BELT AND CHAIN DRIVES

OBJECTIVES

Upon completion of this chapter, the student will be able to:

1. Describe the advantages of a belt drive.
2. Identify several different types of belt designs.
3. Determine the geometric relationships of a belt drive.
4. Analyze the kinematic relationships of two shafts coupled by a belt drive.
5. Describe the advantages of a chain drive.
6. Identify several different types of chain designs.
7. Determine the geometric relationships of a chain drive.
8. Analyze the kinematic relationships of two shafts coupled by a chain drive.

11.1 INTRODUCTION

The primary function of a belt or chain drive is identical to that of a gear drive. All three of these mechanisms are used to transfer power between rotating shafts. However, the use of gears becomes impractical when the distance between the shafts is large. Both belt and chain drives offer the flexibility of efficient operation at large and small center distances.

Consider the chain on a bicycle. This mechanism is used to transfer the motion and forces of the rotating pedal assembly to the rear wheel. The distance between these two rotating components is considerable, and a gear drive would be unreasonable. Additionally, the velocity ratio of the chain drive can be readily altered by relocating the chain to an alternate set of sprockets. Thus, a slower pedal rotation but greater forces are needed to maintain the identical rotation of the rear wheel. The velocity ratio of a belt drive can be similarly altered. Changing a velocity ratio on a gear drive is a much more complex process, as in an automotive transmission.

Belt and chain drives are commonly referred to as flexible connectors. These two types of mechanisms can be "lumped together" because the kinematics are identical. The determination of the kinematics and forces in belt and chain drives is the purpose of this chapter. Because the primary motion of the shafts is pure rotation, graphical solutions do not provide any insight. Therefore, only analytical techniques are practical and are introduced in this chapter.

11.2 BELTS

The function of a belt drive is to transmit rotational motion and torque from one shaft to another, smoothly, quietly, and inexpensively. Belt drives provide the best overall combination of design flexibility, low cost, low maintenance, ease of assembly, and space savings.

Compared to other forms of power transmission, belt drives have these advantages:

- They are less expensive than gear or chain drives.
- They have flexible shaft center distances, where gear drives are restricted.
- They operate smoothly and with less noise at high speeds.
- They can be designed to slip when an overload occurs in the machine.
- They require no lubrication, as do chains and gears.
- They can be used in more than one plane.
- They are easy to assemble and install and have flexible tolerances.
- They require little maintenance.
- They do well in absorbing shock loading.

Belts are typically made of continuous construction of materials, such as rubberized fabric, rubberized cord, reinforced plastic, leather, and fabric (i.e., cotton or synthetic fabric). Many belt shapes are commercially available and are listed here.

1. A *flat belt* is shown in Figure 11.1a. This belt is the simplest type but is typically limited to low-torque applications because the driving force is restricted to pure friction between the belt and the pulley.
2. A *V-belt* is shown in Figure 11.1b. This is the most widely used type of belt, particularly in automotive and industrial machines. The V shape causes the belt to wedge tightly into the pulley, increasing friction and allowing higher operating torque.
3. A *multi-V-belt* is shown in Figure 11.1c. This belt design is identical to several V-belts placed side by side but is integrally connected. It is used to increase the amount of power transferred.

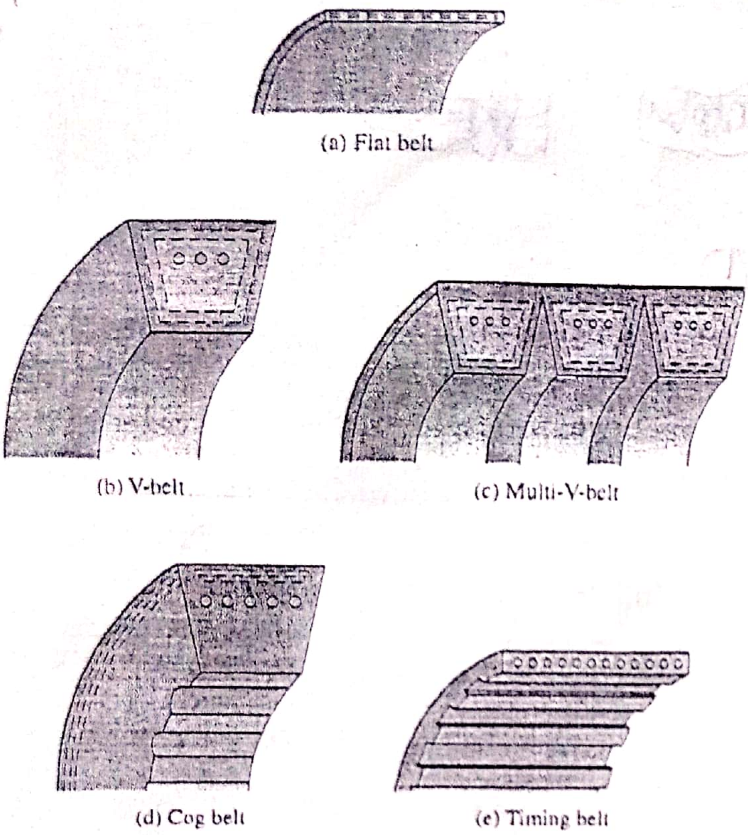


FIGURE 11.1 Types of belts.

