separated by a distance \( s_1 + s_2 \), it must be calculated to resist bending. Taking the crank at right angles to the guide, as the most unfavorable position, and calling the pressure \( Q \), and the distances of the two points of support from the centre of the cross head as \( s_1 \) and \( s_2 \), Fig. 543, we have the bending moment of the bar \( = \frac{Q}{2}(s_1 + s_2) \), and for the relation between the depth and width of bar:

\[
\delta = \sqrt{\frac{O \cdot Q}{S \cdot \left(s_1 + s_2\right)}}
\]  

(177)

The permissible value of stress \( S \) for wrought iron or steel should be small, say 7000 pounds, in order that but little deflection shall occur. Any springing is especially hurtful in this case, since it prevents the entire surface of the slides from bearing fairly, and thus causes greatly increased pressure upon the points which are in contact. Deflections of \( 1/100 \) or more are sometimes found, with corresponding irregular wear upon the slides. This subject can be thoroughly investigated graphically by taking the various positions of the load.

In Fig. 544 is shown a form of cast iron guides, intended to receive pressure only upon the lower guide. This is only subject to compression, and hence very little deflection can occur.

**Fig. 544.**

The sectional view on the left shows the disposition of the material, and it will be noticed that the flanges on the cross head are turned so as to retain the oil. The upper guide is bolted to the lower, and should the motion be reversed, throwing the pressure on the upper guide, the bolts must be made proportionally stronger.

A form of guides which is coming more and more into use for stationary engines is that shown in Fig. 545. Here the flat guide surfaces are replaced by portions of a cylinder. An especial advantage of this construction lies in the possibility of boring the guide surfaces in exact alignment with the cylinder. Any twisting of the cross head is prevented by the connecting rod and crank pin, or, if necessary, a tongue on the lower slide may fit into a groove in the guide.

**Fig. 545.**

The cross head for such guides may be similar to Fig. 537, the lower guide being adjusted by a key.

The single guide bar has been used in locomotive practice, Fig. 546, which was shown both on American and Belgian engines at the Paris Exposition of 1878. The guide is bolted to the cylinder at \( C \), and to the axle at \( A \). The cross head is a simple modification of the form in Fig. 532. Engineer J. J. Birkedl has shown that there is a heavy lateral force on such a guide bar, due to the necessary end play in the driving axles, and a wide bar is therefore necessary. He makes the width \( \delta = 2\frac{5}{4} / \delta \), and makes

\[
h = \text{const.} \sqrt{\frac{G H}{Q}}
\]

in which \( G \) is the weight of the parts subject to lateral vibration, \( Q \) the normal component of the piston pressure, \( L \) the length of guide bar, and \( H \) the distance from centre of bar to centre of rod. In the case of a cylinder \( \frac{12}{16} \) inch diameter at 100 lbs. steam pressure, \( G = 8900 \), \( L = 51.2 \) and \( H = 75.2 \), the values obtained are: \( \delta = 8\frac{7}{16}, h = 3\frac{7}{16} \).

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**Fig. 547.**

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THE TWO APPLICATIONS OF FRICTION WHEELS.

Direct acting friction wheels may be used to accomplish either one of two different functions and their construction varies according to the use to which they are put.

The first application is that in which the wheels are pressed together with sufficient force to prevent the surfaces from slipping upon each other, under which circumstances the motion of one wheel will be transmitted to the other.

The second application is that in which the so-called rolling friction is employed, the motion of friction wheels, when interposed between two surfaces which are relatively in motion, act to reduce the otherwise injurious frictional resistance.

Hence we see that friction wheels may be used:

(a) To transmit motion, and

(b) To reduce resistance.

The first application includes what may be called driving friction wheels, or commonly simple friction wheels, and the second application includes all the various forms of friction rollers, roller bearings, ball bearings, and the like. The two kinds have also been termed friction wheels and anti-friction wheels.

FRICION WHEELS FOR PARALLEL AXES.

