FLYWHEEL

Flywheel is a rotating mechanical device which stores rotational energy and releases it when needed. The main function of a flywheel is to even out variations in the speed or fluctuations of the shaft. For instance, when a vehicle or machine decelerates, kinetic energy is lost as heat through the brakes. Instead of wasting this energy, a flywheel can **store it and release it** later to assist the machine in starting again, thus improving efficiency.

Applications and Function

Flywheels are commonly used:

- In diesel engines, to smooth out power delivery after combustion pulses.
- In punching machines, where large energy bursts are required over short time intervals.
- In reciprocating compressors and presses, where the power demand fluctuates.
- In wind turbines, flywheels help stabilize output power by storing excess energy during strong winds and releasing it when the wind slows down.

Flywheels temporarily store energy during idle phases and release it during peak demands, reducing the required size of the motor and minimizing speed fluctuations.

Application: Punch Press

For a punch press that needs a high burst of energy in a short time, a flywheel provides the energy required for the actual punching, allowing the motor to simply restore that energy during the rest of the cycle. This enables use of a **smaller motor** and smooths machine operation.

Punch press

Engine Flywheel

Application: Diesel engines

In a diesel engine, the power is delivered in pulses—mainly during the combustion phase when fuel ignites. This creates an uneven flow of energy, causing the engine to speed up and slow down during each cycle. To smooth out these fluctuations, a flywheel is used. The flywheel is a heavy rotating disc attached to the crankshaft. When the engine produces excess power during the power stroke, the flywheel stores some of that energy by increasing its speed. Then, during the non-power strokes (intake, compression, and exhaust), when the engine isn't generating power, the flywheel releases its stored energy, helping to keep the crankshaft turning at a steady rate.

Types of Flywheels

Flywheels can be broadly categorized into two main types based on their operating speed and design characteristics: **High Velocity Flywheels** and **Low Velocity Flywheels**. Each type serves specific applications and comes with distinct advantages and limitations.

a) High Velocity Flywheel

High velocity flywheels operate at very high angular speeds—typically ranging from 30,000 rpm to 60,000 rpm, with some advanced designs capable of reaching up to 100,000 rpm. These flywheels are engineered to maximize energy storage while minimizing weight and volume. To achieve this, they are often built using advanced materials such as carbon fiber composites that can withstand the enormous centrifugal forces at high speeds.

Key characteristics:

- Equipped with magnetic levitation (maglev) bearings, which reduce friction and eliminate the need for lubrication, resulting in low maintenance requirements.
- Compact and lightweight, considering the amount of energy they can store.
- Used in cutting-edge energy storage systems (such as in satellites, electric grids, and high-performance hybrid vehicles).
- Expensive due to advanced materials and technologies.
- Housed in vacuum chambers to reduce aerodynamic drag and energy loss.

Applications: Regenerative braking in electric vehicles, satellite attitude control, grid energy storage, and high-performance buses.

