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No 19, Jalan Bilal Mahmood
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Malaysia</td><td>MACHINE DESIGN
THEORY AND APPLICATIONS

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INTRODUCTION

Scope

Mechanical design or machine design is one of the important branches of engineering design. Machine design can be defined as the process by which resources or energy is converted into useful mechanical forms, or the mechanisms so as to obtain useful output from the machines in the desired form as per the needs of the human beings. The design process is the application of mechanical engineering, chemical engineering, petroleum & gas engineering and other engineering talent related processes to the development, planning, design and decisions necessary for the completion of the project economically and with an effective process.

Machine design is the science application of mathematics, kinematics, statics, dynamics, mechanics of materials, materials engineering, mechanical technology metals, workshop processes and engineering drawings. It also involves the application of other science such as thermodynamics, theory of electricity, hydraulics, engines, turbines, pumps etc. Machine drawing is the integral part of the machine design, since all the components or the machines that have been designed should be drawn to manufacture them as per the specifications. Without machine drawing the subject of machine design is incomplete. The knowledge of machine design helps the designers as follows:

1. To select proper materials and best suited shapes.
2. To calculate the dimensions based on the loads on machines and strength of the material.
3. Specify the manufacturing process for the manufacture of the designed component of the machine or the whole machine.

General Considerations

A. Process Design

The process of design is essentially an exercise in applied creativity. Most engineering design can be classified as inventions-devices or systems that are created by human effort and did not exist before or are improvements over existing devices or systems. Inventions, or designs, do not suddenly appear from nowhere. They are the result of bringing together technologies to meet human needs or to solve problems. Sometimes a design is the result of someone trying to do a task more quickly or efficiently. Design activity occurs over a period of time and requires a step by step methodology.

Design problems are usually more vaguely defined than analysis problems. The solution to a design problem does not suddenly appear in a vacuum. A good solution requires a methodology or process. The basic step process usually used in a problem-solving works for design problems as well. Since design problems are usually defined more vaguely and have a multitude of correct answers, the process may require backtracking and iteration. Solving a design problem is a contingent process and the solution is subject to unforeseen complications and changes as it develops.

The long-term of process design is used here to include what is sometimes referred to as process engineering. Yet in some process engineering operations, all process design functions may not be carried out in detail. As discussed, process design is intended to include:

1. Process material and heat balances.
2. Process cycle development, correlation of pilot or research data, and correlation of physical data.
3. Auxiliary services material and heat balances.
4. Flowsheet development and detailed completion.
5. Chemical engineering performance design for specific items of equipment required for a flowsheet, and mechanical interpretation of this to a practical and reasonable specification. Here the process requirements are converted into hardware details to accomplish the process end results at each step in the product production process.
6. Instrumentation as related to process performance, presentation and interpretation of requirements to instrument specialists.
7. Process interpretation for proper mechanical, structural, civil, electrical, instrument, etc., handling of the respective individual phases of the project.
8. Preparation of specifications in proper form or detail for use by the project team as well as for the purchasing function.
9. Evaluation of bids and recommendation of qualified vendor.

B. Standardization Design

Standardization in design is the activity of applying known technology and accepted techniques in the generation of new products. This may be interpreted as almost a contradiction in terms "if something is standard then there is little left to design". On the other hand, if standardization is seen as a means to promote communication in design and manufacture then its usefulness is clearer, then time is not wasted in redesigning the machine. Standardization is seen as provider of product targets that must be achieved to have acceptance criteria in performance and quality [1].

These points illustrate the difficulty in understanding the role of standardization within industry at large, and why it is too often ignored by designers and management. One does not want to be constrained. In fact, the converse is usually true, that by adopting standards in an appropriate manner, the designer is freed from many detail decisions that would otherwise hinder the overall scheme. It this has to be recognized that some standards are inherently retrospective.