4. A *cog belt* is shown in Figure 11.1d. This belt design is similar to a V-belt but has grooves formed on the inner surface. This feature increases belt flexibility, allowing the belt to turn smaller radii. Thus, it can be used on smaller pulleys, reducing the size of the drive.
5. A *timing belt* is shown in Figure 11.1e. This belt design has gear-like teeth that engage with mating teeth on the pulleys. This arrangement combines the flexibility of a belt with the positive grip of a gear drive. This belt is widely used in applications where relative positioning of the respective shafts is desired.

Pulleys, more appropriately referred to as *sheaves*, are the wheels that are connected to the shafts and carry the belt. The pulleys have a groove around the outside, with a shape to match that of the belt. A V-belt sheave is shown in Figure 11.2. Industrial sheaves are machined from steel or cast iron, depending on diameter. For lighter service, sheaves may be made from aluminum, plastic, or die-cast zinc. The construction is either solid or spoked, also depending on size. Large sheaves are typically spoked and constructed from cast iron.

Sheaves are classified with a pitch diameter, which is the diameter slightly smaller than the outside of the groove, corresponding to the location of the center of the belt. Commercially stocked sheaves are commonly sold in fractional-inch inside groove diameters. Table 11.1 illustrates the available sheave diameters.

When belts are in operation, they stretch over time. Machines that utilize a belt drive need some feature that can compensate for the belt stretch, such as an adjustable motor base, or an idler pulley. An *idler pulley* is used to maintain constant tension on the belt. It is usually placed on the slack side of the belt and is preloaded, usually with springs, to keep the belt tight.

As stated, V-belts are the most widely used type of belt. Commercially available industrial V-belts are made to one of the standard sizes shown in Figure 11.3. Of course, the larger cross sections are able to transmit greater power. Often, several belts are used on multiple-groove pulleys to increase

TABLE 11.1 Commercially Available Sheaves

Sheave Pitch Diameters (in.)

3V Belt		5V Belt		8V Belt
2.2	5.3	4.3	8.4	12.3
2.3	5.6	4.5	8.9	13.0
2.5	6.0	4.8	9.2	13.8
2.6	6.5	4.9	9.7	14.8
2.8	6.9	5.1	10.2	15.8
3.0	8.0	5.4	11.1	16.8
3.1	10.6	5.5	12.5	17.8
3.3	14.0	5.8	13.9	18.8
3.6	19.0	5.9	15.5	19.8
4.1	25.0	6.2	16.1	21.0
4.5	33.5	6.3	18.5	22.2
4.7		6.6	20.1	29.8
5.0		6.7	23.5	39.8
		7.0	25.1	47.8
		7.1	27.9	52.8
		7.5		57.8
		8.1		63.8

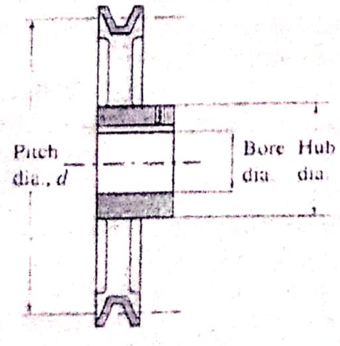


FIGURE 11.2 Single-groove V-belt sheave.

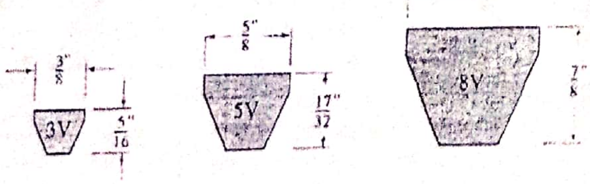


FIGURE 11.3 Industrial narrow-section V-belts.

