Section 13

Machine Elements

Machine elements is the term given to the set of basic mechanical components that are used as building blocks to make up a mechanical product or system. There are many hundreds of these – the most common ones are shown, subdivided into their common groupings, in Fig. 13.1. The established reference source for the design of machine elements is:

Shigley, J. E. and **Mischke, C. R.** *Standard Handbook of Machine Design*, 1986 (McGraw-Hill).

13.1 Screw fasteners

The ISO metric thread is the most commonly used. They are covered by different standards, depending on their size, material, and application.

Engineers' Data Book, Fourth Edition. Clifford Matthews.

Locating

- **Threaded fasteners**
  - Nuts and bolts
  - Set screws
  - Studs
  - Grub screws
  - Expanding bolts
- **Keys**
  - Flat
  - Taper
  - Woodruff
  - Profiled
- **Pins**
  - Split
  - Taper
- **Spines**
- **Retaining rings**
- **Clamps**
- **Clips**
  - Circlips
  - Spring
- **Shoulders and grooves**

Drives and mechanisms

- **Shafts**
  - Parallel
  - Taper
  - Concentric
- **Mechanisms**
  - Crank and sliding
  - Ratchet and pawl
  - Genera
  - Scotch-yoke
  - Carden joint
- **Cams**
  - Constant velocity
  - Uniform accelleration
  - Simple harmonic motion (shm)
- **Clutches**
  - Dog
  - Cone
  - Disc
  - Spring
  - Magnetic
  - Fluid coupling
- **Brakes**
  - Disc
  - Drum
- **Couplings**
  - Rigid
  - Flexible
  - Spring
  - Membrane
  - Cordon
  - Claw

Energy transmission

- **Gear trains**
  - Spur
  - Helical
  - Bevel
  - Worm and wheel
  - Epicyclic
- **Belt drives**
  - Flat
  - Vee
  - Wedge
  - Synchronous
- **Chain drives**
  - Roller
  - Conveyor
  - Leaf
- **Pulleys**
  - Simple
  - Differential
- **Springs**
  - Tension
  - Compression

Rotary bearings

- **Rolling**
  - Ball
  - Roller (parallel)
  - Roller (tapered)
  - Needle
  - Self-aligning
- **Sliding**
  - Axial
  - Radial
  - Bush
  - Hydrodynamics
  - Hydrostatic
  - Self-lubricating
  - Sideways

Dynamic sealing

- **Rotating shaft seals**
  - Face
  - Interstilial
  - Axial radial
  - Bush
  - Labyrinth
  - Lip ring
  - Split ring
- **Reciprocating shaft seals**
  - Piston rings
  - Packing rings

Figure 13.1

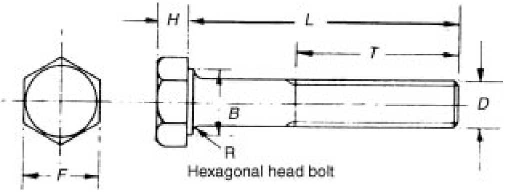


Figure 13.2

USEFUL STANDARDS

1. BS 4190: 2001: Specification for ISO metric black hexagon bolts, screws and nuts. (The term `black' implies loose tolerances for non-precision applications, dia. 5–68 mm.) Similar to ISO 272.
2. BS 3692: 2001: Specification for ISO metric precision hexagon bolts, screws and nuts. (Covers dia. 1.6–68 mm.)
3. BS 3643: ISO metric screw threads.
   Part 1: 1998: Principles and basic data. [Gives data for dia. 1.0–300 mm (see also ISO 68/ISO 261/ISO 965).]
   Part 2: 1998: Specification for selected limits of size. (Gives size data for ISO coarse threads dia. 1.0–68 mm and ISO fine threads dia. 1.0–33 mm.)
4. DIN 13 Part 1: ISO metric screw threads.

Typical BS 3692 sizes (all in mm) are shown in Table 13.1.

Table 13.1

Size	*Pitch*	*Width A/F (F)*		*Head height (H)*		*Nut thickness (m)*	
		Max.	*Min.*	*Max.*	*Min.*	*Max.*	*Min.*
M5	0.8	8.00	7.85	3.650	3.350	4.00	3.7
M8	1.25	13.00	12.73	5.650	5.350	6.50	6.14
M10	1.5	17.00	16.73	7.180	6.820	8.00	7.64
M12	1.75	19.00	18.67	8.180	7.820	10.00	9.64
M20	2.5	30.00	29.67	13.215	12.785	16.00	15.57

13.1.1 Nuts and washers

Useful standards are shown below.

