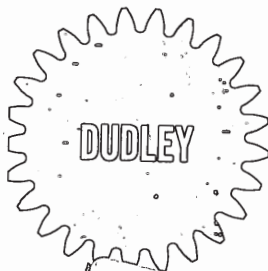


GEAR  
HANDBOOK



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# GEAR HANDBOOK

The Design, Manufacture  
and Application of Gears

DARLE W. DUDLEY

EDITOR IN CHIEF

MCGRAW-HILL BOOK COMPANY

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**GEAR HANDBOOK**

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The Design, Manufacture, and  
Application of Gears

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General Electric Company  
Lynn, Massachusetts*

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## FOREWORD

The design and manufacture of a gear that is no better than the requirement for its successful application is an art rather than a science.

Volumes have been written and said in attempts to attain good gears. Many of them have been rather unsuccessful interpretations of what their authors opined previous authors meant or failed to say.

Thus, much of the information comes under what I call "gear folklore"—just about as obsolete as the cogwheel that sired the quality of gearing we need in modern applications.

The authors of this "Gear Handbook" are seasoned and experienced gear men. They have spent most of their careers in the study of gear phenomena, in tempering theory in the furnace of practicality and economic necessity. Several of them have received the highest honor the American Gear Manufacturers Association has to bestow on contributors to the gear art, its "Edward P. Connell" Award.

These dedicated authors set out to give the gear designer and manufacturer a true and accurate recording of the present state of the art.

They have eminently succeeded in so doing. Therefore, I personally and on behalf of AGMA enthusiastically commend this "Gear Handbook" to all who have a genuine desire and economic need to acquaint themselves with the gear art as it is now being practiced by forward-looking, down-to-earth gear designers and manufacturers.

J. C. SEARS, *Executive Director*  
*American Gear Manufacturers Association*

## PREFACE

Although a rather surprising amount of material has already been written on the subject of gears, it has been hard for the average person to quickly find the detailed gear information that he needs. A wealth of gear information has already been published in trade standards, magazine articles, manufacturers' catalogues, private company reports, and gear books. The key information to solve the design of a gear, plan tooling for a gear job, analyze a gear failure, or pick an appropriate manufacturing process may be hidden almost anywhere in current available technical literature.

The "Gear Handbook" was conceived as a means of solving this problem. In approximately one thousand pages of moderately fine print all aspects of the gear art are covered. The questions that the gear designer, the gear builder, or the gear user may have are all covered. Condensed information is given on the many types of gears that are now in use. Specific information is given on the great diversity of manufacturing processes that may be used. Considering that the field of gearing goes all the way from the little mass-produced gears for toys, clocks, instruments, and the like, up to the massive main propulsion units used for major ships or airplanes, it can be appreciated that the manufacturing techniques will vary widely.

The people who design and build gears comprise only a small fraction of the people engaged in manufacturing work. However, the people who use gears include almost everyone. It has been said quite truthfully that you can't tell the time of day without gears, you can't wash your clothes without gears, you can't drive to work without gears, and you can't make anything in your shop without gears. The user of gears is often very interested in things like the performance of gear equipment, the life expectancy of gearing, or the relative cost of different ways of making gears. Subject matter for the "Gear Handbook" has been selected with the aim of covering the whole wide field of interest in the gear art.

Chapters 1 through 4 introduce the reader to the basic theory of gearing, define the types of gear teeth, explain the many possible gear arrangements, and define the nomenclature and basic geometry of gears.

All of this is necessary background material to acquaint a person with the language and definitions peculiar to the gear trade.

Chapters 5 through 15 are the prime engineering-design chapters. These cover the elements of design, such as tooth proportions, involute calculations, choice of materials, stress calculations, load rating, tolerancing of gear dimensions, efficiency calculations, and design of lubrication systems.

Chapter 14 presents material on how to test gears and how to analyze the several possible kinds of gear failure.

Chapters 16 through 21 cover the machine tools and methods of gear manufacture. Gear cutting, gear grinding, die forming of gears, gear shaving, gear lapping, and gear honing are all covered in these chapters.

Chapter 22 covers tools to make gears, and Chapter 23 covers inspection tools. Chapter 24 presents many tables of data useful in the gear trade.

Over three dozen people were direct contributors to the project. These people were selected because of their knowledge and competence in the various aspects of gear work. The technical knowledge that this group of people was able to put together over a four-year working period represents a depth of technical knowledge in this field that is far beyond that of any one individual. From my own standpoint it has been a most rewarding experience to be associated with this project and learn from experts in all phases of gear work. In many cases, information collected for the "Gear Handbook" represents the first time this information has ever been put in public print.