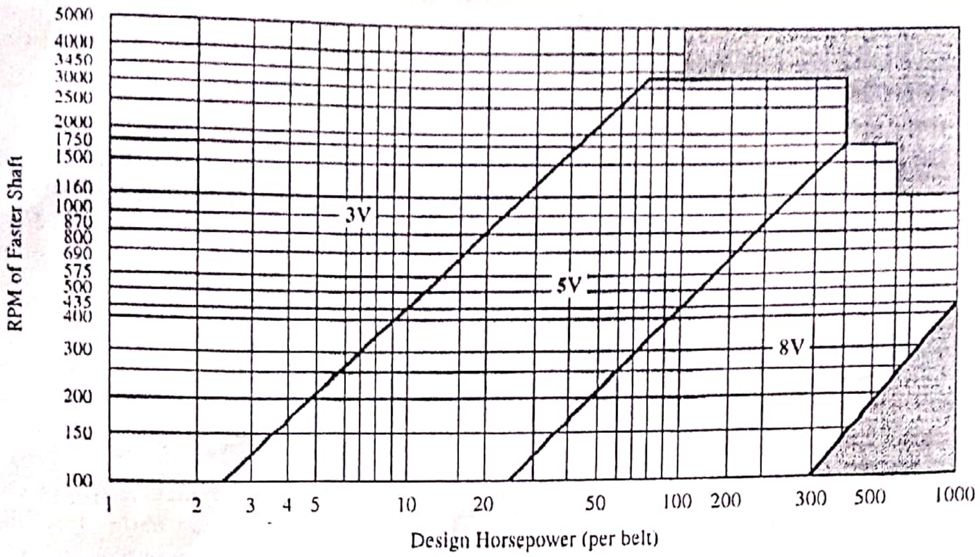


FIGURE 11.4 Industrial V-Belt selection chart.

the amount of power transmitted by the belt drive. A guide to V-belt selection is given in Figure 11.4. The power values are listed "per belt." When the belt drive must transfer 6 hp using a three-groove belt, each of the three belts must be capable of carrying 2 hp.

It must be noted that Figure 11.4 gives only a rough guide to selecting an appropriate belt size. It is important to select the most suitable belt drive based on a detailed study of the application and the power transmission requirements. ~~These detailed selection procedures are given in the manu-~~ facturers' catalogs.

11.3 BELT DRIVE GEOMETRY

A belt drive is intended to provide a constant velocity ratio between the respective shafts. A sketch of the basic geometry in a belt drive is shown in Figure 11.5.

As stated, the *pitch diameter*, d, of the sheave is measured to the point in the groove where the center of the belt sits. This is slightly smaller than the outside diameter of the sheave. Note that the diameters shown for the sheaves in Figures 11.2 and 11.5 are the pitch diameters.

The *center distance*, C, is the distance between the center of the driver and driven sheaves. Of course, this is also the distance between the two shafts coupled by the belt drive.

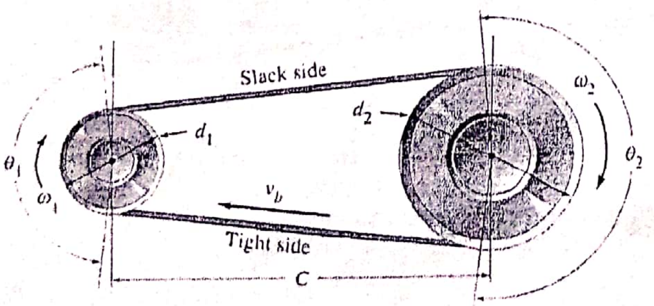


FIGURE 11.5 Belt drive geometry.

Small center distances can cause fatigue, with frequent maximum loading on the belt sections as it enters the small sheave. Large center distances, with the long unsupported span, can cause belt whip and vibrations. Normal center distances for V-belts should be in the following range:

$$d_2 < C < 3(d_1 + d_2)$$

The *belt length*, L, is the total length of the belt. Specifically, the outside length is usually specified. This is the ~~dimension obtained by wrapping a tape measure around the~~ outside of the belt in the installed position. Belts are commercially available at specified lengths. Table 11.2 illustrates the available lengths for industrial V-belts. The center distance and pitch diameters can be mathematically related [Ref. 2].

$$L = 2C + \frac{\pi}{2}(d_2 + d_1) + \frac{(d_2 - d_1)^2}{4C} \tag{11.1}$$

and

$$C = \frac{B + \sqrt{B^2 - 32(d_2 - d_1)^2}}{16} \tag{11.2}$$

where

$$B = 4L - 2\pi(d_2 + d_1) \tag{11.3}$$

The *angle of contact*, θ, is a measure of the angular engagement of the belt on each sheave. It can be computed for each sheave as follows:

$$\theta_1 = 180° - 2\sin^{-1}\left\{\frac{d_2 - d_1}{2C}\right\} \tag{11.4}$$

$$\theta_2 = 180° + 2\sin^{-1}\left\{\frac{d_2 - d_1}{2C}\right\} \tag{11.5}$$

The power ratings for commercially available belts, as shown in Figure 11.4, are for drives with sheaves of the same size. Thus, the "rated" angle of contact is 180°. For smaller

TABLE 11.2 Commercially Available V-Belt Lengths (in.)