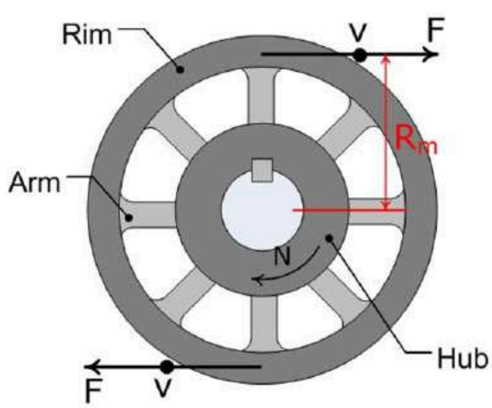
b) Low Velocity Flywheel

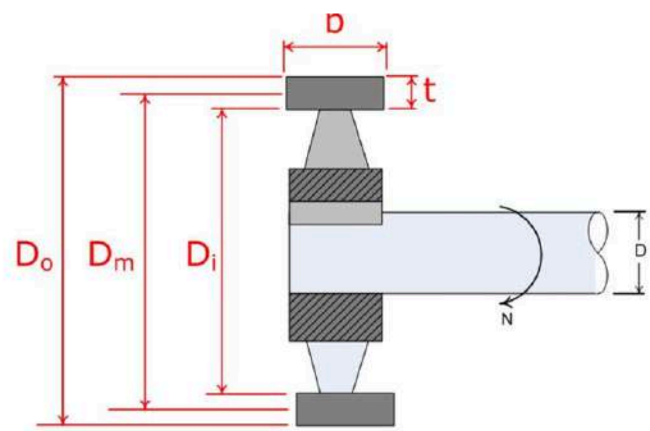
In contrast, low velocity flywheels operate at much slower speeds, typically up to 10,000 rpm. They are bulkier and heavier because they compensate for lower speeds by increasing mass to store equivalent energy. These are more traditional flywheels, often made from cast iron or steel, and are common in industrial or older mechanical systems like steam engines and locomotives.

Key characteristics:

- Do not use magnetic bearings—instead, they rely on conventional mechanical bearings that require regular lubrication and maintenance.
- Require massive support structures, such as concrete foundations, to handle the mechanical stresses and prevent vibration during operation.
- Cheaper than high-speed flywheels due to simpler materials and construction.
- Generate more mechanical stress due to their large size and inertia.

FUNDAMENTALS:





Kinetic energy (in terms of linear velocity)

$$KE = \frac{1}{2}\frac{F}{g_o}v^2 = \frac{1}{2}\frac{m}{g_c}v^2 \quad \text{eq. (1)}$$

Peripheral Speed or Velocity

$$v = \frac{\pi D_m N}{60}$$

$$v = \frac{2\pi R_m N}{60} = R_m\left[\frac{2\pi N}{60}\right]$$

$$v = R_m \omega$$

Substituting to eq. (1)

$$KE = \frac{1}{2}\frac{F}{g_o}R_m^2\omega^2 = \frac{1}{2}\frac{m}{g_c}R_m^2\omega^2$$

Moment of Inertia

$$I = \frac{F R_m^2}{g_o} = \frac{m R_m^2}{g_c}$$

For the kinetic energy (in terms of angular velocity)

$$KE = \frac{1}{2}I\omega^2 \qquad \text{eq. (3)}$$

Where:

D_m = mean diameter, in m

R_m = radius of gyration, in m

Radius of gyration is a measure of how far the material or mass of a body is distributed from its center. The farther it is, the harder it is to rotate or keep stable

N = rotative speed of the flywheel, in rpm

ω = angular velocity, in rad/s

F = unbalanced force/weight the flywheel, in N

m = mass of the flywheel, kg

I = moment of inertia, kg-m^2

g_c = proportionality constant, $\frac{kg-m}{N-s^2}$

g_o = observed gravitational acceleration, m/s^2

Volume of the flywheel:

$$V_{rim} = \pi D_m bt$$

Where: b = width
t = thickness

Mass density of the flywheel, ρ:

$$\rho = \frac{m}{V_{rim}}$$

Note: For cast iron $\rho_{cast\ iron}$ = 0.260 lb/in^3 = 7,200 lb/in^3
For cast steel $\rho_{cast\ steel}$ = 0.283 lb/in^3 = 7,850 lb/in^3

CHANGE IN KINETIC ENERGY

(in terms of linear velocity)

$$\Delta KE = \frac{1}{2}\frac{F}{g_o}\left(v_2^{\,2} - v_1^{\,2}\right) = \frac{1}{2}\frac{m}{g_c}\left(v_2^{\,2} - v_1^{\,2}\right)$$

$$\Delta KE = \frac{1}{2}\frac{F}{g_o}\left(v_2 - v_1\right)\left(v_2 + v_1\right) = \frac{1}{2}\frac{m}{g_c}\left(v_2 - v_1\right)\left(v_2 + v_1\right) \qquad \text{eq. (4)}$$

