MACHINE ELEMENTS

V. DOBROVOLSKY
K. ZABLONSKY
S. MAK
A. RADCHIK
L. ERLIKH

MACHINE ELEMENTS

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В. А. ДОБРОВОЛЬСКИЙ, К. И. ЗАБЛОНСКИЙ,
С. Л. МАК, А. С. РАДЧИК, Л. Б. ЭРЛИХ

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A. TROITSKY

CONTENTS

PART THREE

POWER TRASMISSION

PART FOUR

SHAFTS AND AXLES, BEARINGS AND COUPLINGS AND CLUTCHES

PART FIVE

SPRINGS, MACHINE FRAMES

INTRODUCTION

Machines of various size and complexity are made up of assemblies, units and components.

A *component* is an elementary part of a machine made as one block; a *unit* is a detachable or permanent group of components; an *assembly* is a combination of units and components performing the same functions.

In our further exposition we shall call all these parts, performing the simplest functions, *machine elements* (also components or parts).

There are *general-* and *special-purpose* machine elements.

General-purpose elements include parts of detachable and permanent joints; parts of friction and gear drives; shafts and axles, couplings and clutches; bearings; springs and machine frames. As parts of various machines, machine elements of identical type carry out the same functions; they can therefore be made the subject of special study, a branch of engineering called machine elements.

Special-purpose elements are employed only in individual types of machines. Among them, for example, are such elements as pistons, valves, spindles, ploughshares, etc. The problems of their design are considered in special courses.

The course "Machine Elements", as a branch of engineering, outlines the methods, rules and standards for designing elements on the basis of the conditions of their operation in a machine, with a view to giving them the most advantageous forms and sizes, choosing the required materials, the degree of accuracy and surface finish and providing for adequate conditions of manufacture. In doing this, one of the main tasks of the designer should be to ensure that material is economised wherever possible.

The theory of machine elements is closely related to:

a) theoretical mechanics and the theory of mechanisms and machines, which enable the forces acting on the elements and the laws of their motion to be determined;

b) the theory of the strength of materials, by means of which the strength, stiffness and stability of machine elements can be calculated;

c) the course of metallography, which provides necessary information on the rational choice of materials;

d) methods of casting, forging and welding, heat treatment, machining and assembly, which make their own—production—demands on the design of machine elements;

e) technical drawing.

In the curricula of Soviet higher engineering schools the course "Machine Elements" completes a series of general engineering subjects and links these with a series of special subjects which outline the fundamentals of the theory, design and operation of machines used in practice.

The development of the design of machine elements is closely bound up with the development of machines.

Main Trends in the Development of Machine Design. Machines are means of production which utilise the forces of nature for the benefit of society, facilitate the labour of the workers and increase its productivity. The level of machine production and its technical standards clearly illustrate the industrial development of a country.

Machine designs are being continuously improved as new demands are made on them by the conditions of operation and production, and new potentialities are opened up by the development of science, the appearance of new materials and new methods for giving these materials the required forms and properties.

The following are the main requirements of operation and production which determine the design of modern machines: higher productivity of the machine and greater power and efficiency; simple servicing requiring no concentrated attention or considerable muscular effort on the part of the worker; high reliability—the continuous functioning of the machine without failure; the possibility of producing the designed machine in the quantities required by the national economy with a minimum expenditure of labour, materials and other resources.

The higher productivity of machines and greater engine power are most effectively attained by increasing their velocity and automatising labour processes. Comprehensive automatisation freeing the operator from arduous work involved in auxiliary operations (switching over, erecting and removing parts, handling the operating tools, etc.), higher rates of production processes and increased pressures (of steam, gas and liquid) and temperatures are the most characteristic tendencies in the development of present-day mechanical engineering. The achievements in this sphere can be evaluated from the following data borrowed from various branches of mechanical engineering.

During the last seventy years the speed of automobiles has changed as follows:

	1895-1900	1900-1915	1915-1930	1930-1945	1945-1955
Maximum attained speed in km/hr	105.9	210.9	372.4	594.8	634.5
Maximum cruising speed in km/hr	15-20	30-40	55-75	90-110	130—150

The speed of cutting steel during the last 100 years has changed as follows:

	Before 1850	1864	Early 20th century	1927	1950
Material of cutting tools	Carbon steel	Chrome-tungsten steel	High-speed steel	Hard alloys	
Cutting speed in m/min	5	7-8	30	70-80	400 and more

The speeds of cold rolling of strip steel have increased in the last twenty-five years as follows:

	1925-1930	1940	1945	1950
Rolling speed in m/sec	0.3-0.5	5	20	30

A similar increase in speed can be observed in machines employed for other processes. For example, the average speed of machines producing corrugated cardboard has risen from 3 m/min in 1895 to 165 m/min today; the speeds of sewing machines have increased from 600-800 rpm in 1915 to 3,500 rpm in 1947, etc.