The surfaces of a pair of friction wheels in contact are almost always of circular curvature, and when a pair of such wheels roll freely upon each other the number of revolutions will bear an inverse relation to the radii of the respective circles. This ratio is called the velocity ratio of the wheels. If we call the revolutions per minute of each wheel \( n \) for the driver and \( n_1 \) for the driven wheel; and the corresponding radii \( R \) and \( R_1 \); we have for the velocity ratio:

\[
\frac{n}{n_1} = \frac{R_1}{R} \tag{178}
\]

Friction wheels for parallel axes are made with cylindrical surfaces. Fig. 548. In order that there shall be no slipping between the surfaces we must have a pressure \( Q \) which, to transmit a force \( P \) at the periphery of the wheels, must not be less than

\[
Q = \frac{P}{f} \tag{179}
\]

Where \( f \) is the co-efficient of friction.

The value of \( f \) for various materials may be taken as follows:

- For Iron on Iron ........... 0.10 to 0.30
- Wood on Iron ........... 0.10 to 0.20
- Wood on Wood ........... 0.40 to 0.60

Friction driving is often very simple and practically effective. It had been almost neglected for general uses, when it was very successfully applied in various forms of saw mill machinery. This was especially the case in the lumber regions of America.

The best results are obtained in practice from surfaces of wood on iron, the wooden surface being preferable to the driver, so that any stoppage on starting shall not wear hollows in the softer material. The rim is built up in such a manner as to place the grain of the wood as nearly as possible in the direction of its sufficient force to prevent slipping. The wood for the purpose is maple, but limber, poplar, and pine have been used with good results. Great care must be taken to make the wheels truly cylindrical, and they should be key and bolted upon their axles and finished with the best in their own proper bearings. Under these conditions a wheel of maple can transmit a circumferential force of about 28 pounds per inch of face width, or from 15 to 20 pounds for the other woods above mentioned.

This gives for maple face:

\[
b = \frac{2}{25} \times 180 (HP) \tag{180}
\]

and a width 1½ to 2 times greater for other woods, \( HP \) being the horse power transmitted, and \( b \) the circular velocity in feet per minute. Substituting for \( 2 \pi b \), we have

\[
b = \frac{244}{\pi \times \frac{HP}{n}} \tag{181}
\]

Such wheels are made in practice up to 6 feet in diameter and 30 inches face, transmitting upwards of 500 horse power. According to the experiments of Wickham, the coefficient of friction is about 0.40 to 0.50, from which the pressure of contact must be \( Q = 3 \frac{1}{2} P \). The case with which these wheels can be thrown out of gear is a very convenient feature.

Example 1. Let \( HP \) be required to be transmitted by friction wheels, the speed of shaft being 60 revolutions per minute, and a circumferential velocity of 120 feet per minute given. We get from (166) \( b = \frac{180}{\pi} \times \frac{HP}{(60) \times \frac{120}{12}} \).

If the driven shaft is run at 200 revolutions per minute, the radius of the wheel will be \( R_1 = \frac{120}{200} \times 0.8 \times 0.5 = 0.3 \). If pine is used, this should be doubled, giving \( b = 0.68 \) ft.

The method of construction of these wheels is as follows: For large wheels, 4 to 10 feet in diameter, the rims are made from 6 to 7 inches deep, built up of wooden segments 1½ in. thick, forming 1½ to 2½ the circumference, and so placed that the direction of the fibre shall follow the circumference of the wheel as nearly as possible. These segments are firmly clamped together and secured by bolts or nails. The actual face is made about 2 in. narrower than the working face. This rim is then accurately fastened to the arms, which are very strong and made with feet or pads which are mortised into the rim and bolted and bolted fast. The number of arms varies from 6 to 8, and, for very wide faces, two sets are used; see Fig. 549. An additional ring of wood is then put on each side, bringing the width up to the full value of \( b \), and these outer segments are deeper than the others, so that the ends of the keys are entirely covered; the completed wheel is then turned and finished in place, as before stated.

Smaller wheels are built upon iron drums, the segments being screwed together and clamped between the outer rims, Fig. 550. Projections on the iron rim, let into wood, prevent the latter from turning. The total thickness of rim is about 4 in. Care must be taken that the wood is thoroughly dry.

The driven wheel of iron is made similar to a belt pulley, but with a much stronger rim and more and heavier arms; when a wider face than 18 in. to 18 in. double arms are used. Both wooden and iron wheels should be carefully balanced, in order to avoid vibration.