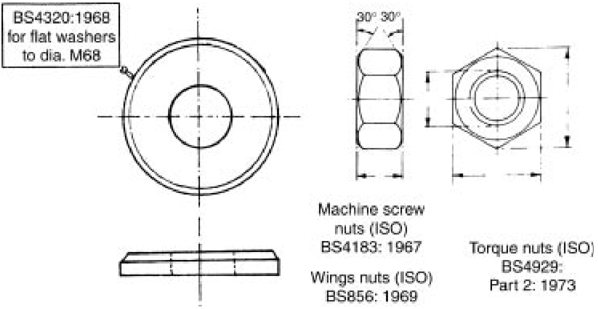


Figure 13.3

13.2 Bearings

13.2.1 Types

Bearings are basically subdivided into three types: sliding bearings (plane motion), sliding bearings (rotary motion) and rolling element bearings (see Fig. 13.4). There are three lubrication regimes for sliding bearings:

- *Boundary lubrication* There is actual physical contact between the surfaces.
- *Mixed-film lubrication* The surfaces are partially separated for intermittent periods.
- *Full-film 'hydrodynamic' lubrication* The two surfaces 'ride' on a wedge of lubricant.

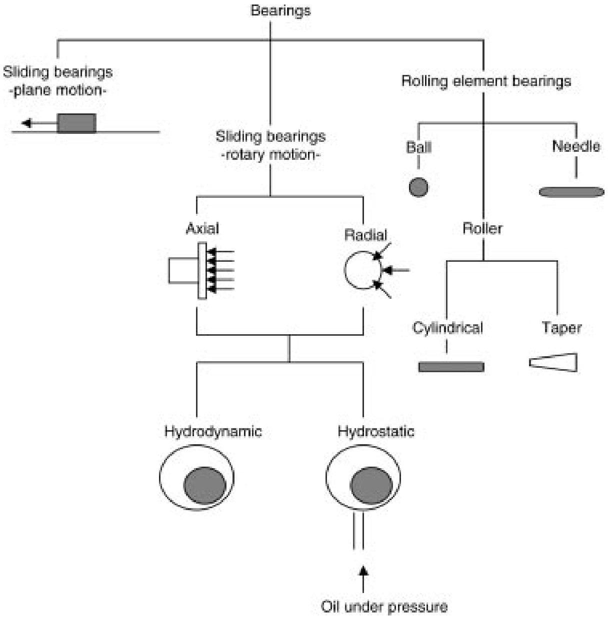


Figure 13.4

13.3 Ball and roller bearings

Some of the most common designs of ball and roller bearings are as shown. The amount of misalignment that can be tolerated is a critical factor in design selection. Roller bearings have higher basic load ratings than equivalent sized ball-types.

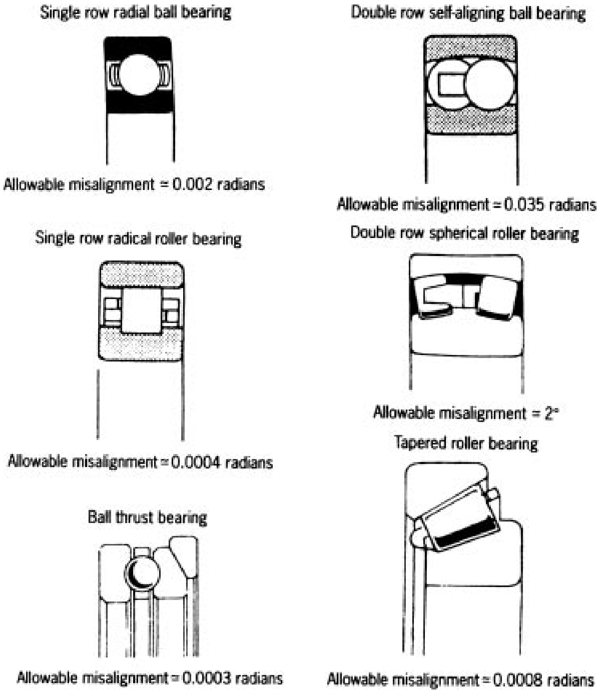


Figure 13.5

13.4 Bearing lifetime

Bearing lifetime ratings are used in purchasers' specifications and manufacturers' catalogues and datasheets. The rating life (L_{10}) is that corresponding to a 10% probability of failure and is given by:

$$\begin{aligned}
\mathrm{L}_{10}\ \text{radial ball bearings} &= (\mathrm{Cr}/\mathrm{Pr})^{3} &&\times\ 10^{6}\ \text{revolutions}\\
\mathrm{L}_{10}\ \text{radial roller bearings} &= (\mathrm{Cr}/\mathrm{Pr})^{10/3} &&\times\ 10^{6}\ \text{revolutions}\\
\mathrm{L}_{10}\ \text{thrust ball bearings} &= (\mathrm{Ca}/\mathrm{Pa})^{3} &&\times\ 10^{6}\ \text{revolutions}\\
\mathrm{L}_{10}\ \text{thrust roller bearings} &= (\mathrm{Ca}/\mathrm{Pa})^{10/3} &&\times\ 10^{6}\ \text{revolutions}
\end{aligned}$$

Cr and Ca are the static radial and axial load ratings that the bearing can theoretically endure for 10^6 revolutions. Pr and Pa are corresponding dynamic equivalent radial and axial loads.

So, as a general case:

Roller bearings: L_{10} lifetime $= [16667(C/P)^{10/3}]/n$

Ball bearings: L_{10} lifetime $= [16667(C/P)^{3}]/n$

where

$$\left.\begin{array}{l} C = \mathrm{Cr\ or\ Ca} \\ P = \mathrm{Pr\ or\ Pa} \end{array}\right\}\text{as appropriate}$$

n = speed in rev/min

13.5 Coefficient of friction

The coefficient of friction between bearing surfaces is an important design criterion for machine elements which have rotating, meshing, or mating parts. The coefficient value (μ) varies depending on whether the surfaces are static or already sliding, and whether they are dry or lubricated. Table 13.2 shows some typical values.

Table 13.2 Typical friction coefficients

	Static		*Sliding*	
Material	*Dry*	*Lubricated*	*Dry*	*Lubricated*
Steel/steel	0.75	0.15	0.57	0.10
Steel/cast iron	0.72	0.20	0.25	0.14
Steel/phosphor bronze	–	–	0.34	0.18
Steel/bearing 'white metal'	0.45	0.18	0.35	0.15
Steel/tungsten carbide	0.5	0.09	–	–
Steel/aluminium	0.6	–	0.49	–
Steel/Teflon	0.04	–	–	0.04
Steel/plastic	–	–	0.35	0.06
Steel/brass	0.5	–	0.44	–
Steel/copper	0.53	–	0.36	0.2
Steel/fluted rubber	–	–	–	0.05
Cast iron/cast iron	1.10	–	0.15	0.08
Cast iron/brass	–	–	0.30	–
Cast iron/copper	1.05	–	0.30	–
Cast iron/hardwood	–	–	0.5	0.08
Cast iron/zinc	0.85	–	0.2	–
Hardwood/hardwood	0.6	–	0.5	0.17
Tungsten carbide/tungsten carbide	0.2	0.12	–	–
Tungsten carbide/steel	0.5	0.09	–	–
Tungsten carbide/copper	0.35	–	–	–

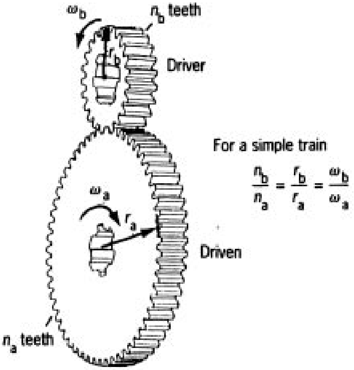
Note: The static friction coefficient between like materials is high, and can result in surface damage or seizure.

13.6 Gear trains

Gear trains are used to transmit motion between shafts. Gear ratios and speeds are calculated using the principle of relative velocities. The most commonly used arrangements are simple or compound trains of spur or helical gears, epicyclic, and worm and wheel.

13.6.1 Simple trains

Simple trains have all their teeth on their 'outside' diameter.