The standardized design method or procedure is bound to be based on past practice. and in some circumstances this may inhibit flexibility in adopting new methods. But to counter this, the designer may well contribute to updating and development of new standards. Indeed, the standards organizations have development groups and committee structures for this very purpose.

In design, the aim is to use as many standard components as possible for a given mechanism. Standardization is defined as obligatory norms or standards to which various characteristics of a product should conform. The characteristics include materials, dimensions and quality of the product, method of testing and method of marking, packing and storing of the product. Standardization becomes a global activity to cover all economical, technical and material aspects of engineering products. The work of standardization is accomplished by national or international organizations. The following standards are used in mechanical engineering design:

1. Standards for materials, their chemical compositions, mechanical properties and heat treatment.
2. Shapes and dimensions of commonly used machine elements such as bolts, screws and nuts, rivets, belts and chains, Bearings, wire ropes, keys, gears etc..
3. Standards for fits, tolerances and surface finish of components.
4. Standards for testing of products such as pressure vessels, boilers, overhead traveling cranes.
5. Standards for engineering drawing of components.

C. Design of Machine Elements [2]

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 of the machine elements. These calculations form an integral part of the design of machine elements.

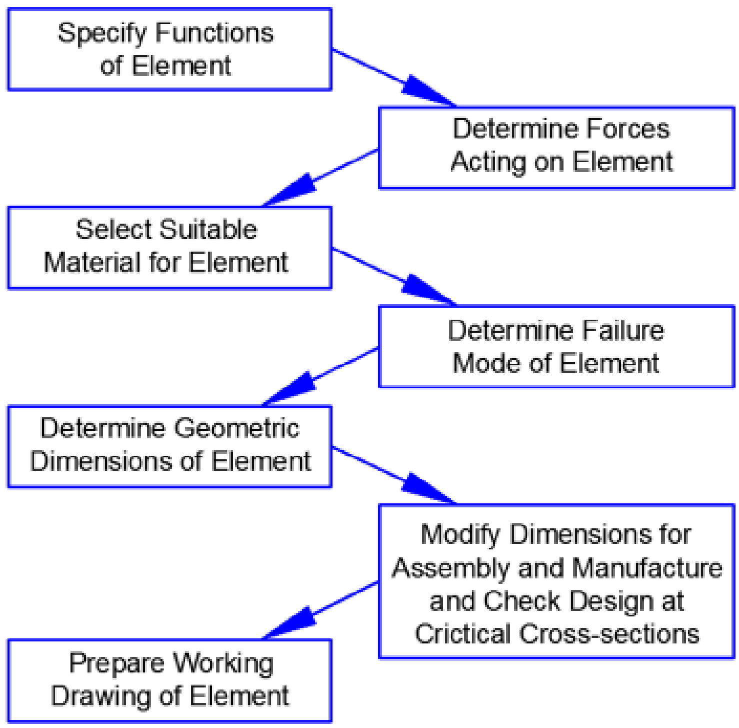

Figure 1 : Basic procedure design of machine elements.

I. Specify Functions of Element

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

a. Bearing : To support the rotating shaft and confine its motion.
b. Key : To transmit the torque between the shaft and the adjoining machine part like gear, pulley or sprocket.
c. Spring in Clock : To measure the force.
d. Screw Fastening : To hold two or more machine parts together.
e. Power Screw : To produce uniform and slow motion and to transmit the force.

II. Determine Forces Action on Element

Is 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 :

a. The external force due to energy, power or torque transmitted by the machine part, often called “useful” load.
b. Static force due to deadweight of the machine part.
c. Force due to frictional resistance.
d. Inertia force due to change in linear or angular velocity.
e. Centrifugal force due to change in direction of velocity.
f. Force due to thermal gradient of variation in temperature.
g. Force set up during manufacturing the part resulting in residual stresses.
h. Force due to particular shape of the part such as stress concentration due to abrupt change in cross-section.

For every machine element, all force 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.