3V Belt Lengths			
25.0	40.0	63.0	100.0
26.5	42.5	67.0	106.0
28.0	45.0	71.0	112.0
30.0	47.5	75.0	118.0
31.5	50.0	80.0	125.0
33.5	53.0	85.0	132.0
35.5	56.0	90.0	140.0
37.5	60.0	95.0	
5V Belt Lengths			
50.0	90.0	160.0	280.0
53.0	95.0	170.0	300.0
56.0	100.0	180.0	315.0
60.0	106.0	190.0	335.0
63.0	112.0	200.0	355.0
67.0	118.0	212.0	
71.0	125.0	224.0	
75.0	132.0	236.0	
80.0	140.0	250.0	
85.0	150.0	265.0	
8V Belt Lengths			
100.0	160.0	236.0	355.0
112.0	170.0	250.0	400.0
118.0	180.0	265.0	450.0
125.0	190.0	280.0	
132.0	200.0	300.0	
140.0	212.0	315.0	
150.0	224.0	335.0	

angles, the amount of friction that can be developed around the sheave is reduced, and therefore, the amount of power that a belt can transfer is reduced. Table 11.3 shows the percent of actual rated power that can be transferred by a belt riding over a sheave with a contact angle smaller than 180°. Belt manufacturers suggest keeping the contact angle greater than 120° when possible.

11.4 BELT DRIVE KINEMATICS

In a manner identical to gear drives, the *velocity ratio, VR,* is defined as the angular speed of the driver sheave (sheave 1) divided by the angular speed of the driven sheave (sheave 2).

$$VR = \frac{\omega_{driver}}{\omega_{driven}} = \frac{\omega_1}{\omega_2} \qquad (11.6)$$

Because a ratio is valid regardless of units, the velocity ratio can be defined in terms of revolutions per minute, radians per time, or any other convenient set of rotational velocity units. Using the same logic as the derivation of equation (10.19) yields the following equation:

$$\frac{\omega_1}{\omega_2} = \frac{r_2}{r_1} = VR$$

Introducing the pitch diameters gives

$$\frac{d_2}{d_1} = \frac{2r_2}{2r_1} = \frac{r_2}{r_1} = VR$$

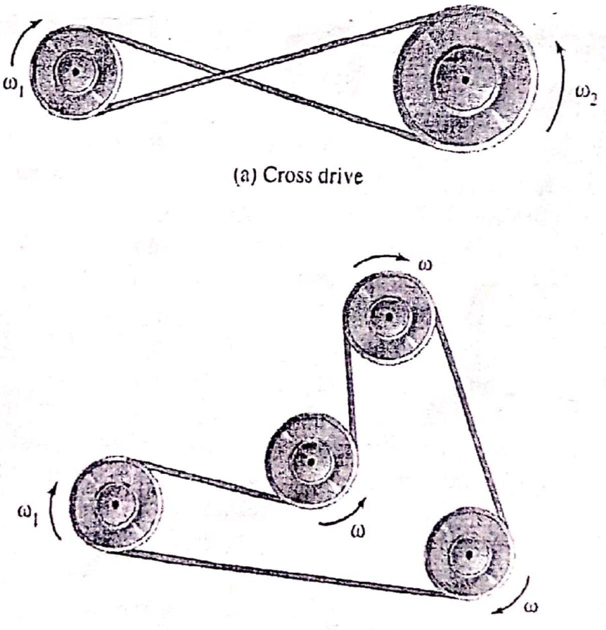
Thus, a comprehensive definition of a velocity ratio is given as

$$VR = \frac{\omega_1}{\omega_2} = \frac{r_2}{r_1} = \frac{d_2}{d_1} \qquad (11.7)$$

Notice that for the typical arrangement, as shown in Figure 11.3, the sheaves rotate in the same direction. Crossed drives or serpentine drives, as shown in Figure 11.6, can be used to reverse the direction of sheave rotation.

Many industrial applications require belts to reduce the speed of a power source. Therefore, it is typical to have velocity ratios greater than 1. As can be seen from equation (11.6), this indicates that the drive sheave rotates faster than the driven sheave, which is the case in speed reductions.

The *belt speed, v_b,* is defined as the linear velocity of the belt. The magnitude of this velocity corresponds to the magnitude of the linear velocity of a point on the pitch diameter of each sheave. Therefore, the belt speed can be related to the



(b) Serpentine drive

FIGURE 11.6 Alternate forms of belt drives.