For a simple train

$$\frac{n_b}{n_a} = \frac{r_b}{r_a} = \frac{\omega_b}{\omega_a}$$

Spur gears – simple train

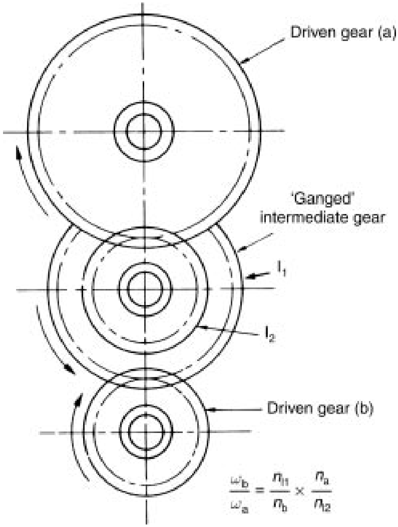
If an idler gear of radius r_i and n_i teeth is placed in the train, it changes the direction of rotation of the driver or driven gear but does not affect the relative speeds.

Figure 13.6

13.6.2 Compound trains

Speeds are calculated as follows.

Hence the number of teeth on the idler gear does affect the relative speeds of the driver and driven gear.

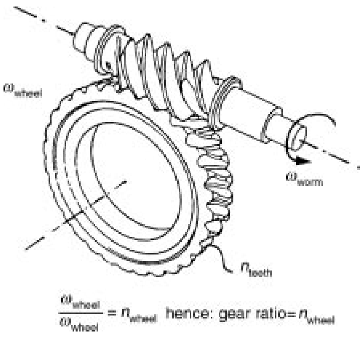


$$\frac{\omega_b}{\omega_a} = \frac{n_{I1}}{n_b} \times \frac{n_a}{n_{I2}}$$

Figure 13.7

13.6.3 Worm and wheel

The worm and wheel is used to transfer drive through 90°, usually incorporating a high gear ratio and output torque. The wheel is a helical gear.



$$\frac{\omega_{wheel}}{\omega_{wheel}} = n_{wheel} \text{ hence: gear ratio} = n_{wheel}$$

Figure 13.8

13.6.4 Double helical gears

These are used in most high-speed gearboxes. The double helices produce opposing axial forces which cancel each other out.

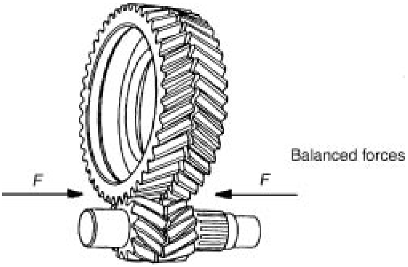


Figure 13.9

13.6.5 Epicyclic gear

An epicyclic gear consists of a sun gear on a central shaft, and several planet gears which revolve around it. A second coaxial shaft carries a ring gear whose internal teeth mesh with the planet gears. Various gear ratios can be obtained depending upon which member is held stationary (by friction brakes). An advantage of epicyclic gears is that their input and output shafts are concentric, hence saving space.

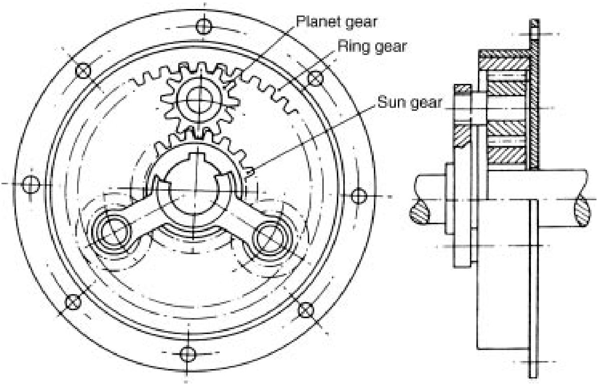


Figure 13.10

13.6.6 Gear nomenclature

Gear standards refer to a large number of critical dimensions of the gear teeth. These are controlled by tight manufacturing tolerances. (See Fig. 13.11.)

USEFUL STANDARDS

1. ISO 1328: 1975: Parallel involute gears – ISO system of accuracy. This is a related standard to BS 436.
2. BS 436: Part 1: 1987: Basic rack form, pitches and accuracy.
3. BS 1807: 1988 (withdrawn): Specification for main propulsion gears and similar drives.
4. The AGMA (American Gear Manufacturers' Association) range of standards.
5. API 613: 2005: Special purpose gear units for refinery service.
6. BS 978 (various parts): Specification for fine pitch gears.
7. BS 4582: Part 1: 1990: Involute, spur and helical gears.
8. DIN 3990: 2002: Calculation of load capacity of cylindrical gears.

