for Materials, their Chemical Compositions, Mechanical Properties and Heat Treatment For example, Indian standard IS 210 specifies seven grades of grey cast iron designated as FG 150, FG 200, FG 220, FG 260, FG 300, FG 350 and FG 400. The number indicates ultimate tensile strength in N/mm^2. IS 1570 (Part 4) specifies chemical composition of various grades of alloy steel. For example, alloy steel designated by 55Cr3 has 0.5–0.6% carbon, 0.10–0.35% silicon, 0.6–0.8% manganese and 0.6–0.8% chromium.