TABLE 11.3 Reduced Power Capability with Contact Angle

Angle of Contact, θ	180°	160°	140°	120°	100°	80°
Actual Capability (% of rated power)	100	95	89	82	74	63

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otational velocities of the sheaves and their pitch radii using equation (6.5).

$$v_b = r_1\omega_2 = \frac{d_1}{2}\omega_1 = r_2\omega = \frac{d_2}{2}\omega_2 \qquad (11.8)$$

Note that, as in Chapter 6, the angular velocity in this equation must be specified in radians per unit time.

A belt transfers maximum power at speeds of 4000 to 5000 fpm (ft/min). Therefore, it is best to design a belt drive to operate in this range. Large sheaves for industrial use are cast iron and typically are limited to a maximum belt speed of 6500 fpm. This is because the inertial forces created by the normal acceleration become excessive. Special balance may be needed for speeds exceeding 5000 fpm, as vibration can be caused by the centrifugal acceleration. Finally, another type of drive, specifically chains, is typically more desirable for speeds under 1000 fpm.

11.5 CHAINS

As with belts, chain drives are used to transmit rotational motion and torque from one shaft to another, smoothly, quietly, and inexpensively. Chain drives provide the flexibility of a belt drive with the positive engagement feature of a gear drive. Therefore, chain drives are well suited for applications with large distances between the respective shafts, slow speed, and high torque.

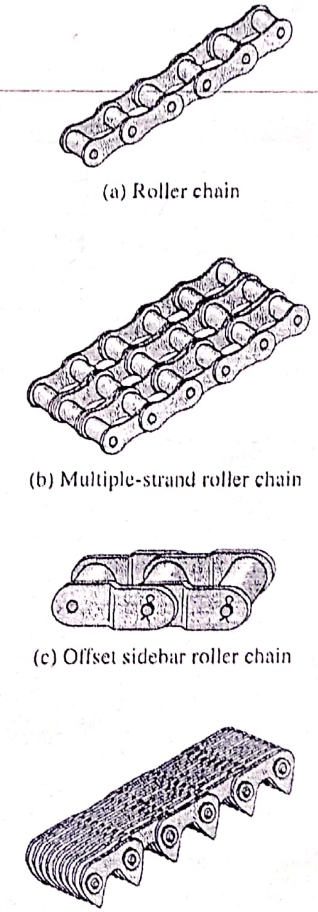
Compared to other forms of power transmission, chain drives have the following advantages:

- They are less expensive than gear drives.
- They have no slippage, as with belts, and provide a more efficient power transmission.
- They have flexible shaft center distances, whereas gear drives are restricted.
- They are more effective at lower speeds than belts.
- They have lower loads on the shaft bearings because initial tension is not required as with belts.
- They have a longer service life and do not deteriorate with factors such as heat, oil, or age, as do belts.
- They require little adjustment, whereas belts require frequent adjustment.

11.5.1 Types of Chains

Chains are made from a series of interconnected links. Many types of chain designs are commercially available and are listed here.

1. A *roller chain* is shown in Figure 11.8a. This is the most common type of chain used for power transmission. Large roller chains are rated to over 600 hp. The roller chain design provides quiet and efficient operation but must be lubricated.
2. A *multiple-strand roller chain* is shown in Figure 11.8b. This design uses multiple standard roller chains built into parallel strands. This increases the power capacity of the chain drive.



(a) Roller chain

(b) Multiple-strand roller chain

(c) Offset sidebar roller chain

(d) Silent chain

FIGURE 11.8 Types of chains.

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3. An *offset sidebar roller chain* is shown in Figure 11.8c. This is less expensive than a roller chain but has slightly less power capability. It also has an open construction that allows it to withstand dirt and contaminants, which can wear out other chains. These chains are often used on construction equipment.
4. An *inverted tooth, silent chain* is shown in Figure 11.8d. This is the most expensive chain to manufacture. It can be efficiently used in applications that require high-speed, smooth, and quiet power transmission. Lubrication is required to keep these chains in reliable operation. They are common in machine tools, pumps, and power drive units.

11.5.2 Chain Pitch

Technical organizations maintain standards (e.g., ANSI standard B29-1) for the design and dimensions of power transmission chains to allow interchangeability. Roller chains are classified by a *pitch, p,* which is the distance between the pins that connect the adjacent links. The pitch is illustrated in Figure 11.9. Roller chains have a size designation ranging from 25 to 240. This size designation refers to the pitch of the chain, in eightieths of an inch. Thus, a 120 chain has a pitch of 120/80 or $1\frac{1}{2}$ inches. The larger-pitch chains have greater power capacity. Roller chain pitch selection is dependant on the power transmitted and speed of the system. A general guide to selecting an appropriate chain pitch is given in Figure 11.10. Manufacturers' catalogs provide detailed procedures to select the most suitable chain drive based on a detailed study of the application and the power transmission requirements.