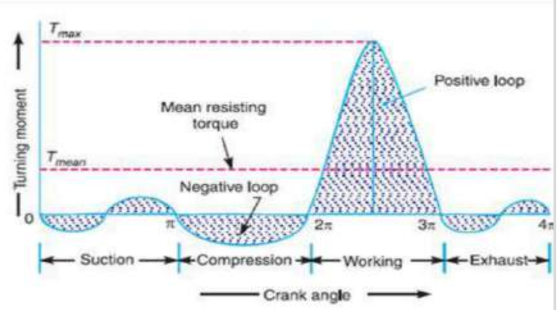
(in terms of angular velocity)

$$\Delta KE = \frac{1}{2}\frac{F}{g_o}R_m^{\,2}\left(\omega_2^{\,2} - \omega_1^{\,2}\right) = \frac{1}{2}\frac{m}{g_c}R_m^{\,2}\left(\omega_2^{\,2} - \omega_1^{\,2}\right)$$

$$\Delta KE = \frac{1}{2}\frac{F}{g_o}R_m^{\,2}\left(\omega_2 - \omega_1\right)\left(\omega_2 + \omega_1\right) = \frac{1}{2}\frac{m}{g_c}R_m^{\,2}\left(\omega_2 - \omega_1\right)\left(\omega_2 + \omega_1\right) \qquad \text{eq. (5)}$$

Fluctuations in Flywheel

A **flywheel** is a mechanical device designed to store rotational kinetic energy. It plays a vital role in mechanical systems where the torque output is cyclic or non-uniform, particularly in internal combustion engines (ICEs). These engines generate power only during the power stroke, while other strokes in the four-stroke cycle — intake, compression, and exhaust — do not contribute to net positive torque. As a result, the torque output from the engine shaft fluctuates significantly.



The **turning moment diagram** for this engine shows large fluctuations between high positive and negative torque, highlighting the need for a flywheel to stabilize output.

Flywheels serve to absorb energy during periods of torque excess (typically the power stroke) and release it during periods of torque deficit (the remaining strokes), thereby smoothing out the torque delivery over a full engine cycle. This reduces vibrations, mechanical stress, and increases the overall efficiency and stability of the machine.

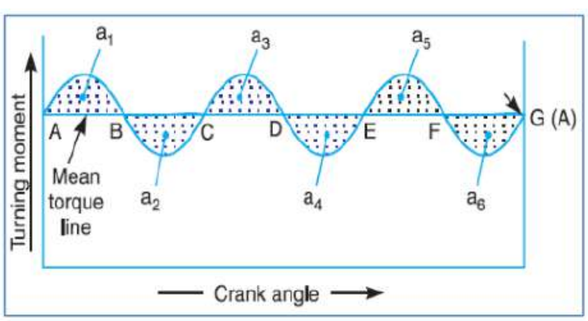
Torque Fluctuation in a Four-Stroke Engine

In a single-cylinder, four-stroke ICE, torque production varies throughout the 720° crank rotation (two full revolutions):

1. **Intake Stroke** – Slightly negative torque due to suction.
2. **Compression Stroke** – High negative torque as work is done on the gas.
3. **Power Stroke** – Large positive torque as combustion occurs.
4. **Exhaust Stroke** – Moderate negative torque due to expelling gases.

Multi-Cylinder Engines and Flywheel Smoothing

In multi-cylinder engines, each cylinder fires at staggered intervals (e.g., 120° apart for a 3-cylinder engine). This overlapping of power strokes inherently reduces torque fluctuations compared to a single-cylinder engine. However, even in multi-cylinder engines, some level of fluctuation remains. The flywheel still plays a critical role in equalizing the composite torque output from all cylinders, ensuring uniform rotational speed of the crankshaft.



As illustrated in the diagram, the flywheel absorbs or supplies energy during periods of torque deviation from the mean. The area between the torque curve and the mean resisting torque line represents this energy exchange.