These figures give an idea of the rates of growth in the speeds of various machines and of the future prospects.

These general tendencies have predetermined the following important features in the development of the design of various machines:

1. *The use of mechanisms with uniform rotary motion instead of those with reciprocating motion.* At the beginning of machine-building the extensive employment of mechanisms with reciprocating motion was quite natural; it could be accounted for by the fact that man strove to imitate by means of a mechanism the movements of arms used for identical processes. At the same time reciprocating motion inevitably involves the loss of time on idle strokes and overruns and also dynamic loads which restrict the speed of manufacturing processes. It is quite natural therefore that all modern machines should preferably employ continuous rotary motion instead of periodic reciprocating motion. Illustrations of this tendency are: steam and gas turbines which are used for higher speeds and powers than piston engines; centrifugal, gear and wing pumps as well as turbo-

compressors which have ousted piston reciprocating pumps and compressors; rotary boring drills which have replaced percussion drills; rotary printing machines instead of flat types, etc. The development of design in this direction is far from completed. For example, in earth-moving works a power shovel with one bucket is as yet the main machine employed and in the weaving industry it is a loom with a reciprocating shuttle. There are many such machines. However, specialists in all branches of mechanical engineering are keenly aware of the necessity of replacing machines with periodic operation by continuously operating machines with the result that an experimental earth-digging machine and a circular weaving loom have been recently developed.

2. *The application of block designs.* Machines have long been made in separate parts for convenient servicing, or even manufacture, assembly and conveyance. However, during the last twenty-five years the division of machines into parts, which earlier was dictated exclusively by the above motives, has become an independent and important way of improving the economical indices of production and operation. Designs of machines split into rational units from the considerations outlined below are called *aggregate designs* (machine-tool building, aircraft industry) or *block designs* (crane building). They offer the following advantages.

a) When setting up a machine from independent units, the elaboration of various versions or modifications, their testing and putting into serial production can be limited only to one unit at a time. This greatly simplifies the process of carrying out improvements.

b) Unit design allows the design of machines for various purposes, using only a small number of units (blocks).

c) Splitting into units shortens the time of assembly operations, because all units can be assembled and tested simultaneously and brought together for erection ready-made.

d) Unit design facilitates the maintenance of machines, since this can be reduced to the replacement of one unit by another—either reconditioned or new.

Examples of splitting machines into assemblies are shown in Fig. 25.

3) *The employment of various drives.* Until recently power was transmitted from the prime mover to the driving mechanisms almost exclusively by shafts, toothed wheels, belts, pushers, levers and other similar devices. Modern machines are characterised by the wide use also of electric, hydraulic and pneumatic drives. The wide use of these drives considerably facilitates the control of mechanisms, which can even be made completely automatic, mechanisms being remotely controlled to carry out a programme of any complexity (see also p. 174).

4. *The reduction of the weight of machines* together with the improvement of their quality is an important trend in the development of designs of modern machines. A reduction in weight is important in several respects.

a) The weight of a machine G together with the factor accounting for the consumption of metal η_{con} determine the weight of metal needed to manufacture the machine. Economy of metal is of prime national importance. With the same amount of metal produced in the country, after curtailing unproductive expenditure, the quantity of machines and other items produced can be materially increased. Besides, expenditure on metal comprises a considerable part of the cost price of machines. For example, in machine-tool building it amounts to 30-40% of the total production expenditure; on an average it is 3.5 times larger than the labour costs.

b) The weight of transport machines, besides its importance in the sense of the amount of metal required, is important in other respects too. For example, the cost per ton of transit of passenger waggons amounts to 5-6 thousand rubles annually.

An index of a rational design from the point of view of metal consumption is its specific weight—the ratio between the weight of the machine and the useful load which it is intended to carry.

Thus, for engines this index equals the weight in kg per 1 h. p. (or 1 kw). The specific weight of gasoline engines is:

aircraft engines	0.6-1.1 kg/h.p.
car engines	2.5 kg/h.p.
lorry engines	6-15 kg/h.p.
tractor engines	10-40 kg/h.p.

For railway passenger cars this index is the factor accounting for the ratio between the weight of the car in tons and the number of passengers. The average values of this factor are:

for suburban two-axle cars	0.30-0.40
for four-axle cars	0.45-0.5
for sleeping cars	3-3.4

An index analogous in structure may serve for estimating the rationality of the use of metal in individual units. For example, for gearboxes and reduction gears it equals the ratio between the weight of the gearbox (reduction gear) and the maximum transmitted torque. For the gearboxes of some lorries the values of this index are given in Table 1.

