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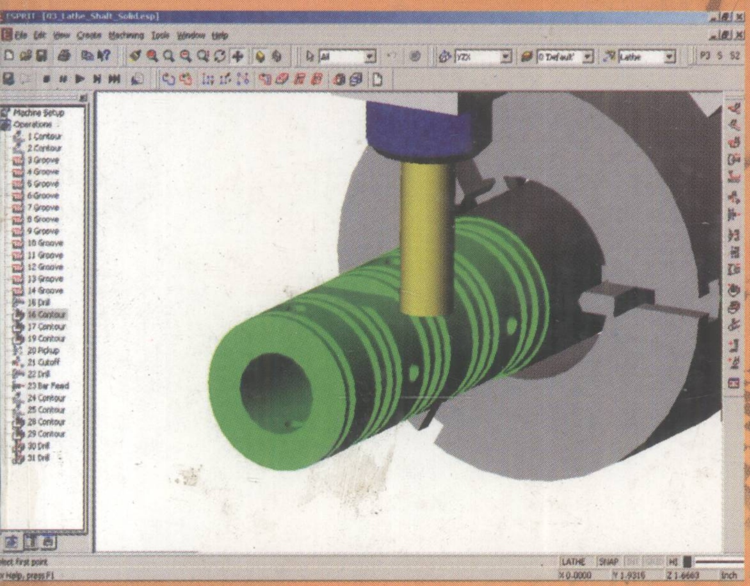
COMPUTER AIDED ANALYSIS AND DESIGN OF MACHINE ELEMENTS



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Computer Aided Analysis and Design of Machine Elements

Revised Second Edition

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Computer Aided Analysis and Design of Machine Elements

PREFACE

The purpose of the book is to present the useful and general methods for the analysis and design of basic machine elements. The methods discussed are oriented towards the use of a digital computer. The advent of the computer has, of course, had a dramatic impact on design work and techniques such as finite element methods have come to be regarded as natural tools by the stress analysis.

This is to serve as a textbook for engineering students at the senior undergraduate or beginning graduate level course. Students are expected to have studied or their preparation in mathematics should include the elements of determinant and matrix theory, the calculus, and a first course in ordinary differential equations. The book is also quite useful for practicing engineers and designers. All of the essential tools of computer aided design pertinent to the methods described are developed in each chapter. Their structure is made clear through indenting, and a rich use of comments makes the algorithm being implemented quite self-evident. In addition to a good number of illustrative worked examples, the book contains an unusual number of problems for solution by the student. Because of worldwide acceptance of the metric system, this book uses SI units in text material, tables, and problems. However, the U.S. customary units have been retained without interfering with the text material.

AUTHORS

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Computer Aided Aspects of Mechanical Design

1.1 INTRODUCTION

Engineering activity involves building and realizing contrivances, machines or structures to harness the environmental resources and energy for human needs. Design is an integral part of this activity. After the final design is complete, the ultimate realization and use of these engineering products would involve production, marketing, commissioning etc. This book focuses on the design activity in general, and the design of machine elements in particular.

The design activity is the major part of the final realization of any engineering product. This involves the following:

(i) Identification of the need for a specific engineering product.
(ii) Identification of the environmental conditions in which the product has to operate.
(iii) Conceptual design of the product, which draws on the past experience of the designer, aesthetics of the final product, limitations in terms of space, time and cost of production etc.
(iv) Detailed design, involving mathematical modelling and analysis of the component to be designed, to verify whether the design can withstand the environmental conditions under which it has to function. This includes optimization to minimize the production costs, the weight or any other specified objective criterion. Optimization will involve redimensioning and reanalysis under some relevant constraint conditions until the objective criterion is satisfied.
(v) Finally, transmission of the design information in the form of detailed drawings, and material and production specifications to the production shop.