I am very grateful to the many contributors for their unselfish effort in getting the required information and laboring through all the trials of putting it into handbook style. In addition, I feel particularly grateful to certain key individuals who were most helpful in providing technical guidance for the project and in making the resources of their organizations available to ferret out key items of information. My special thanks go to the officers and Headquarters staff of the American Gear Manufacturers Association, the "engineering body for the gear industry," for their assistance in checking many parts of this work. I also wish to give special thanks to Wells Coleman of the Gleason Works for his assistance in the bevel-gear field; to Mr. Gerald Brophy of International Nickel Co. for his advice on gear material developments; to Mr. Fred E. Birtch, Cone-Drive Division, Michigan Tool Co., for his assistance on double-enveloping wormgears; to Mr. S. L. Eastman, Cleveland Worm & Gear Division, Eaton Manufacturing Co., for his help on cylindrical wormgears, and to Mr. F. Bohle and Mr. W. Nelson, Spiroid Division of Illinois Tool Works, for their assistance on the Spiroid family of gears. Mr. Laurence Collins and others in the General Electric Company were very helpful in encouraging me to carry out this project and in making

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available to me extensive test and field data on spur and helical gears.

In spite of the fact that most of the gear technical material was received from contributors and others associated with this project, I must accept the responsibility for having made the final decisions that determined the technical content of this work. I believe this "Gear Handbook" will represent an important step forward in the development of knowledge in the gear field. It makes this knowledge available for the widest possible benefit of the great host of people who buy, design, build, or use geared equipment.

DARLE W. DUDLEY

*Lynnfield, Mass.*

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**GEAR HANDBOOK**

The length-to-diameter ratio of helical and spur gears can be fairly large. In most other gear types the pinion will not have face width more than about one-third the pinion pitch diameter. In spur gearing the  $L/D$  ratio may be as great as 1 while in double-helical gearing it may approach 2. Needless to say, high accuracy is needed in boring the casings and machining the teeth when a relatively large face width is used. Low-hardness gearing of about 200 BHN will exhibit some tendency to wear in and improve contact. As much as 0.001" may be worn off the high ends of the teeth to equalize the contact without too serious a result. Medium- to high-hardness gears have but slight tendency to wear in. If the contact across the face width is not good at full load, the teeth may break before any equalizing wear occurs. (See Chap. 13 for data on how to handle misalignment when load-rating gears.)

Large pinions with an  $L/D$  ratio of 1 or more will twist elastically under load an appreciable amount. It is necessary to provide helix modification to compensate for this on large gears where the material is fairly hard and the horsepower is high. (Helix modification was necessary on the gears shown in Figs. 3-4 and 3-7.)

Nested pinions tend to suffer from bowing and twisting of the long shaft between the two pinion halves. Helix compensation is often needed.

In multiple-power-path units, each power path must be able to have the teeth engage simultaneously when a slight torque is applied. In addition errors in tooth spacing and runout must be slight enough in the gears so that the flexibility of the connecting shafts can keep a uniform load on each branch. If the connections are too stiff or the teeth not precise enough, the load will shift rapidly from one power path to another as the gear revolves.

In multiple-power-path gearing, the gears will not assemble if there is a random orientation between the teeth of a gear and a pinion connected by the same shaft. Either the teeth and coupling means must be cut so that the orientation is exactly alike on each like assembly or adjustment must be provided so the proper tooth "timing" is achieved at assembly. Generally the teeth are cut at a random orientation. Then at assembly the parts are rotated until the pinion and gear by chance have their teeth in almost the right orientation. Then the final adjustment is made by some mechanical means like axial shimming (single-helix design), elongating coupling boltholes, redoweling, or using a stepped key. Incidentally, a shrewd choice on tooth numbers can make the timing problem work out much more easily.

**3-4. Parallel-axis Epicyclic Gearing.** A large family of gear arrangements goes under the general name of "epicyclic" gearing. Generally speaking the epicyclic train has a central "sun" gear, several "planets" meshing with the sun and spaced uniformly around the sun and an "annulus" or ring gear meshing with the planets. The sun and planets are externally toothed while the ring is internally toothed.

The name epicyclic comes from the fact that points on the planets trace out epicycloidal curves in space.

The name "planetary" gear is sometimes used interchangeably with epicyclic to denote the whole family of gears. In a more strict sense the *planetary* is one of the types of epicyclic gears.