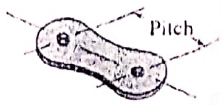

FIGURE 11.9 Chain pitch.

11.5.3 Multistrand Chains

In a similar fashion to belts, multiple-strand chains can be used to increase the amount of power transmitted by the chain drive. However, a multiple-strand chain does not provide a direct multiple of the single-strand capacity. When the chain drive requires multiple strands, equation (11.9) is used to calculate the power transmitted through each chain. A multistrand factor has been experimentally determined and is tabulated in Table 11.4.

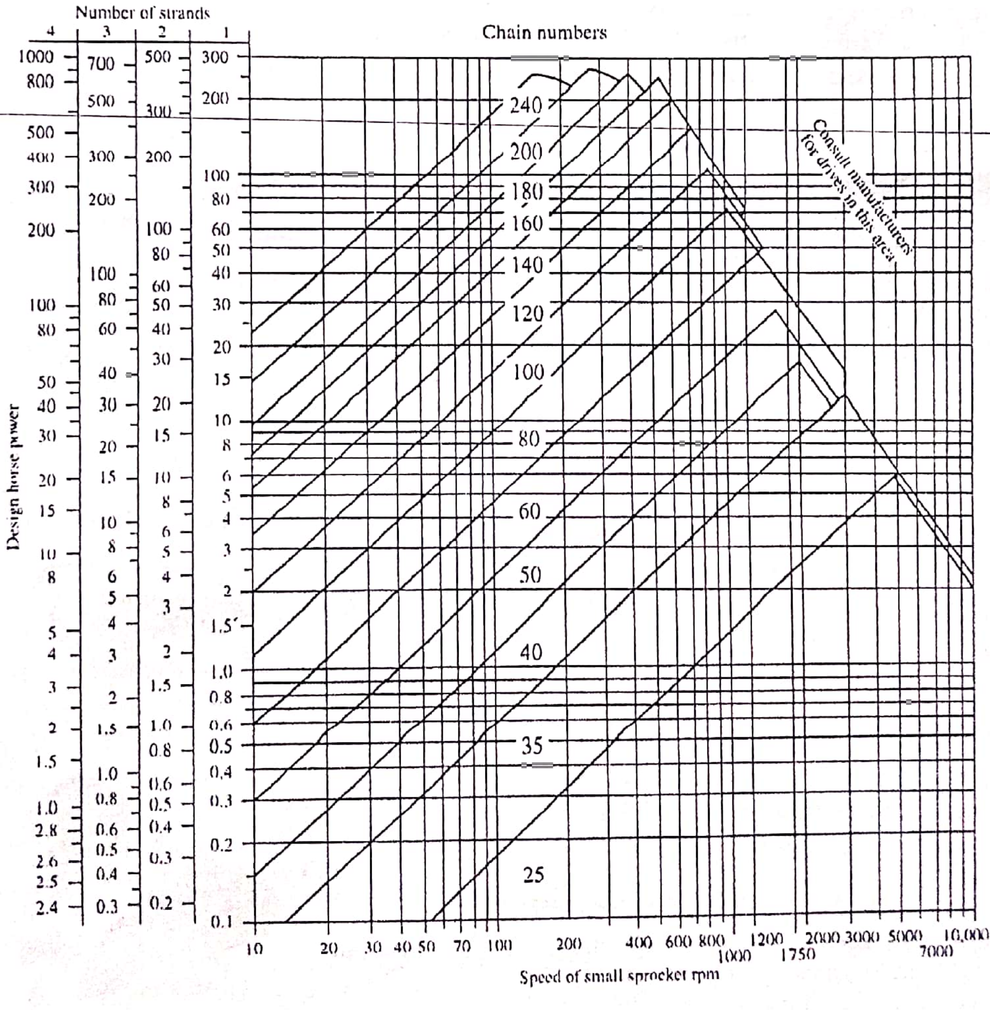

FIGURE 11.10 Chain pitch selection guide.

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TABLE 11.4 Multistrand Factor

Number of Roller Chain Strands	2	3	4	5	6	8	10
Multistrand Factor	1.7	2.5	3.3	3.9	4.6	6.2	7.5

$$\text{Power per chain} = \frac{\text{total power transmitted}}{\text{multistrand factor}} \tag{11.9}$$

The vertical axis of Figure 11.10 displays the power capacity based on different numbers of strands. Equation (11.9) has already been implemented in generating Figure 11.10.