Some of the component activities in the design process need human expertise, whereas some of them are repetitive. Once the methodology is clearly spelt and described, human expertise is not essential. The analysis and optimization activity is one which can be very efficiently implemented in a computer. Once an expert identifies the need for the product, conceptualizes the design, formulates the mathematical model and specifies the method of analysis and optimization criterion, the actual analysis and optimization can be done quickly and efficiently in a computer.

With the ever-widening capabilities of the present day computers, their use can be extended to the initial design phase of conceptualization including aesthetics, visualizing the design with animated graphics during the optimization phase and to the final design phase of preparation of drawings and specifications for transmitting the design information for production.

Elaborating a little bit on these extended uses of computers in the design activity, we can note the increasing use of expert systems in various fields. Expert systems draw upon the experience and expertise of human experts which are stored in their knowledge base. In this way, even a novice designer can benefit from the vast expertise of the entire design community available literally at the designer's fingertips punching keys on the keyboards of expert systems. More about the expert systems will be discussed later in Section 1.4.

The final design information can be directly transmitted to the machines in the production shop. Numerically controlled machine tools and robots involved in specific machining or assembling process can be directly supplied with the design information and instructions from the computers.

The above discussion gives a brief idea of the extent to which computers can be usefully employed in the design exercise. The design exercise, when aided by the capabilities of the computer, is aptly described as computer aided design. It is worth noting that reference to the computer is not the important thing here. A computer is a tool just as calculators, slide rules, logarithmic tables or abacus which were used at various times as aids in performing calculations needed during design. There may be a time in the future when computers as we know today may be replaced by super intelligent machines and the present day computers may find places in science history museums. But the rudiments of the design exercise itself will remain essentially unchanged except that the tools used in the design process will be different. It is in this light that we should see the name computer aided design.

1.2 MECHANICAL DESIGN

Mechanical design can be defined as the selection of materials and geometry which would satisfy specified functional requirements while remaining within the confines of inherently unavoidable limitations. For most of the practical design problems there exists an infinite number of possible design solutions, any one of which might be designated an adequate design. By defining more clear cut and explicit objectives, it is possible to narrow down the vast range of possible solutions.

Associated with any mechanical element are certain inherent undesirable effects and limitations. The environmental conditions in which the element must function may induce undesirable stresses, deflections, vibrations and in addition there may be limitations in terms of space, weight and cost. Also, associated with any mechanical element are certain desirable effects such as power transmission capability, speed capability and usable length of life.

Depending on the design problem at hand, we can explicitly define our design objectives so as to minimize the most significant undesirable effects. This process results in a mechanical design which is the best possible one, among all the numerous possible designs and this is called as the optimum design.

1.3 FORMULATION OF A SPECIFIC DESIGN PROBLEM

Suppose it is required to install a see-saw in a children's park located in a residential area. The design process starts with this identification of the need for the see-saw. A sketch of the sea-saw is shown in Fig. 1.1. Let us identify the conditions under which the see-saw must function.

(a) The average weight of children who would be using it. It is also possible that there may be a child at one end and it may be an adult on the other end. It is also possible that when children are playing on other rides in the park, two adults may use the see-saw. Therefore, it is better to design the see-saw for the worst possible

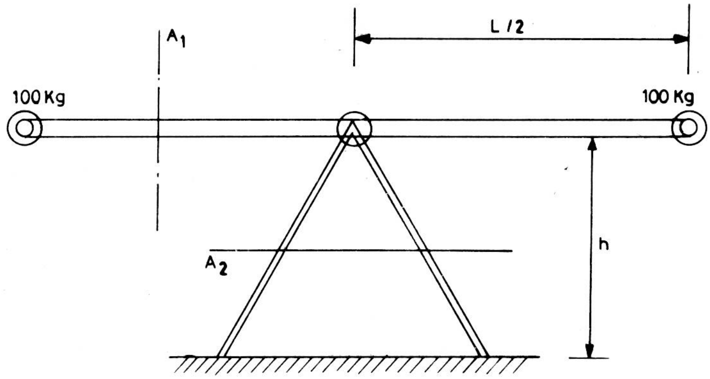

Fig. 1.1 Design of a see-saw

situation of two adults with above average weight.