There are a large number of possible epicyclic arrangements. These may be divided into three general groups:

1. Single epicyclic trains
2. Compound epicyclic trains
3. Coupled epicyclic trains

**Single Epicyclic Trains.** The simple epicyclic train consists only of the elements of sun, planet, and ring gear. This arrangement is often called a "simple" epicyclic

gear or a "simple" planetary gear to distinguish it from the more complicated arrangements.

Figure 3-13 shows schematic arrangements of the three simple epicyclic gears. These are the *planetary*, the *star*, and the *solar arrangements*. The figure shows only three planets. The number of planets will vary quite considerably in actual practice. With some ratios it has been possible to squeeze in as many as twenty planets. As few as one is sometimes used for light load applications.

The derivation of ratios for planetary units is somewhat complicated. Several references<sup>1,2,3,\*</sup> go into the derivation of ratios in considerable detail. Table 3-5 shows the over-all ratio for each of the three single epicyclic trains. If one of these units were driven backward, the ratio would be less than one and would simply be the reciprocal of the ratio as a speed-reducing set.

A range of ratios is shown for each kind of epicyclic gear. Note that only the solar will handle very low ratios. The ratio range of 1.7:1 to 2:1 is a range that is rather difficult to handle with simple epicyclic gearing. The star will work in this range, but it turns out to be rather awkward.

Epicyclic gears will not assemble unless the tooth numbers are properly chosen. Assuming the planets are equally spaced around the sun—which is the usual case—the equations given at the bottom of Table 3-5 must be met. The sum of the ring and sun teeth must be equally divisible by the number of planets. If there were three planets, the ring teeth plus sun teeth would have to divide evenly by three.

The tooth load at each planet is balanced between the sun-planet mesh and the planet-ring mesh. This tangential driving load may be calculated by

$$W_t = \frac{126,050 P_H}{n_s d_s \text{ No. planets}} \quad (3-2)$$

where  $n_s$  = rpm of sun

$d_s$  = pitch diameter of sun

$P_H$  = horsepower transmitted

It should be appreciated that Eq. (3-2) determines the theoretical load only when there is perfect sharing of load between the planets. There is quite a problem in load sharing in epicyclic gears plus the possibility of appreciable dynamic overload due to tooth errors. More will be said on this subject later in this article.

Table 3-5. Simple-epicyclic-gear Data

| Kind of arrangement | Fixed member | Input member | Output member | Over-all ratio $m_G$  | Range of ratios normally used |
|---------------------|--------------|--------------|---------------|-----------------------|-------------------------------|
| Planetary.....      | Ring         | Sun          | Cage          | $\frac{N_R}{N_S} + 1$ | 3:1-12:1                      |
| Star.....           | Cage         | Sun          | Ring          | $\frac{N_R}{N_S}$     | 2:1-11:1                      |
| Solar.....          | Sun          | Ring         | Cage          | $\frac{N_S}{N_R} + 1$ | 1.2:1-1.7:1                   |

$N_S$  = number of sun teeth

$N_P$  = number of planet teeth

$N_R$  = number of ring (annulus) teeth

To assemble,

$$N_R = N_S + 2N_P \quad (3-3)$$

$$\frac{N_R + N_S}{\text{No. planets}} \text{ must equal an integer} \quad (3-4)$$

\* Superscript numbers refer to references at the end of the chapter.