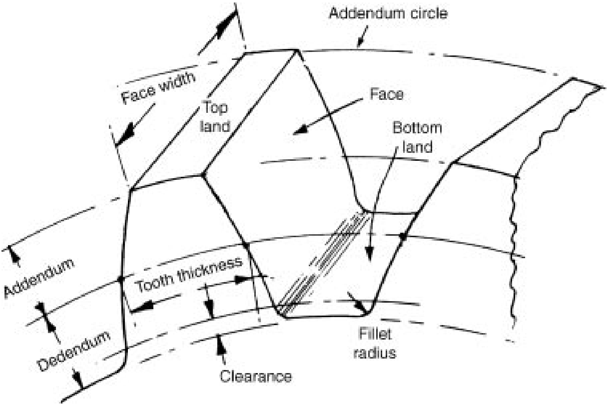


Figure 13.11

13.7 Seals

Seals are used to seal either between two working fluids or to prevent leakage of a working fluid to the atmosphere past a rotating shaft. They are of several types.

13.7.1 Bellows seal

This uses a flexible bellows to provide pressure and absorb misalignment.

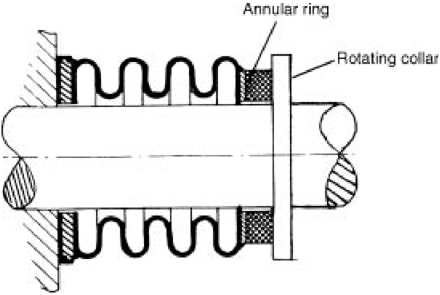


Figure 13.12

13.7.2 Labyrinth gland

This consists of a series of restrictions formed by projections on the shaft and/or casing. The pressure of the steam or gas is broken down by expansion at each restriction. There is no physical contact between the fixed and moving parts.

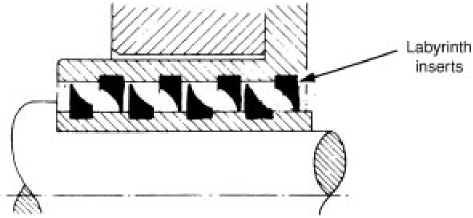


Figure 13.13

13.7.3 Mechanical seals

The key parts of a mechanical seal are a rotating ‘floating’ seal ring and a stationary seat or collar. Both are made of wear-resistant material and the floating ring is kept under an axial force from a spring (and fluid pressure) to force it into contact with its mating surface.

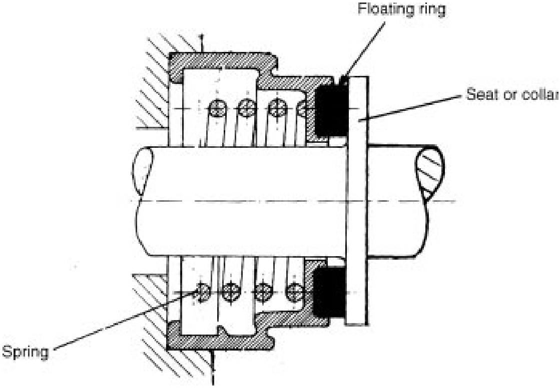


Figure 13.14

Mechanical seals are used to seal either between two working fluids or to prevent leakage of a working fluid to the atmosphere past a rotating shaft. They can work with a variety of fluids at pressures of up to 500 bar and sliding speeds of more than 20 m/sec. The core parts of the seal are the rotating 'floating' seal ring and the stationary seat (see Fig. 13.15).

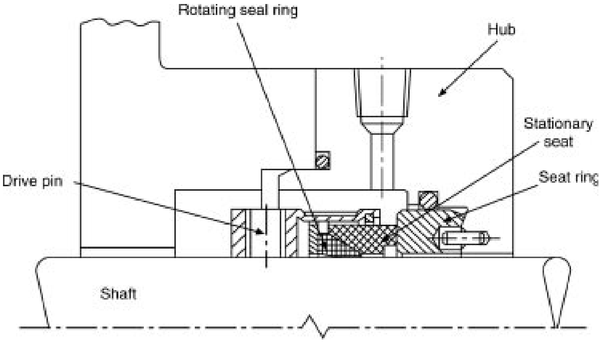


Figure 13.15

Web sites
www.flexibox.com
www.garlock-inc.com

13.8 Shaft couplings

Shaft couplings are used to transfer drive between two (normally co-axial) shafts. They allow either rigid or slightly flexible coupling, depending on the application.