(b) In addition to the weight, there will be effective forces due to the motion of the riders and the lever itself. The lever, the hinge and the support structure must be able to withstand the dynamic loads to which they are subjected. The stresses on these parts should be within the fatigue limit.

(c) The weather conditions in parks throughout the year must be considered. If it is in a cold country such as Canada, there will be snow in winter. Will it be left in snow or will it be dismantled and stored during winter? Does it rain too much? If the lever is made of wood, it may rot due to too much rain or moisture. If it is made of iron it may rust and will have to be painted regularly.

The above are some typical environmental considerations. Next, a conceptual design must be evolved. Some points to be considered at this stage are:

(a) When very small children are using it, the maximum height to which it goes should be such that an adult must be able to hold the child there for safety. This height may be taken as 1 m, say, and hence the hinge at the center must be at a height of 0.5 m.

(b) Much of the fun in the see-saw is when one side goes up, the child there can look down at the other end and "feel" the height. Similarly, the child at the lower end sees that the other child has gone very high. Hence the angle of elevation must be quite large. This is not possible if the lever is very long. Let us take the total lever length $L = 3$ m resulting in an angle of elevation of approximately 20°.

At this stage, the material, cross sectional shapes for the lever and the support structure, the type of seats and handle etc. may either be decided based on the weather conditions, availability and cost or they may be considered as design variables in the design analysis and optimization process. The cost may be considered as the objective function which must be minimized.

If the material and cross-sectional shapes are chosen, then the allowable stresses* are known. Design optimization will obtain the actual cross-sectional dimensions, so as to minimize the cost of the total structure keeping the stresses within safe limits. If the material and the cross sectional shapes also must be obtained through design optimization, then the procedure is more involved. We must decide as to whether the cost of the effort involved in this complicated optimization procedure will be balanced by the savings in cost of the final structure

The analysis will consider the loads acting on the structure and obtain the resulting stresses. A proper mathematical model must be formulated for the analysis. It may be a simple model or an elaborate finite element model. The lever is subjected to bending loads. Since the legs kick on the ground to lift one end of the see-saw, a pulse loading with resulting transient phenomenon can be anlaysed for the dynamic stresses. Axial forces on the support structure induce longitudinal stresses in them which must be analyzed. The bending and shear stresses in the hinge pin must be analyzed. These analyses will be repeated several times during optimization procedure for each set of new design variables proposed.

Some additional considerations to be taken into account are the surface finish of the lever and the support structure, the details of the installation procedure, the type of foundations for the support, the type and quality of the paint or preservative coatings etc.

1.4 COMPUTER AIDED ASPECTS OF DESIGN

Computers can be used efficiently in several aspects of the design process. The capabilities of the computer in terms of storing vast amounts of information, the astonishing speed with which it can retrieve the required information buried in its knowledge base, and also the speed with which it can perform routine and repetitive computations with accuracy for the required analysis and optimization of the design, the graphics capabilities which enable visual representation of the design at every stage in the design, convenience with which design information can be transmitted to the production shop in the form of computer drafted drawings or directly to CNC machines, industrial robots etc, make it a very useful tool for the designer. Some of these computer aided aspects in design will be discussed briefly in this chapter. The analysis and optimization aspects will be dealt with in greater detail in the latter chapters.

1.4.1 Expert System

Expert systems are computers with their knowledge base filled with knowledge gathered from human experts and with capabilities to process this stored knowledge to solve difficult problems in the same way an expert would. This is a new computing technology which has emerged from research in Artificial Intelligence (AI) and can be applied to a variety of technical and nontechnical domains. The knowledge base in expert systems is structured and encoded in such a way that the system can readily explain the rationale in arriving at the answer. It is also possible to operate them in a tutorial mode, allowing a novice to learn how an expert proceeds in solving a problem. Expert systems have been developed in medicine for diagnostic purposes, in computer manufacturing and sales, mineral exploration, telephone systems, power plants, aircraft, insurance risk evaluations and so on. We will limit ourselves to the use of expert systems in design.