III. Select Suitable Material for Element

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 their higher strength. The automobile body and hood are made of low carbon steel 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 its higher fatigue strength.

IV. Determine Failure Mode of Element

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 :

a. Failure by elastic deflection.
b. Failure by general yielding.
c. 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, 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 such as rolling elements, inner and outer races fail due to fatigue cracks after certain number of revolutions. Sliding contact bearings fail due to to corrosion and abrasive wear by foreign particles.

V. Determine Geometric Dimensions of Element

The shape of the machine element depends on two factors, 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.

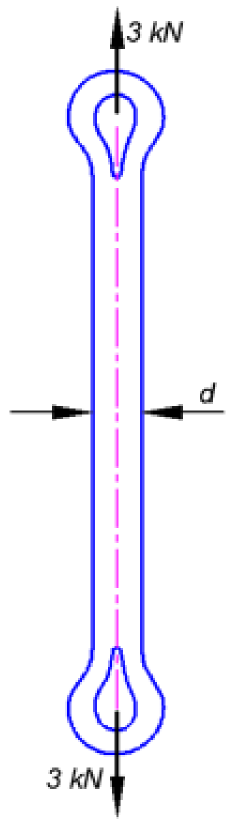

Figure 2 : Tension rod.

A tension rod in figure 2, is subjected to a load of 3 *kN*. The rod is made of plain carbon steel and the permissible tensile stress is 95 N/mm^2. The diameter of the rod is determine on the basis of allowable stress using the following expression :

$$\text{Stress}(\sigma) = \frac{\text{load}}{\text{area}} = \frac{P}{A} \quad \text{.......... (1)}$$

And then, $95 \, N/mm^2 = \dfrac{(3 \times 10^3) N}{\left(\dfrac{\pi . d^2}{4}\right)}$

Then, d = 6.34 *mm*

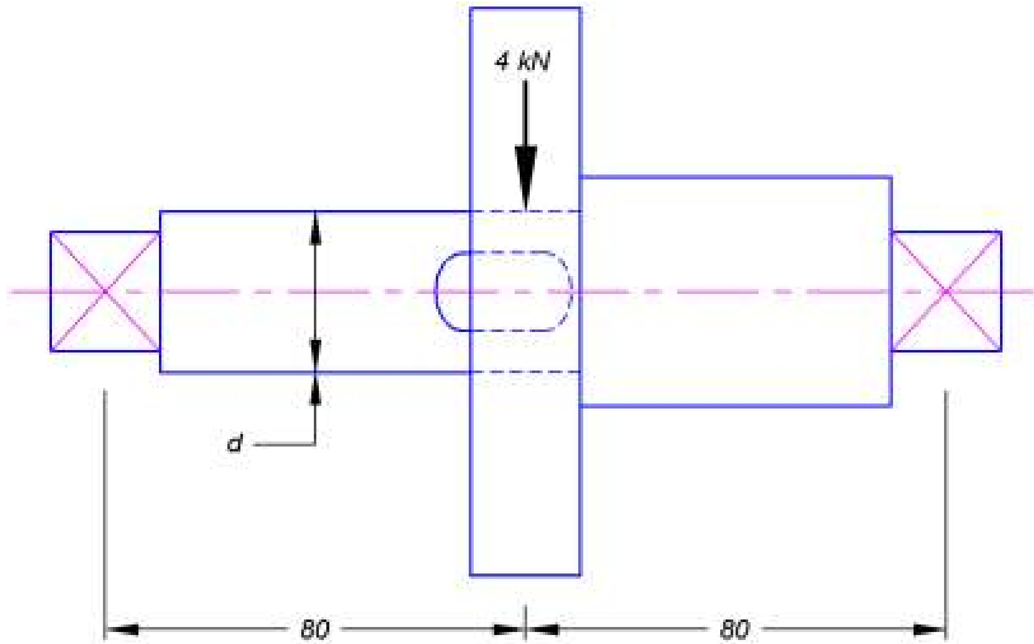

Figure 3 : Transmission shaft.

