DAMIR JELASKA

GEARS
AND GEAR DRIVES

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Preface

Since gear drives operate with a power efficiency significantly higher than any other mechanical drive, or any electrical, hydraulical or pneumatical power transmission, they have the widest use in transforming rotary motion from the prime mover to the actuator, and their importance is growing day by day. Although efficiency is not the only criterion for choosing the type of transmission, the gear drive, due to its robustness and operational reliability, presents an inevitable component of most mechanical engineering systems. Gear drives are known to be highly demanding in design, manufacture, control and maintenance.

The entire field is well provided with standards, books and journal and conference papers. Thus, why a necessity for this book? There are three main reasons:

1. Much knowledge has lost its validity through the statute of limitations, so it needs to be renewed. This book incorporates up-to-date knowledge.
2. Despite the body of data available through the Internet, there is obviously still a lack of real knowledge. Namely, a basic knowledge is necessary for one to be able to apply the data. By collecting the data and by using the gear standards, a designer can get all the necessary information for gear drive design. Nevertheless, if someone wants to become a gear drive designer, he must primarily have basic knowledge. This book is conceived to enable both the basic knowledge and the data necessary to design, control, manufacture and maintain gear drives.
3. There is no single book so far which incorporates almost all types of gears and gear drives: spur, helical, bevel and worm gear drives and planetary gear trains.

This book is written with the presumption that the reader has a basic knowledge of mechanics and general mechanical engineering. It is primarily addressed to graduate and undergraduate students of mechanical engineering and to professionals dealing with the manufacturing of gears and gear drives. For all of these, it is supposed to be a primary text. Groups with an occasional need for this material are students of industrial engineering, technology, automotive engineering, students of marine engineering, aviation engineering and space engineering and professionals in control and maintenance. The objective of this book is to provide all of these with everything they need regarding the subject matter in a single book: (i) a background for dealing with gears and gear trains (classification, power, torque, transmission ratio distribution), (ii) a complete geometry and kinematics for almost any type of gears and gear drives, (iii) assessments of load capacities in accordance with recent standards, including the calculation of micro-pitting load capacity, (iv) directions and suggestions for the practical design of gears and gear drives, (v) detailed instructions and formulae for determining the tolerances and procedures for measuring and controlling the accuracy of drives and their members in accordance with the latest standards. The reading matter is accompanied with a large number of figures and every important formula is derived and discussed.

This book consists of seven chapters. The first chapter introduces the reader to the fundamental parameters of mechanical drives – transmission ratio, power, efficiency, torque and rotational speed – and explains the way for determining them. The classification of mechanical drives and gear drives is also included. The second chapter explains in depth the geometry of cylindrical gear toothing as the basis of the entire field of gear drives, beginning with the idea of rolling, through the manufacturing of gears, the mesh and interference of teeth, tooth modifications, to the gear tolerances. The third chapter deals with the integrity of cylindrical gears, presenting the ways of calculating the load capacities for pitting, tooth root strength, scuffing and micro-pitting. In the fourth chapter the cylindrical gear drive design process is suggested and the selection of gear materials and their heat treatment are explained in depth, as well as gear drive lubrication and the efficiency and temperature of the lubricant. The fifth chapter deals with bevel gear drives: geometry, manufacturing, control, tolerances and load capacity checks. Crossed gear drives are also explained. In the sixth chapter simple planetary gear trains are first presented: transmission ratio, torques, efficiency of power and branching. Special trains, like harmonic and composed trains and also coupled, closed and reduced coupled trains are explained, as well as planetary reducers. The seventh chapter deals with worm gear drives: their geometry, manufacture, deviation control and load capacity assessments for the wear, pitting, heating, wormwheel tooth root and worm shaft deflection.

The book assumes that the reader is familiar with the metric (SI) system of units. However, some remarks are given herein: since standard modules are given in millimetres, all gear dimensions should be expressed in millimetres as well. Hence, in all equations where only length units appear, all physical quantities are to be substituted in millimetres. The exceptions are the allowance equations, where gear dimensions are to be substituted in millimetres to obtain the allowance in microns. In other equations, where the dimensions of physical quantities are not only their lengths, the SI scale of units should be applied and gear dimensions should be substituted in metres, regardless of being marked in millimetres in the list of symbols at the end of each chapter. Relationship equations make an exception where the units of both sides of the equation are not the same. In each such equation the units of physical quantities (those which are to be substituted) are specified, as well as the unit of physical value obtained on the left side of the equation.

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Introduction

1.1 Power Transmissions and Mechanical Drives

Mechanical power transmissions[1] consist of units which, in distinction from electrical, pneumatic and hydraulic ones, transfer power from the prime mover to the actuator (operational machine or operational member) with the assistance of *rotary motion*. These units are called mechanical drives and are situated between the prime mover and the actuator (Figure 1.1). The drive is connected with both the prime mover and the actuator by couplings or clutches forming an entirety whose function is defined by the purpose of the actuator.

The embedding of a power transmission to link the prime mover and the machine operating member can be due to a number of reasons:

- The required speed of the machine operating member very often differs from the speeds of the standard prime movers.
- One prime mover has to drive several actuators.
- The driven side speed has to be frequently changed (regulated), whereas the prime mover cannot be used to full advantage for this purpose.
- Certain periods of the driven side operation may require torques far from those obtained on the motor shaft.
- As a rule, standard motors are designed for uniform rotary motion, while operating members have sometimes to move with varying speed or periodic halts.
- If a resonant vibration of some member in the chain of power transmission cannot be solved in any other way, the frequency of rotary motion can be changed by building-in a drive.
- Sometimes considerations of safety, convenience of maintenance or the dimensions of the machine, especially if the prime mover and operational machine shaft axes are not coaxial, do not allow the direct coupling of the prime mover shaft with operating member.