13.8.1 Bolted couplings

The flanges are rigidly connected by bolts, allowing no misalignment. Positive location is achieved using a spigot on the flange face.

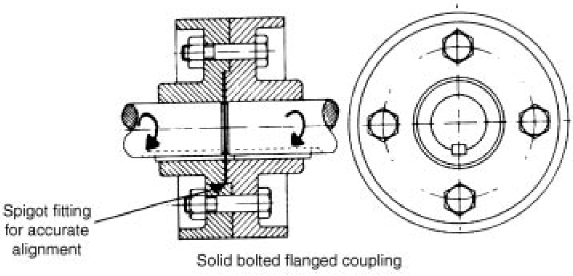


Figure 13.16

13.8.2 Bushed-pin couplings

Similar to the normal bolted coupling but incorporating rubber bushes in one set of flange holes. This allows a limited amount of angular misalignment.

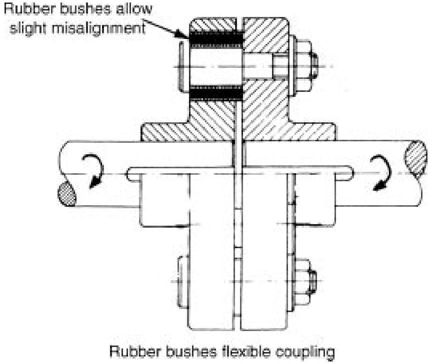


Figure 13.17

13.8.3 Disc-type flexible coupling

A rubber disc is bonded between thin steel discs held between the flanges.

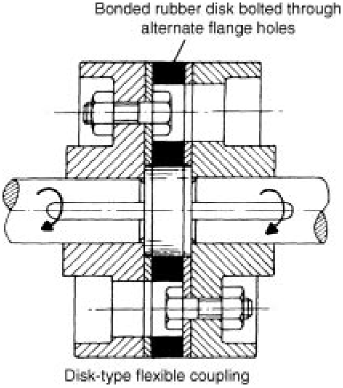


Figure 13.18

13.8.4 Diaphragm-type flexible couplings

These are used specifically for high-speed drives such as gas turbine gearboxes, turbocompressors, and pumps. Two stacks of flexible steel diaphragms fit between the coupling and its mating input/output flanges. These couplings are installed with a static prestretch – the resultant axial force varies with rotating speed and operating temperature.

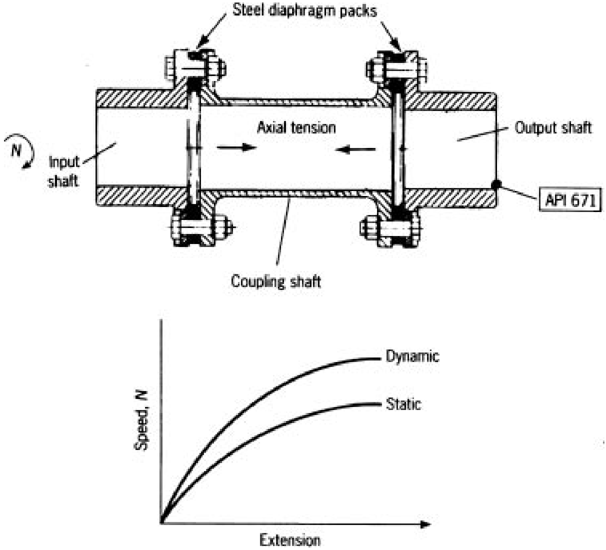


Figure 13.19

13.9 Cam mechanisms

A cam and follower combination are designed to produce a specific form of output motion. The motion is generally represented on a displacement/time (or lift/angle) curve. The follower may have knife-edge, roller, or flat profile.

13.9.1 Constant velocity cam

This produces a constant follower speed and is only suitable for simple applications.

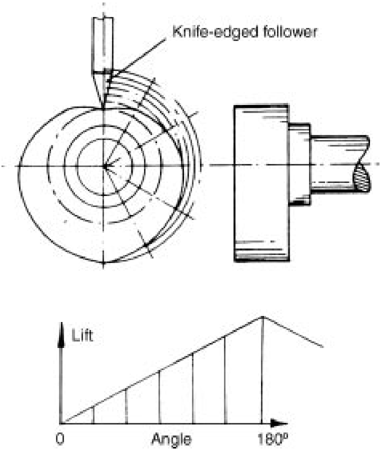


Figure 13.20

13.9.2 Uniform acceleration cam

The displacement curve is second-order function giving a uniformly increasing/decreasing gradient (velocity) and constant d^2x/dt^2 (acceleration).