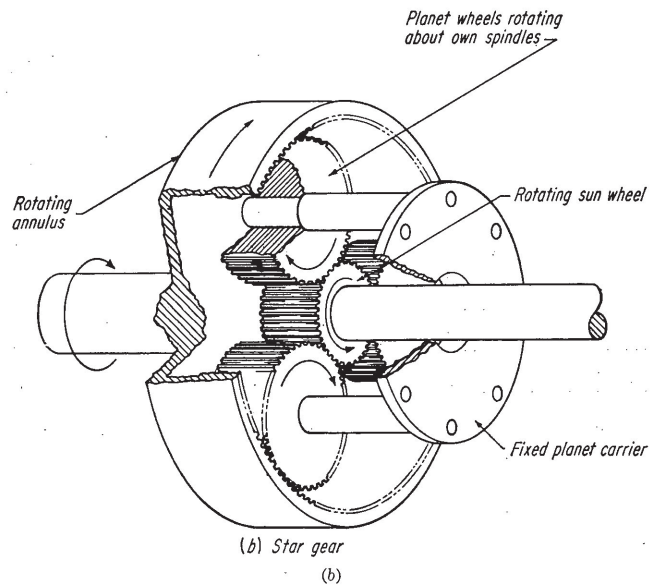
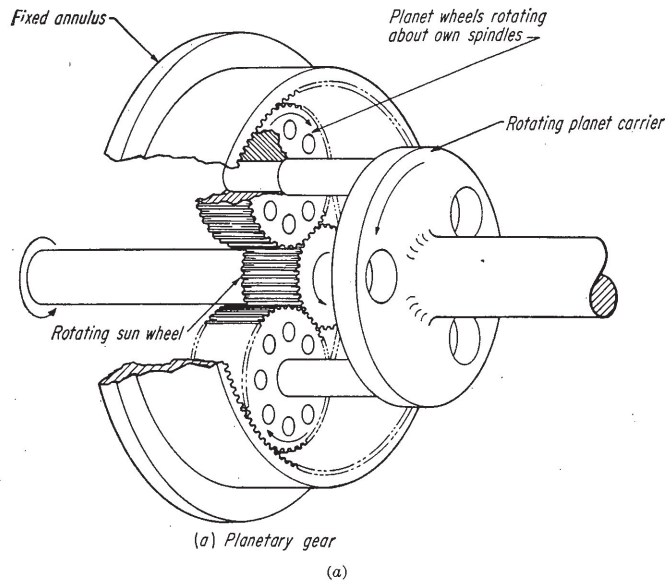


FIG. 3-13. Simple epicyclic gears. (a) Planetary

**Compound Epicyclic Trains.** The "compound" epicyclic train has two planet members attached together on a common shaft. Figure 3-15 shows the schematic arrangement of a compound star gear. Note the large planets (or stars) which mesh only with the sun and the small planets which mesh only with the ring gear.

Table 3-6. Compound-epicyclic-gear Data

| Kind of arrangement     | Fixed member | Input member | Output member | Over-all ratio $m_G$                  | Range of ratios normally used |
|-------------------------|--------------|--------------|---------------|---------------------------------------|-------------------------------|
| Compound planetary..... | Ring         | Sun          | Cage          | $\frac{N_R N_{P_1}}{N_S N_{P_2}} + 1$ | 6:1-25:1                      |
| Compound star.....      | Cage         | Sun          | Ring          | $\frac{N_{P_1} N_R}{N_S N_{P_2}}$     | 5:1-24:1                      |
| Compound solar.....     | Sun          | Ring         | Cage          | $\frac{N_S N_{P_2}}{N_R N_{P_1}} + 1$ | 1.05:1-2.2:1                  |

$N_S$  = number of sun teeth

$N_{P_1}$  = number of first-reduction planet teeth

$N_{P_2}$  = number of second-reduction planet teeth

$N_R$  = number of ring teeth

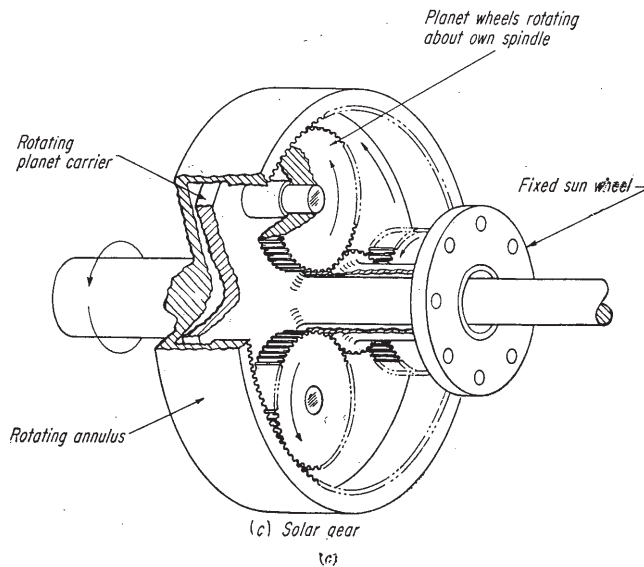
To assemble,

$$D_R = D_S + D_{P_1} + D_{P_2} \quad (3-5)$$

where  $D_R$  = ring pitch diameter

$D_P$  = planet pitch diameter

$$\frac{N_{P_1} N_R + N_{P_2} N_S}{\text{No. planets}} \text{ must equal an integer} \quad (3-6)$$



gear. (b) Star gear. (c) Solar gear.

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