Applications and Observations

- A larger flywheel increases inertia and provides smoother operation but also adds weight and requires more energy to accelerate.
- The diagrams and torque graphs illustrate how the use of a flywheel flattens torque fluctuations and improves system performance.

Coefficient of fluctuation, C_f

The coefficient of fluctuation of energy is a dimensionless number that quantifies the relative amount of energy fluctuation:

$$C_f = \frac{v_2 - v_1}{v_a} = \frac{N_2 - N_1}{N_a} = \frac{\omega_2 - \omega_1}{\omega_a}$$

$$C_f v_a = v_2 - v_1 \qquad \text{eq. (6)}$$

Average velocity

$$v_a = \frac{v_2 + v_1}{2} \qquad \text{eq. (7)}$$

Where: v_a, N_a and ω_a = average velocity, rotative speed and angular velocity

Substituting eq. (6) and eq. (7) to eq. (4), hence we'll have:

$$\Delta KE = \frac{F}{g_o} C_f v_a^2 = \frac{m}{g_c} C_f v_a^2$$

$$\Delta KE = \frac{F}{g_o} C_f R_m^2 \omega_a^2 = \frac{m}{g_c} C_f R_m^2 \omega_a^2$$

$$F = F_r + F_h + F_a$$

Where:
F = Force/weight of the flywheel
F_r = Force/weight on the rim
F_h = Force/weight of the hub
F_a = Force/weight of the arm
F_w = Force/weight of the wheel (flywheel effect)
$F_r + F_h + F_a$ = 5% to 10% of F
Use: 10% if not given
C_f = Coefficient of Fluctuation, Flywheel Page 534: Design of Machine Elements 4th Edition by Virgil Faires.

This parameter helps assess the smoothness of engine operation and is a key consideration in flywheel sizing.

Radius of Gyration – neglecting effect of hub and arm

$$R_m = \sqrt{8.68 \, x \, 10^{-4}\left(D_o^{\,2} + D_i^{\,2}\right)}$$ unit: in

Where: D_o = outside diameter, in
D_i = inside diameter, in

Energy required to punch a hole

$$E = \frac{1}{2}F\,t = \frac{1}{2}S_{Su}\,A\,t$$

Where: E = energy needed to punch metal
F = force required to punch a hole
S_{Su} = ultimate shearing stress
A = shear area
$A = \pi Dt$ (for circular hole)
t = thickness of metal plate
d = diameter of hole

Pressure or force required to punch a hole

$$P = 80 \cdot d \cdot t$$ unit: tons

Where: t = thickness of metal plate, in inches
d = diameter of hole, in inches

Stresses in Flywheel Rims

As a flywheel rotates at high speeds, its rim experiences centrifugal force, which pulls the material outward. This force can generate significant tensile stress, especially in the rim where most of the flywheel’s mass is concentrated. These stresses must be carefully considered in design because they can cause deformation or even failure of the rim if not properly managed

$$S = \frac{D_m^{\,2}\omega^2\rho}{144\,g_o}$$

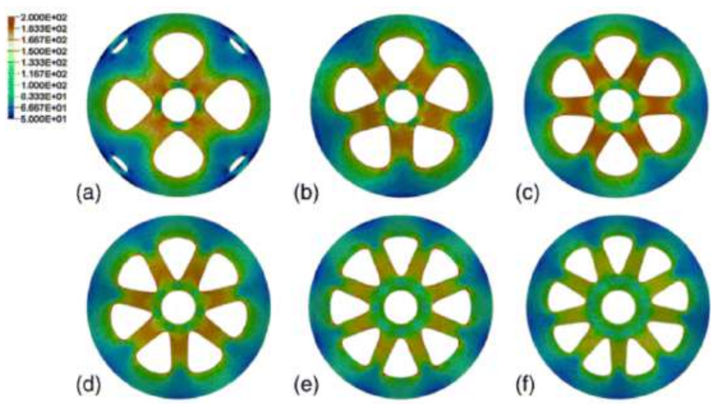
The centrifugal stress in the rim is created as each part of the rotating rim wants to move outward due to its inertia. This stress is greatest when the flywheel is spinning rapidly and when the rim is heavy. If the rim is joined to the hub through arms or spokes, the arms themselves will also be under bending stress and tensile load due to the pull from the rotating rim.