[1] The power is a feature of some machine or device and cannot be transmitted. Actually, only the energy is transmitted, but it is globally common to say that the power is transmitted.

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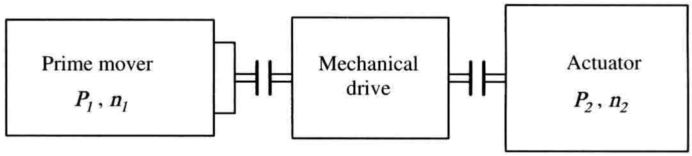

Figure 1.1 Schematic account of a mechanical drive application

The capital task of the designer is to select such an assembly 'prime mover – transmission (drive)' which should optimally meet the needs of the operational machine or member. This act of choosing is a complex task, whose solution depends on: (i) accessibility of the energy source and its price, (ii) efficiency of the entirety of prime mover – transmission – operational machine, (iii) investment costs, (iv) operational machine features, primarily the (v) variability of its speed of rotation, (vi) service conditions, (vii) drive maintainability and so on. Within the framework of this task, a particularly complex problem is defining the transmission: mechanical or some other? This question is beyond the scope of this book, but generally it may be affirmed that the basic advantage of mechanical drives in relation to all the others is their very high efficiency, which is becoming more and more important day by day.

The comparative advantages offered by possible transmissions and drives are outlined in Table 1.1 which gives only a general illustration. Recently, a prominent feature in power transfer has been the extensive employment of electric, hydraulic and pneumatic transmissions. Frequently, such transmissions together with mechanical drives are simultaneously used to actuate various mechanisms. The proper choice of a drive for each specific case can be made only by comparing the technical and economical features of several designs.

The mechanical drive driving shaft receives power P_1 at speed of rotation n_1 from the prime mover driven shaft, and the mechanical drive driven shaft supplies power $P_2 < P_1$ at

Table 1.1 Advantages of transmissions and drives

Advantage	Transmission		Mechanical drive		
	Electric	Hydraulic	Pneumatic	Friction	Mesh
Centralized power supply	+		+		
Simplicity of power transmission over large distances	+				
Easy accumulation of power			+		
Step by step speed change over a wide range	+			+	+
Stepless change over a wide range	+	+		+	
Maintaining accurate transmission ratio					+
High speed of rotation	+		+		
Simplicity of machine designed for rectilinear motion		+	+	+	+
No effect of ambient temperature	+		+		+
Comparatively high practically obtainable loads acting upon actuators of machine		+			+
Easy control, automatic and remote	+				

speed of rotation n_2 to the operational machine driving shaft. The difference $P_1 - P_2 = P_L$ is called power loss and the ratio:

$$\eta = \frac{P_2}{P_1} = \frac{P_1 - P_L}{P_1} = 1 - P_L/P_1$$

is called efficiency; it takes a special place amongst power transmission characteristics because it shows unproductive power expenditure and so indirectly characterizes the wear of the drive and its warming up – the capital problems in power transmissions. Warming up causes strength and lifetime decrease of drive parts. Their corrosion resistance and the functional ability of lubricant are also imperilled. The importance of efficiency is raised to a power by the global lack of increasingly expensive energy and its value also decisively affects the price of the drive.

The power loss consists of constant losses which on the whole do not depend on load, and variable losses which on the whole are proportional to the load. The value of constant losses approximates the power of idle run, that is, the power needed to rotate the drive at $P = 0$ on the driven shaft. It depends on the weight of the drive parts, the speed of rotation and the friction in the bearings and on other surfaces of contact.

The second fundamental parameter of a mechanical drive is the *transmission ratio* i defined as the ratio of its driving n_1 and driven n_2 shaft speeds of rotation or angular speeds:

$$i = \frac{n_1}{n_2} = \frac{\omega_1}{\omega_2}. \tag{1.1}$$

If $i > 1$ ($n_1 > n_2$) the mechanical drive is called an *underdrive* and its member is called a *reducer*. It reduces the speed of rotation and the transmission ratio is also called a speed reducing ratio. If $i < 1$ the mechanical drive is called an *overdrive*, its member is called a *multiplicator* and the transmission ratio is also called a speed increasing ratio. It multiplies the speed of rotation. An overdrive usually works less efficiently than an underdrive. This is especially true for a toothed wheel gearing.

1.2 Classification of Mechanical Drives

The basic division of mechanical drives falls into:

- *Drives with a constant transmission ratio.*
- *Drives with a variable transmission ratio.*

In **constant transmission ratio drives**, the constant speed of driving shaft rotation results in a constant speed of driven shaft rotation, $n_2 = n_1/i$. Their design should, as a rule, include at least the following data: (i) transmitted power of the driving (P_1) or driven (P_2) shaft or related torques, (ii) speed of rotation (rpm) of the driving (n_1) and driven (n_2) shaft, mutual location of the shafts and distance between them, (iii) overall dimensions and drive operating conditions, especially the dependence of driven shaft rpm or torque on time.

In general, this design has several solutions, that is, given conditions can be used to develop drives of various types. All possible designs should be compared according to their efficiency, weight, size, original and operational costs in order to select the most advantageous one. Some general considerations, mainly the available experience of design,