Consider a transmission shaft (see figure 3) which is used to support a gear. The shaft is made of steel and the modulus of elasticity is 185000 N/mm^2. For proper meshing between gear teeth, the permissible deflection at the gear is limited to 0.06 *mm*. the deflection of the shaft at the centre is given by :

$$\delta = \frac{Pl^3}{48EI} \quad \text{.......... (2)}$$

And then, $0.06\,\text{mm} = \dfrac{(4\times 10^3\,N).(160\,\text{mm})^3}{48.(185000\,N/mm)\left(\dfrac{\pi d^4}{64}\right)} \Rightarrow$

Then, d = 28 *mm*

The following observations are made from the above example :

a. Failure mode for the tension rod is general yielding while elastic deflection is the failure criterion for the transmission shaft.
b. 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.

Determine 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.

VI. Design Modifications

The geometric dimensions of the machine element are modified from assembly and manufacturing considerations. For example, the transmission shaft illustrated in figure 3 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 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.

VII. Prepare Working Drawing of Element

The last step in the design of machine elements is to prepare a working drawing of the machine element showing dimensions, 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. These 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.

D. Analysis Tools [3]

I. Finite Element Analysis

Mechanical components in the form of simple bars, beams, etc., can be analyzed quite easily by basic methods of mechanics that provide closed form solutions. Actual components, however, are rarely so simple, and the designer is forced to less effective approximations of closed form solutions, experimentation, or numerical methods.

There are a great many numerical techniques used in engineering applications for which the digital computer is very useful. In mechanical design, where Computer Aided Design (CAD) software is heavily employed, the analysis method that integrates well with CAD is Finite Element Analysis (FEA). The mathematical theory and applications of the method are vast.

II. Statistical Considerations

Statistics in mechanical design provides a method of dealing with characteristics whose values are variable. Products manufactured in large quantities (automobiles, watches, lawnmowers, washing machines) for example, have a life that is variable. One automobile may have so many defects that it must be repaired repeatedly during the first few months of operation while another may operate satisfactorily for years, requiring only minor maintenance.

Methods of quality control are deeply rooted in the use of statistics, and engineering designers need a knowledge of statistics to conform to quality control standards. The variability inherent in limits and fits, in stress and strength, in bearing clearances and in a multitude of other characteristics must be described numerically for proper control. It is not satisfactory to say that a product is expected to have a long and trouble free life. Designer and engineer must express such things as product life and product reliability in numerical form in order to achieve a specific quality goal.

DEFINITIONS

Addendum, The radial distance between the pitch circle and the major diameter of a gear.

Annealing, Heating a metal to, and holding at, a suitable temperature and cooling at a suitable rate so as to reduce hardness, improve machineability, ease cold working .

Angular Velocity, The rate of change of angulas displacement with respect to time, expressed in radians per second.

Bending Moment, The algebraic sum of the moments of all the forces to either side of a transverse section of a beam, etc.

Butt Welding, The welding together of abutting memberslying in the same plane.

Centrifugal Force, A body constrained to move in a curved path reacts with a force (centrifugal force) directed away from the centre of curvature. It is equal and opposite to the force deviating the body from a straight line called the ‘centripetal force’. Both are equal to the mass multiplied by the ‘centripetal acceleration’. mechanical loads.

Clutch, A device used to connect or disconnect two rotating shafts, etc., either while rotating or at rest.

Compressive Strength, The maximum compressive stress a material will withstand, based on the original cross-sectional area.

Compressive Stress, Compressive force divided by area of cross-section.

Deflection, The amount of bending, compression, tension, or twisting of a part subject to load.

Elastic Deformation, Change of dimensions in a material due to stress in the elastic range.

Elongation, In tensile testing the increase in length of a specimen at fracture as a percentage of the original length.