An important and ingenious use of friction wheels is in connection with a drop hammer. The wheels being used to raise the drop. Merrill's drop hammer, Fig. 554, is operated by two iron friction wheels A and B, which together act upon the oak plank B, to which the hammer drop is attached. The roller D is the driven one, and its shaft runs between bearings on each side, which are operated by levers D and press the parts together.
similar designs both rollers are driven, as in the hammer of Hotchkiss and Stiles, and also in the so-called "Precision Hammer," of Haase & Co., of Berlin.†

§ 194.
FRICITION WHEELS FOR INCLINED AXES.

When the axes are inclined to each other, the surfaces of the wheels, unless they are very narrow, become portions of cones, with a common apex at the intersection of the axes. Fig. 552. Each of these circles in the surface then roll together as if cylindrical. Wheels of this sort may be constructed in a similar manner to those described in the preceding section. In Fig. 553 are shown, at \( a \) and \( b \), two sizes of conical wooden friction wheels. The outer disk is placed with the axis in a radial direction, but the others have the grain of the wood arranged as nearly as possible circumferentially. These disks should be most carefully fitted, glued and bolted together. Especially important is it that conical surfaces should be turned to the correct angle. The pressure is applied from the end of one of the two shafts in such a manner that the force may be applied or removed at the thrust bearing.

The most extensive application of friction driving, both with cylindrical and conical surfaces, is found in locomotive engines. The high pressures necessarily used compel in this case the use of iron or steel tires. The force \( O \) here exceeds 6 tons.†

In some cases a combination of one conical wheel and one narrow wheel with rounded edge, as in Fig. 554, may be used for the transmission of small powers. In this case both wheels are made of iron. The pressure is easily applied to the disk wheel \( B \), and the mechanism is so arranged that it can be shifted along its axis, so that a variable speed motion is obtained. It must be noted that in this form the surfaces in contact are necessary very limited, and hence it is desirable, as in the case of friction couplings, to have the diameters as large as possible.

‡ German Patent No. 64. In this hammer the lower part of the plane is reduced, and the whole design very ingeniously worked out.

The surfaces in contact are usually finished. Braun’s experiments showed that, with a pressure of 12,000 pounds, a steel tire on an iron rail gave a surface of contact of slightly above 1 in., and with a pressure of 4000 pounds, a surface of over 2 sq. in. In the Pasture railway the pressure of contact was about 4 tons on each wheel.

and the linear velocity high, in order that the driving force may be kept as small as practicable. The most convenient modification of this form is that in which the angle \( \beta \) of the cone is made 180°, when we obtain a pair of friction disks, Fig. 555.

The velocity ratio, when \( A \) is the driver and \( B \) the driven, and \( x \) the distance from the axis of \( a \), is expressed by:

\[
\frac{n_1}{n} = \frac{x}{r}, \quad \text{which is} \quad \frac{n_1}{n} = \frac{x}{r} \quad \ldots \quad (182)
\]

when \( \beta = 180^\circ \). The change of velocity is expressed by the line \( ON \). If \( B \) is the driver and \( A \) driven, we have

\[
\frac{n_2}{n} = \frac{r}{x}, \quad \text{which is} \quad \frac{n_2}{n} = \frac{r}{x} \quad \ldots \quad (183)
\]

when \( \beta = 180^\circ \); \( a \) being the number of revolutions of \( B \). These are the equations of an equilateral hyperbola; see Fig. 555. When the value of \( x \) approaches zero, the driving of \( A \) by \( B \) becomes impracticable.†

† In the variable speed gear of LeCouër (German Patent 17,098) a loose disk is fixed in the centre of \( A \), so that if \( B \) approaches too near the centre the driving ceases.
‡ See Berliner Verhandlungen, 1886, p. 79. This arrangement has been used especially for regulating the speed of cotton-spinning machinery.
thin disks, all loose upon the shaft. This does not appear to be advantageous in view of formula (184), since there is a different ratio for each disk, and hence some of them must slip.

A similar device is that of Bahruth, Fig. 558, in which the disk is placed between two cones.

\[ \text{Fig. 557.} \]

By making two of the disks fast on one shaft, and placing the driving wheel between them, with sufficient clearance to enable either to be brought in contact with the driver, the driven shaft may be operated in either direction or allowed to remain at rest. Fig. 559. \( A_1, A_2 \) are the driven, and \( B \) the driver. This is ingeniously applied in Cheret's Press, in which the screw of the press is on the axis of \( B \), and is turned in either direction by the friction wheels.

\[ \text{Fig. 558.} \]

\[ \text{Fig. 559.} \]

FRICITION WHEELS WITH INCLINED AXES NOT INTERSECTING.