This formula shows that stress increases with the square of the speed and the diameter. Therefore, flywheels operating at high speeds must be carefully designed to handle these forces.

Rules of thumb for materials indicate that:

- Cast iron flywheels are safe up to **6000 ft/min**
- Cast steel flywheels can go up to **10,000 ft/min**

If the flywheel is split into sections (such as halves), extra care must be taken in the design of the connections between sections because they experience high stress during operation. Additionally, if the flywheel acts as a pulley or is used in systems with shock loads or high acceleration, the stresses can be even greater due to bending moments and transmitted torque.



The colors represent the level of stress, with red areas showing the highest stress and blue areas showing the lowest. As you add more arms to the flywheel, the stress becomes more evenly spread out. For example, the 4-arm flywheel (a) has more red areas, meaning higher stress, while the 10-arm flywheel (f) shows better stress distribution with fewer red zones. This means that adding more arms can help make the flywheel stronger and safer.

Centrifugal stress is one of the most important factors that limits how fast and large a flywheel can be. Good design, material selection, and stress-relief treatments are needed to make sure the flywheel operates safely and reliably.

Bearings are used whenever there is a need to reduce friction, control motion, guide or support a weight between two machine members that move relative to one another. The motion can be rotational, translational or combination of the two.

Plain bearings, also called sliding contact bearings, are fundamental mechanical components that support rotating or sliding shafts by allowing relative motion with direct surface contact rather than rolling elements. These are widely used in machines requiring simplicity, quiet operation, and compactness.

Classifications:

1. Sliding bearings
2. Rolling bearings
    a. Ball bearings
    b. Roller bearings

SLIDING BEARINGS

Sliding bearings, also known as **plain bearings**, are mechanical components that facilitate smooth motion between two surfaces by allowing one surface to slide over another. Unlike rolling bearings, they do not contain rolling elements. These bearings are commonly used in applications where high load capacity and simplicity are essential.

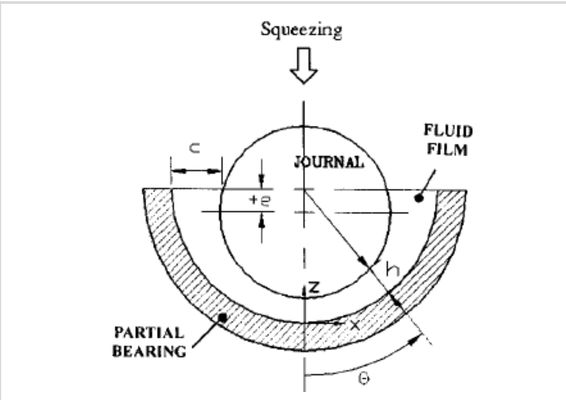
Types of Sliding Bearings:

Journal Bearings: Support radial loads and are commonly used in shafts.	
Thrust Bearings: Designed to handle axial loads Helpful Video	
Guide Bearings: Used to guide linear motion.	

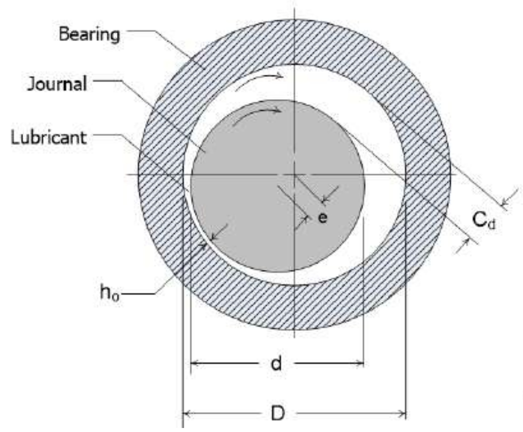
Journal bearings have a shaft surrounded by a cylinder and filled with lubricants that support the shaft to prevent metal to metal contact, this type of bearings are also known as fluid film bearings.