As the speeds increase and the machine designs are improved the specific weight is reduced. For example, the following figures are characteristic for the development of screw-cutting lathes with a centre height of 225 mm and centre distance of 1,000 mm (Table 2).

Table 1

Ratio between the Weight of Gearboxes and the Maximum Transmitted Torque for Some Lorries

Model	Maximum load-carrying capacity in tons	Maximum torque on the gearbox in kgm	Weight of the gearbox in kg	Specific weight in kg/kgm
ГАЗ-51	2.5	134.5	59	0.4
ЗИЛ-150	4.0	190.9	110	0.6
МАЗ-200	7.0	296.0	224	0.8

Table 2

Change in the Specific Weight of Screw-Cutting Lathes

Parameters of the lathe	Year of manufacture		
	1875	1934	1949
Power in kw	1.1	7.4	14.5
Weight in kg	750	2,350	3,500
Specific weight in ton/kw . .	0.68	0.32	0.24

PART ONE

FUNDAMENTALS OF DESIGNING MACHINE ELEMENTS

CHAPTER I

CRITERIA OF OPERATING CAPACITY AND CALCULATION OF MACHINE ELEMENTS

A machine under design should satisfy various requirements outlined in specifications. These are, first of all, its output capacity and operating velocity, its cost—initial and operational, its weight and expected (guaranteed) life. In certain cases additional requirements are made concerning overall dimensions and transportability (in transit by rail, the machine, loaded onto a freight flatcar, should have proportions in conformity with the loading gauge), uniformity of rotation, noiseless operation, simple and easy control, styling, etc.

For these reasons individual components should have adequate strength and rigidity and effectively resist vibration (oscillations of high intensity); they should also allow the use of common cheap materials for their manufacture.

Some of these requirements are so essential that the normal operation of a machine becomes impossible if they are not satisfied; these requirements are regarded therefore as the *main criteria of operating capacity*. They are first and foremost the necessary and sufficient strength (volume and surface) and rigidity; for many components vibration and thermal resistance are also important.

To ensure these main criteria of operating capacity appropriate calculations (for strength, rigidity, elastic oscillations, etc.) are required and this is an integral part of the process of designing machine elements.

This process is usually carried out in the sequence outlined below.

1. A design scheme is worked out in which the design of the component and its conjunction with other components are greatly simplified and the forces applied to it are assumed to be either concentrated or distributed in conformity with the given or arbitrary regularities.

2. The magnitudes of loads acting upon the component are determined.

During operation machine elements are subjected primarily to the action of varying loads. The nature of variation of these loads may depend on a number of systematic or occasional factors. Thus, for machines which perform definite technological functions in the production process the nature of load variation for one production cycle remains nearly constant. In other cases, for example for automotive vehicles, the nature of force variation depends on a number of fortuitous factors (resistance arising in motion due to the terrain and the roadbed, the effects of inertia and the wind, etc.). It is, therefore, an extremely complex and important task to determine and assign the loads which will act on the machine components.

In calculations use is made of *rated* and *design* loads.

A *rated* load is an arbitrary constant load chosen from among the operating loads; usually it is the maximum or the most continuously operating load; sometimes it is the mean load.

A *design* load is a load constant in time, which can be used instead of the actual operating varying load, on the assumption that by their effect with respect to the corresponding criteria of operating capacity the design and actual loads are equivalent.

3. Material is selected on the basis of its physico-mechanical properties, including machinability, taking into account the economical factors—cost, accessibility, etc.

4. Some of the most characteristic dimensions of the component are determined by calculation according to those criteria of operating capacity which are most important in the given case and these dimensions are coordinated with the standards in force. As a rule, these calculations are *preliminary*, since they are based on the simplified schemes mentioned above, which do not allow the precise evaluation of the actual operating capacity of the component. Besides, with the loads usually met with in mechanical engineering practice, which cause alternating stresses to develop in cross-sections of machine elements, the mechanical characteristics of strength (for example, limit of endurance) are not constant for a given material for they depend on the absolute dimensions and on the form of the component together with some other factors.

Therefore, a reliable calculation is possible only when the forms and absolute dimensions of the component and some other factors are already known. For this reason these calculations are used to find only the initial dimensions for designing a unit; it is only in the simplest cases that they are also final, in which case they are called *design* calculations.

5. A general sketch of the assembly is drawn followed by a detailed elaboration and indication on the working drawing of all the