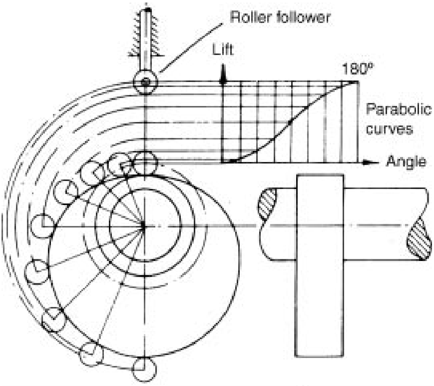


Figure 13.21

13.9.3 Simple harmonic motion cam

A simple eccentric circle cam with a flat follower produces simple harmonic motion (SHM).

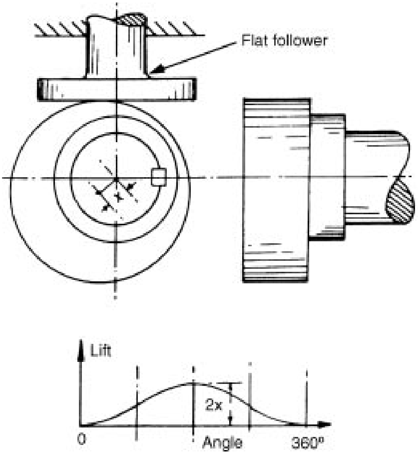


Figure 13.22

The motion follows the general SHM equations:

$$d^2x/dt^2 = -\omega^2 x$$

where

x = displacement
ω = angular velocity
T = periodic time
$dx/dt = -\omega a \sin \omega t$
$T = 2\pi/\omega$

13.10 Clutches

Clutches are used to enable connection and disconnection of driver and driven shafts.

13.10.1 Dog clutch

One half of the assembly slides on a splined shaft. It is moved by a lever mechanism into mesh with the fixed half on the other shaft.

The clutch can only be engaged when both shafts are stationary. Used for crude and slow-moving machines such as crushers.

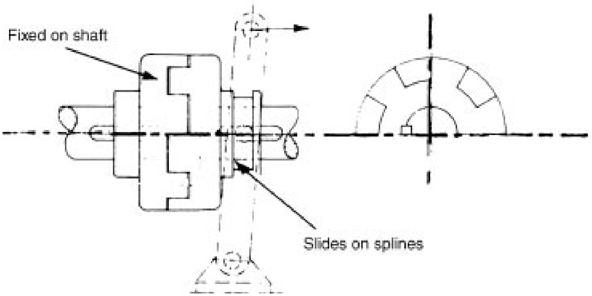


Figure 13.23

13.10.2 Cone clutch

The mating surfaces are conical and normally lined with friction material. The clutch can be engaged or disengaged when the shafts are in motion. Used for simple pump drives and heavy-duty materials handling equipment.

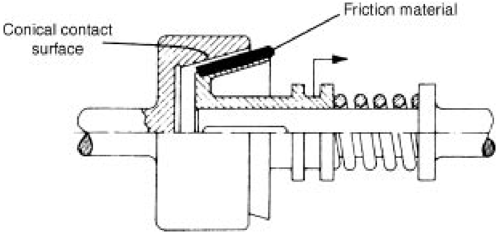


Figure 13.24

13.10.3 Multi-plate disc clutch

Multiple friction-lined discs are interleaved with steel pressure plates. A lever or hydraulic mechanism compresses the plate stack together. Universal use in cars and other motor vehicles with manual transmission.

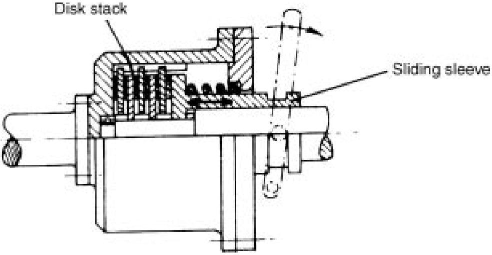


Figure 13.25

13.10.4 Fluid couplings

Radial-vaned impellers run in a fluid-filled chamber. The fluid friction transfers the drive between the two impellers. Used in automatic transmission motor vehicles and for larger equipment such as radial fans and compressors.