The term 'expert system' refers to a computer program which is essentially a collection of heuristic rules (rules of thumb) and detailed domain facts that have been collected from practicing experts over a period of time and have proven useful in solving special problems in the technical area. Expert system may be characterized by their accuracy, speed and cost-effectiveness of information gathering techniques. Some additional properties, many of which are taken for granted in human experts, are:

(a) Ability to explain and justify answers, either using relevant theory or citing relevant heuristic rules or citing past case histories;

(b) Similarities in reasoning procedures to those used by human experts;

(c) Ability to deal with problem situations involving incomplete or uncertain information;

(d) Ability to summarize and point out factors, in the order of their importance, which are responsible in leading to an answer;

(e) Ability to communicate in easily understandable natural language.

(f) Ability to add new pieces of knowledge from each problem solving exercise, which can be readily used in solving problems later.

The steps to be taken to build an expert system involve building up the knowledge base from the simplest elements to the most complex, such as building up the concepts first, then rules, then models and strategies. To start with, test cases are considered to build up initial set of rules and to establish the overall model organization. Once this is complete, more and more details can be put in, primarily with the acquisition of rules. After the building phase is complete, field evaluations are carried out to gain confidence in the system to deal with different problem situations.

A design engineer does not necessarily have to start with the difficult languages used in building expert systems. There are commercially available skeletal programs in natural languages which are known as shells. Expert system shells are computer programs whose knowledge base has been removed, leaving only a shell that can perform the functions of inference mechanism, user interface capabilities and knowledge storage medium. However, the full capabilities of an expert system can be exploited in design only by building custom-built and dedicated expert systems for specific design areas. The most important potential impact of an expert system on the design process are:

(a) Rapid checking of preliminary design concepts, comparing several design alternatives.

(b) Strategies for iterating the design process.

(c) Integration of the various stages of design, manufacture, aesthetics, marketing, use of a product, by having knowledge bases that can be readily distributed for wide access.

Design process starts with synthesis, which is assembling or gathering concepts around which the design is developed. In this phase of design, the emphasis is on exploring a set of alternative preliminary designs, from which the designer chooses one, for more detailed configuration and evaluation. Selection for the layout of the design, selection of materials etc. can be made at this stage.

Expert systems can also be built to analyze and optimize the designs and integrate this activity with the initial conceptual design. However, computer aided design tools are difficult to integrate to embrace all aspects of the design due to their diverse subject manner, diverse algorithms and data structures, and their applications to different stages of the design process such as synthesis, manufacturing and maintenance. Further, often they are programmed by different people in different languages using different operating systems and hardware.

1.4.2 Computer Aided Analysis

Machine elements are required to operate in environmental conditions where they may be subjected to forces, extreme thermal conditions, unfavorable weather conditions and so on. The element must be designed to withstand the harmful effects of the environment and to operate satisfactorily. Hence, the designer must formulate a mathematical model for the element, represent the behavior or the response of the element using differential equations, and analyze for the response when subjected to the environmental conditions. The stresses developed in the element due to the external forces under other unfavorable conditions must be obtained and compared with the maximum stresses that the element can withstand safely.

The mathematical model for the element as well as mathematical models for the external forces must be formulated by the designer. There are several methods available to solve the resulting differential equations describing behavior of the element or the system, of which the element is a part. The past experience in solving similar equations using all the available techniques may be stored in an expert system, which can suggest the best analysis method for the design problem. Alternatively, the designer can make a choice of the analytical method from past experience in solving similar problems. Finite difference methods, transfer matrix methods, finite element methods are some typical methods that can be used for the mathematical representation of the system and direct numerical integration or modal analysis techniques are some possible analysis techniques to obtain the system response when subjected to environmental excitations. More detailed account of some of these techniques will be given in the next chapter.