Factor of Safety, The ratio between ultimate (or yield) stress for a material and the permissible stress. (Abbreviation FS or FOS).

Friction, The resistance to motion which takes place when attempting to move one surface over another with contact pressure.

Heat Treatment, Heating and cooling of solid metals to obtain the desired properties.

Hoop Stress, The circumferential stress in a cylinder wall under pressure or in a rotating wheel.

Inertia, The property of a body proportional to mass, but independant of gravity. Inertia opposes the state of motion of a body.

Key, A piece of material inserted between usually a shaft and a hub to prevent relative rotation and fitting into a 'keyway'.

Modulus of Elasticity, A measure of the rigidity of a material. The ratio of stress to strain in the elastic region.

Moment of Inertia, The moment of inertia of a body of mass m about a point *P* is equal to mk2 where *k* is the 'radius of gyration' from P at which the whole mass may be assumed to be concentrated as a ring.

Tensile Strength, Ratio of maximum load to original cross-sectional area of a component. Also called 'ultimate strength'.

Tensile Stress, Tensile load divided by cross-sectional area.

Torque, The algebraic sum of couples, or moments of external forces, about the axis of twist. Also called 'torsional moment'.

Torsion, A twisting action resulting in shear stress.

Velocity, The rate of change of position of a point with respect to time.

Viscosity, The resistance of a fluid to shear force. The shear force per unit area is a constant times the velocity gradient, the constant being the coefficient of viscosity.

Welding, The joining of two or more pieces of material by applying heat and/or pressure, with or without a filler material, to produce local fusion.

Yield Stress (Yield Point), The stress at which a material exhibits a deviation from proportionality of stress and strain.

NOMENCLATURE

P	= Load (Force),	(N)
A	= Area,	(mm^2)
δ	= Deflection,	(mm)
E	= Elasticity,	(N/mm^2)
T	= Twisting Moment (or Torque) ,	($lb\text{-}inch$)
J	= Polar Moment of Inertia	
τ	= Torsional Shear Stress	
d_o, d_i	= Outside and Inside Diameter,	(mm or $inch$)
k	= Ratio of Inside Diameter and Outside Diameter	
N, n	= Speed (Revolutions Per Minute),	(rpm)
R, r	= Radius,	(mm or $inch$)
M	= Bending Moment,	($N\text{-}mm$)
I	= Moment of Inertia,	($kg.m^2$)
σ_b	= Bending Stress,	(psi)
y	= Distance From Neutral Axis to The Outer-Most Fibre,	(mm)
T_e	= Equivalent Twisting Moment,	($N\text{-}mm$)
K_m	= Combined Shock and Fatigue Factor for Bending	
K_t	= Combined Shock and Fatigue Factor for Torsion	
M_e	= Equivalent Bending Moment,	($N\text{-}mm$)
F	= Force (Axial Loads),	(lb)
σ	= Stress,	(psi)
FS	= Factor of Safety	
σ_c	= Compressive Stress,	(psi)
σ_s	= Shearing Stress,	(psi)
ε	= Elongation	

V	= Velocity,	(*fpm*)
V_s	= Velocity,	(*fps*)
T_0	= Initial Force in Belt,	(*lb*)
T_1	= Force in Tight Side (Belt),	(*lb*)
T_2	= Force in Slack Side (Belt),	(*lb*)
F_c	= Centrifugal Force,	(*lb*)
g	= Gravitation,	(kg/m^2)
c	= Center Distance	
p	= Pressure,	(*psi*)
h	= Size of Weld,	(*mm* or *inch*)
l	= Length of Weld,	(*mm* or *inch*)
t	= Thickness,	(*mm* or *inch*)
σ_t	= Circumferetial or Hoop Stress,	(N/mm^2)
η	= Efficiency,	(%)
μ	= Poisson Ratio	
E	= Young's Modulus (Pressure Vessel),	(N/mm^2)