In the case of friction wheels whose axes are rigidly held, and while inclined, do not intersect each other, there is always more or less lateral slipping. The figures which, under these conditions, exert a maximum amount of rolling action and a minimum of slipping are a pair of hyperboloids of revolution (see § 218). If, however, the axes are so arranged as to permit longitudinal motion, either with the bearings or in them, the wheels will be relieved from slipping. Such an arrangement, by Robertson, is shown in Fig. 560.† The disk \( A \) acts upon a cylinder \( B \), the axis of which makes a small angle with that of \( A \). When the disk \( A \) is revolved, it rolls a helical path upon the cylinder, and also moves in the direction of its axis. The angle \( \alpha \) corresponds to the angle of the screw thread. Robertson has applied this device as a feed motion to a wood lathe. This arrangement may also be reversed, \( A \) being held in its bearings, and \( B \), with its bearings, permitted to travel. The same principle may be used with cones on disks, but the devices appear to possess limited practical application.

Friction wheels, the axes of which coincide, are the same as friction couplings.

\[ \text{§ 196.} \]

WEDGE FRICTION WHEELS.

Wedge friction wheels are those in which the cross section of the rim is wedge-shaped. They were designed in Italy by Minotto and in England by Robertson, and are also known by both names; in both cases being applied to wheels with parallel axes. Two forms of rim section are given in Fig. 561. In this case the radial pressure \( Q \) is much less than with cylindrical wheels, and for any wedge angle \( \theta \) it is equal to

\[ Q = P \left( \sin \frac{\theta}{2} + \sqrt{\cos \frac{\theta}{2}} \right) \]  

(184)

A disadvantage of this form is the fact that true rolling action only takes place in one cylindrical section through each rim, and hence there is much harmful friction from the slippage at other points; this defect becomes less as the ratio of the wedge depths \( h, k \) to the radii \( R_1, R_2 \) diminishes.† In order that the ratio \( h/k \) and \( h/k \) may be kept as small as possible without reducing the surface of contact, the rim is made with multiple grooves, as in the form of the right. The angle \( \theta \) is generally made \( = 30^\circ \), although Robertson made much smaller angles.

\[ \text{Fig. 560.} \]

\[ \text{Fig. 561.} \]

These wheels grow warm and wear rapidly when operated continuously at high speeds. Minotto has also made special efforts to design bevel wedge friction wheels; he uses only one groove, and adjusts the position so that wedge profile shall always act at the same point. Robertson makes the grooves non-adjustable, as in spur wheels. Wedge friction driving has been proposed for locomotive driving, and models made on this plan have ascended steep grades; the wear in this case comes mainly upon the track.

Wedge friction wheels have been used in America for many years on winding engines; and they are especially useful in driving ship's windlasses, on account of the ease with which they can be thrown in and out of gear.† More recently wedge friction wheels have been used by Gwynne and also by Weber in Berlin, at high speeds, and apparently with good endurance.

† Hansen, in Engineering's Journal, vol. 105, p. 352, says that the normal rolling circle is always on that portion of the wedge surface towards the driving wheel, and changes its position when the driver becomes the driven. See also Ad. press. in Zeit. chem. V. W. deutcher ingenieur, 2nd ed., p. 543.

† H. D. Andrews' steam windlasses are made with wedge gear of from 4 to 8 grooves. The diameters of the friction wheels are as follows:

| HP. | Slow speed | Fast speed | Drum
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<tr>
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<tr>
<td>5</td>
<td>40&quot;</td>
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<td>5&quot;</td>
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<tr>
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<td>38&quot;</td>
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<tr>
<td>18</td>
<td>34&quot;</td>
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† See Engineer, June, 1860, p. 454; also H. König, German patent No. 2526.

† See Engineer, 1867, p. 450, in which many interesting designs by Robertson are given.
driving centrifugal pumps at 700 revolutions per minute. These wheels are with single groove and wedge, the wedge being of curved profile, and hence acting somewhat like the adjustable device of Minard.  

![Diagram of a single-groove friction wheel](image)

**Fig. 562.**

Single-groove friction wheels have also been used in America for mill gearing.  