When the element being designed is quite complex or when the element behavior can be understood only by analyzing the complete system, of which the element is a part, then calculations done manually will be unmanageable and prone to errors. Computers can be very efficiently used for the routine and repititive computations involved in all these analysis methods.

1.4.3 Computer Aided Optimization

It has been mentioned earlier that there are several solutions possible for a design problem. The number of variables in a design problem are enormous. The material properties, overall shape and geometry, detailed dimensions of individual elements in a system, manufacturing methods and the corresponding costs are all parameters that can be chosen so as to optimize a required objective in a design problem. The objective may be to minimize the overall cost of the final product, minimize the weight of the product as in aerospace applications or maximize the strength or maximize the aesthetic appeal.

Some of the design parameters may be changed without any restrictions imposed on them, however, there may be some constraints applied on some parameters. The material may be available only in a particular shape and size, the production shop may have limitations on the maximum and minimum sizes of parts that can be machined, the deflection at a specific point in a part may not exceed certain value due to the space limitations, stresses cannot exceed the safe limits and so on. Hence the optimum design must ensure that all these constraints are satisfied while trying to meet the required objective.

An initial design can be formulated based approximatively on past experience or using heuristic rules which have been put in an expert system. Subsequently this initial design must be analyzed to see whether it can satisfy all constraint requirements. If it satisfies, the next step is to see whether it can be improved by optimizing the objective function. If the initial design does not satisfy all the constraints, the immediate task is to vary the parameters in a logical fashion so as to satisfy the constraint requirements. In either case, the newly proposed design must be reanalysed. In the course of an optimization exercise, several reanalyses may have to be performed.

The large number of analyses necessary in design optimization and proposing new design parameters at every stage by using some meaningful criteria based on the previous analysis is a task which is tedious and better left to the computer. Hence, optimization part of the design process is ideally suited to be carried out in a computer.

1.4.4 Computer Aided Interactive Graphics

Designers conceive their ideas first in the mind, proceed to make some sketches for visual representation, modify the sketches with several alternative shapes and sizes and finally decide on a few choices that are to their satisfaction and also meet the design specifications. Traditionally, the chosen designs will be drawn by a draughtsman using rules, compass, protractors, pens of varying sizes and other devices. Because the task is time consuming and laborious, only drawings of the final design or one alternative design may be drawn in this way. However, with the present day capabilities of the computer along with cathode ray tube display devices it is possible to see the display of the final design in a very short time. If what the designer sees on the display terminal is not satisfactory, changes can be made right then and there to the designers satisfaction.

During optimization, the changing shape of the design can be continously monitored on the display terminal. The final version of the design or many intermediate versions can be plotted readily by using a plotter.

The cathode ray tube screen is like a gridwork and the intercepts of the horizontal and vertical lines, called dots, grids, nodes or pixels are usable points. It is up to the user to effectively utilize these pixels on the screen to be lighted to draw diagrams, graphs, and characters. The displayed image of a curve is composed of the usable points on the screen as shown in Fig. 1.2. The resolution of the graphics unit dictates the appearance of the curve.

The advantage of the computer aided graphics and its display cannot be overemphasized. By proper programming, it is possible to rotate, translate, scale down to reduce the size or scale up to magnify the size, obtain different views of the design, perspective projections of three-dimensional objects, focus on the specific region of the display by windowing etc. Parts lists and bills of materials also can be prepared. Drawings can be checked for tolerancing and dimensioning etc. using the computers quite efficiently.

The workstation replaces the draughtsman's drawing boards and the essential element of any computer aided design (CAD) workstation is the graphic display terminal where all work activities are focussed. A typical workstation would consist of a graphic terminal, either a storage tube type or raster graphics type. To address the computer by menu commands there would be a digitizing tablet on which the menus are mounted, with a joystick for control of the screen cursor. A small screen,