11.5.4 Sprockets

Sprockets are the toothed wheels that connect to the shaft and mate with the chain. The teeth on the sprocket are designed with geometry to conform to the chain pin and link. The shape of the teeth varies with the size of the chain and the number of teeth. A sprocket designed to mate with a roller chain is shown in Figure 11.11.

Sprockets are commonly referenced by the corresponding chain size and the number of teeth. Commercially available sprockets are given in Table 11.5. As with gears and sheaves, the pitch diameter is an important kinematic property. The pitch diameter is the diameter across the middle of the sprocket teeth, which corresponds to the centerline of the chain. It can be determined from the chain size and number of teeth, as will be presented in the next section.

11.6 CHAIN DRIVE GEOMETRY

The basic geometry in a chain drive is virtually identical to that of a belt drive, as shown in Figure 11.12.

The *number of teeth*, N, in the sprocket is a commonly referenced property. It is generally recommended that sprockets have at least 17 teeth, unless they operate at very low speeds—under 100 rpm. Of course, a higher number of teeth will result in a bigger sprocket. The larger sprocket should normally have no more than 120 teeth.

As stated, the *pitch diameter*, d, of the sprocket is measured to the point on the teeth where the center of the chain rides. This is slightly smaller than the outside diameter of the

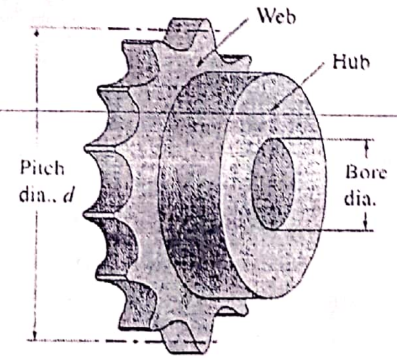

FIGURE 11.11 Roller chain sprocket.

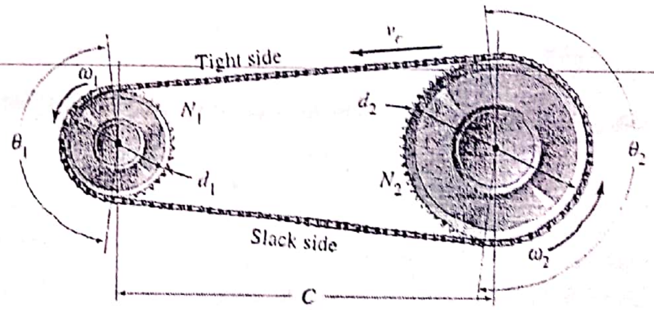

FIGURE 11.12 Chain drive geometry.

TABLE 11.5 Commercially Available Single-Strand Sprockets

Chain Size	Number of Teeth on the Sprocket
25	8 through 30, 32, 34, 35, 36, 40, 42, 45, 48, 54, 60, 64, 65, 70, 72, 76, 80, 84, 90, 95, 96, 102, 112, 120
35	4 through 45, 48, 52, 54, 60, 64, 65, 68, 70, 72, 76, 80, 84, 90, 95, 96, 102, 112, 120
40	8 through 60, 64, 65, 68, 70, 72, 76, 80, 84, 90, 95, 96, 102, 112, 120
50	8 through 60, 64, 65, 68, 70, 72, 76, 80, 84, 90, 95, 96, 102, 112, 120
60	8 through 60, 62, 63, 64, 65, 66, 67, 68, 70, 72, 76, 80, 84, 90, 95, 96, 102, 112, 120
80	8 through 60, 64, 65, 68, 70, 72, 76, 78, 80, 84, 90, 95, 96, 102, 112, 120
100	8 through 60, 64, 65, 67, 68, 70, 72, 74, 76, 80, 84, 90, 95, 96, 102, 112, 120
120	9 through 45, 46, 48, 50, 52, 54, 55, 57, 60, 64, 65, 67, 68, 70, 72, 76, 80, 84, 90, 96, 102, 112, 120
140	9 through 28, 30, 31, 32, 33, 34, 35, 36, 37, 39, 40, 42, 43, 45, 48, 54, 60, 64, 65, 68, 70, 72, 76, 80, 84, 96
160	8 through 30, 32 through 36, 38, 40, 45, 46, 50, 52, 53, 54, 56, 57, 60, 62, 63, 64, 65, 66, 68, 70, 72, 73, 80, 84, 96
180	13 through 25, 28, 35, 39, 40, 45, 54, 60
200	9 through 30, 32, 33, 35, 36, 39, 40, 42, 44, 45, 48, 50, 51, 54, 56, 58, 59, 60, 63, 64, 65, 68, 70, 72
240	9 through 30, 32, 35, 36, 40, 44, 45, 48, 52, 54, 60