Sellers has devised an ingenious form of wedge friction gear for changing the rate of feed on engine lathes. This is composed, Fig. 563, of two simple disks and a pair of very obtuse cone plates, the latter being pressed together by springs. The axis of the cone plates is movable, thus giving change of speeds. The ratio of change is similar to Rupp's gearing, formula (184).  

§ 197.

**Special Applications of Friction Wheels.**

The previously stated condition of wedge friction wheels, that there is but one line at which rolling action takes place, and that slipping occurs at all other points of contact, is utilized in various methods in machine design, as, for example, in rolling mill machinery.

In this case a third place is driven, compressed and altered in form between two friction rolling members. The rolls and the metal may be considered as a train of friction gearing. In the case of a plate mill, the plate may be considered a pair of friction wheels of infinitely great radii; this is also the case in rolling bars. In a bar mill one surface is an internal and one external wheel, of variable radius. The thicken mill may be similarly compared to a train of friction gears.  

![Diagram of friction wheel application](image)

**Fig. 563.**

A very interesting application is that referred to in § 196, as in use at the Kirkstall Forge, and shown in Fig. 563. A and B are plane friction disks. The round bar C passes between them, slightly above the centre and partly rolling, partly sliding, receives both an endwise motion and a motion of revolution upon its axis. The disks revolve in the same direction, and of the opposed forces which tend to cause revolution of the bar those which act in the portion of the disks between their axes, i.e., between the vertical dotted lines in the figure, preponderate, and determine the direction in which the round bar revolves. The horizontal components of the sliding forces at all points of the disks, act to carry the bar forward, so that it receives a combined spiral motion and is at the same time rolled and straightened. The earlier method of rolling round bars was by means of semicircular grooves, but this does not give either round or as straight a product. Many similar examples in rolling mill machinery will be found, resembling friction driving gear.

In the same way, various forms of grinding mills are made upon the principle of friction combinations, as in the case of the Bogardus mills, with flat grinding disks, and also in the case of grinding rollers, Fig. 564. Here the round trough A revolves, and in it act the rollers B, B, and the width of face of the rollers compels a sliding action, forward on the outer edge and backward on the inner. The trough may be stationary and the shaft C, carrying the rollers, revolve. Rollers with inclined axes are also used for grinding, and a similar device has been made for straightening round rods.  

![Diagram of grinding mill](image)

**Fig. 564.**

§ 198.

**Roller Bearings.**

Roller bearings, sometimes called anti-friction rollers, may be used in either of two forms:  

(a) in such manner that the rollers are carried in their own bearings, the latter receiving the load;  

(b) in such manner that the rollers are placed between two moving surfaces and act with a rolling motion upon both of them.

Roller bearings are used in connection with surfaces which are flat, round, or even spiral. Examples of rollers upon cylindrical surfaces are given in Fig. 565, in which a and b are rollers used on pillar cranes, and c is the more general form of roller. Rollers are also used in axle bearings, and in heavy pulley blocks, where indeed the shafts themselves are a form of friction roller.  

![Diagram of roller bearings](image)

**Fig. 565.**

A form of roller bearing which is subject to very heavy loads is that used to carry the ends of bridge beams and trusses, to provide for expansion and contraction. These are made either with round rollers, as at a, Fig. 566, or with double segments, as at b.

For round, solid rollers, the load may approximately be investigated as follows: Let t be the length, r the radius of each roller, and P the load. This load will be carried by a surface of a width δ, included in the angle (measured at the centre of the roller) π/3.

We have for the relation of these elements:  

\[ P = \frac{t}{36} \sqrt{E} \sqrt{S} \]  

and  

\[ S = \frac{0.83 \sqrt{E}}{L} \]  

\[ \frac{P}{L} = \frac{4}{3} \sqrt{\frac{S}{E}} \]

E being the modulus of elasticity, and S the stress upon the material.  

Also,  

\[ S = 0.83 \sqrt{E} \sqrt{\frac{P}{t}} \]

It will be seen that for any given material the relation \( \frac{P}{t} \) can be so made as to keep the stress within practicable limits.  

*See Engineer, 1889, pp. 90, 92, and 1899, p. 515. Engineer Drum, instructor in the Royal Technical High School, has attempted to adapt the principle of the Western Church (359) to friction wheels. The bearings are made of a number of thin plates, with rubber washers between them, and a slight axial pressure is sufficient to cause them to grip each other with much friction. A description will be found in Berlin Verhandlungen, 1877, p. 956.