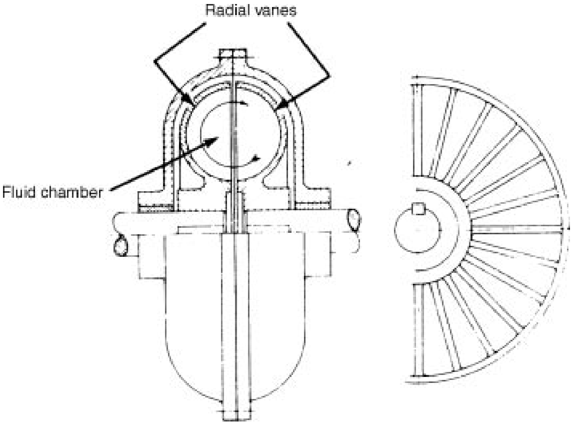


Figure 13.26

13.10.5 Clutch friction

The key design criterion of any type of friction clutch is the axial force required in order to prevent slipping. A general formula is used, based on the assumption of uniform pressure over the contact area.

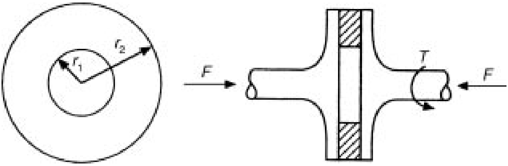


Figure 13.27

$$\text{Force } F = \frac{3T\left(r_2^2 - r_1^1\right)}{2\mu\left(r_2^3 - r_1^3\right)}$$

T = torque
μ = coefficient of friction

USEFUL STANDARDS

BS 3092:1988: Specification for main friction clutches for internal combustion engines.

13.11 Pulley mechanisms

Pulley mechanisms can generally be divided into either *simple* or *differential* types.

13.11.1 Simple pulleys

Velocity ratio, VR = the number of rope cross-sections supporting the load.

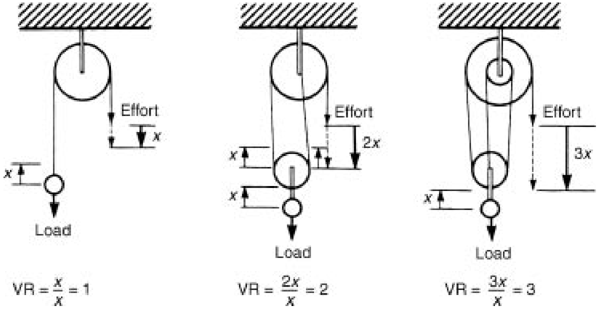


Figure 13.28

13.11.2 *Differential pulleys*

These are used to lift very heavy loads and consist of twin pulleys 'ganged' together on a single shaft.

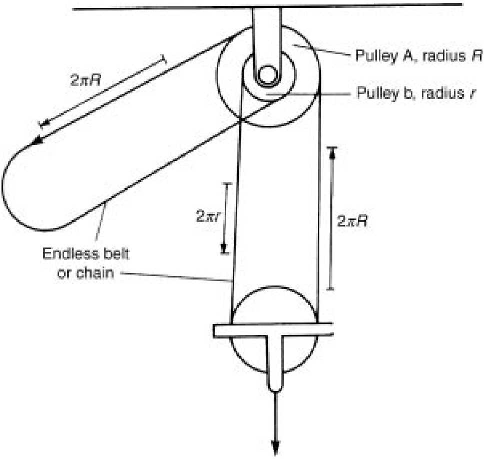


Figure 13.29

$$\mathrm{VR} = \frac{2\pi R}{\pi(R-r)} = \frac{2R}{R-r}$$

13.12 Drive types

The three most common types of belt drive are flat, vee, and ribbed. Flat belts are weak and break easily. Vee belts can be used in multiples. An alternative for heavy-duty drive is the 'ribbed' type incorporating multiple v-shaped ribs in a wide cross-section.

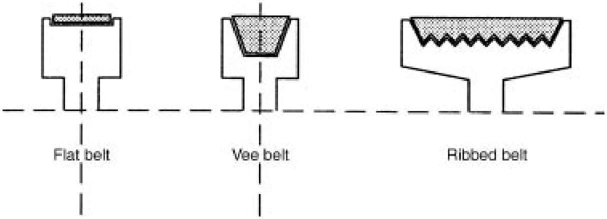


Figure 13.30