sprocket. Note that the diameters shown for the sprockets in Figure 11.11 are the pitch diameters. The pitch diameter of a sprocket with N teeth for a chain with a pitch of p is determined by

$$d = \frac{p}{\sin(180°/N)} \tag{11.10}$$

The *center distance*, C, is the distance between the center of the driver and driven sprockets. Of course, this is also the distance between the two shafts coupled by the chain drive. In typical applications, the center distance should be in the following range:

$$30p < C < 50p$$

The *chain length* is the total length of the chain. Because the chain is comprised of interconnected links, the chain length must be an integral multiple of the pitch. It is preferable to have an odd number of teeth on the driving sprocket (17, 19, . . .) and an even number of pitches (links) in the chain to avoid a special link. The chain length, L, expressed in number of links, or pitches, can be computed as

$$L = \frac{2C}{p} + \frac{(N_2 + N_1)}{2} + \left\{\frac{p(N_2 - N_1)^2}{4\pi^2 C}\right\} \tag{11.11}$$

The center distance for a given chain length can be computed as

$$C = \frac{p}{4}\left[L - \frac{(N_2 + N_1)}{2} + \sqrt{\left\{L - \frac{(N_2 + N_1)}{2}\right\}^2 - \frac{8(N_2 - N_1)^2}{4\pi^2}}\right] \tag{11.12}$$

It should be restated that the chain length, L, in Equation (11.12) must be stated in the number of links.

The *angle of contact*, θ, is a measure of the angular engagement of the chain on each sprocket. It can be computed as

$$\theta_1 = 180° - 2\sin^{-1}\left\{\frac{p(N_2 - N_1)}{2C}\right\} \tag{11.13}$$

$$\theta_2 = 180° + 2\sin^{-1}\left\{\frac{p(N_2 - N_1)}{2C}\right\} \tag{11.14}$$

Chain manufacturers suggest keeping the angle of contact greater than 120° when possible.

Finally, when in operation, chains have a tight side and a slack side. In most applications, chain drives should be designed so that the slack side is on the bottom or lower side. Due to the direction of shaft rotation and the relative positions of the drive and driven shafts, the arrangement shown in Figure 11.12 has the slack side on the bottom.

11.7 CHAIN DRIVE KINEMATICS

Once again, the *velocity ratio*, VR, is defined as the angular speed of the driver sprocket (sprocket 1) divided by the angular speed of the driven sprocket (sprocket 2). Using the same derivations as for gear and belt drives, the velocity ratio consists of

$$VR = \frac{\omega_{\text{driver}}}{\omega_{\text{driven}}} = \frac{\omega_1}{\omega_2} = \frac{d_2}{d_1} = \frac{N_2}{N_1} \tag{11.15}$$

Because a ratio is valid regardless of units, the velocity ratio can be defined in terms of revolutions per minute, radians per time, or any other convenient set of rotational velocity units. Many industrial applications require chains to reduce the speed of a power source. Therefore, it is typical to have velocity ratios greater than 1. As can be seen from equation (11.15), this indicates that the drive sprocket rotates faster than the driven sprocket, which is the case in speed reductions.

Similar to belts, the linear velocity of the chain, or *chain speed*, is defined as v_c. The magnitude of this velocity corresponds to the magnitude of the linear velocity of a point on the pitch diameter of each sprocket. As with belt speed, chain speed can be computed by

$$v_c = \frac{d_1}{2}\omega_1 = \frac{d_2}{2}\omega_2 \tag{11.16}$$

In equation (11.16), the rotation velocities must be stated in radians per unit time.

Lubrication for the chain is important in maintaining long life for the drive. Recommended lubrication methods are primarily dictated by the speed of the chain. The recommended lubrication is as follows:

- Low speed ($v_c < 650$ fpm): manual lubrication, where the oil is periodically applied to the links of the chain.
- Moderate speed ($650 < v_c < 1500$ fpm): bath lubrication, where the lowest part of the chain dips into a bath of oil.
- High speed (1500 fpm $< v_c$): oil stream lubrication, where a pump delivers a continuous stream onto the chain.

EXAMPLE PROBLEM 11.3

A single-strand roller chain drive connects a 10-hp engine to a lawn waste chipper/shredder, as shown in Figure 11.13. As the engine operates at 1200 rpm, the shredding teeth should rotate at 240 rpm. The drive sprocket has 18 teeth. Determine an appropriate pitch for the chain, the number of teeth on the driven sprocket, the pitch diameters of both sprockets, and the chain speed. Also indicate the number of links in a suitable chain and specify the required center distance.

$$d = \frac{p}{\sin(180/N)}$$