Classification of Journal Bearings

1. **Based on Load Coverage**
   - Full Journal Bearing
     The bearing surface surrounds the entire journal (360° contact). It is designed for uniform load distribution and stable operation
   - Partial Journal Bearing
     The bearing surface covers less than 180° of the journal. It is used where directional loading is consistent, such as in crankshaft main bearings.



2. **Based on Load Application**
   - Centrally Loaded Bearings
     The load acts along the centerline of the bearing, resulting in symmetrical pressure distribution.
   - Eccentrically Loaded Bearings (Offset Bearings)
     The load is displaced from the center, creating a variable film thickness and pressure gradient.
3. **Based on Fit or Clearance**
   - **Clearance Bearing**
     The bearing inner diameter is slightly larger than the journal diameter, allowing an oil film to form.
   - **Fitted Bearing**
     The bearing tightly fits the journal and allows minimal or no clearance. These are used where alignment and stiffness are critical but lubrication is still provided through grooves or oil holes.



Diametral Clearance, C_d

$$C_d = D - d$$

Radial Clearance, C_r

$$C_r = R - r = \frac{D - d}{2}$$

$$C_r = \frac{C_d}{2}$$

Unit Loading on Bearing or Bearing Pressure, P

$$P = \frac{F}{LD}$$

Eccentricity, e

Eccentricity is defined as the radial distance between the centers of the bearing to the deviated center of the journal.

$$e = \frac{C_d}{2} - h_o = C_r - h_o$$

Bearing modulus, BM

$$BM = \frac{\mu N}{60P}$$

Where:
D = diameter of the bearing, in
d = diameter of the journal, in
F = radial load, lbs
h_o = film thickness or lubricating space, in
N = speed, rps

Bearing Frictional Torque

$$T = \frac{F f_b D}{2}$$

Petroff's Equation for Bearing Frictional Torque

Petroff's equation estimates the torque due to fluid friction in a lightly loaded journal bearing. It's a useful tool for quick calculations in high-speed, low-load conditions. It helps engineers understand how viscosity, clearance, speed, and bearing dimensions affect energy loss due to friction. Page 302: Design of Machine Elements 4th Edition by Virgil Faires.

$$T = \frac{4\mu \pi^2 r^3 L N}{C_r}$$

Where: T = Frictional torque, in-lb
μ = viscosity, reyn

reyn is a unit of viscosity named after Osborne Reynolds (1842–1912), a British engineer and physicist, best known for the Reynolds number in fluid mechanics.
Use AF 16, Typical Viscosities of Oils, page 595: Design of Machine Elements 4th Edition by Virgil Faires.

$$1\, reyn = 1 \frac{lb-sec}{in^2}$$
$$1\, reyn = 68,947.57\, poise$$

$$1\, poise = 1 \frac{dyne-sec}{cm^2}$$

L = axial length of bearing, in
C_r = radial clearance, in
r = journal radius, in
N = revolution per second

Lubrication in Sliding Bearings

Lubrication is crucial in sliding bearings to reduce friction, wear, and heat generation between moving surfaces. It also helps in preventing corrosion and contamination.

Lubricants must be chosen based on viscosity, temperature, speed, and expected film regime. Greases are suitable for boundary lubrication or intermittent service but less ideal for high-speed full-film needs.

Types of Lubrication:

1. Hydrodynamic Lubrication: A full fluid film separates the bearing surfaces, generated by the relative motion of the surfaces.
2. Hydrostatic Lubrication: An external pump supplies pressurized lubricant to maintain the fluid film, independent of motion.
3. Boundary Lubrication: Occurs when the lubricant film is thin, and surface asperities may come into contact.
4. Solid Lubrication: Utilizes solid materials like graphite or molybdenum disulfide, suitable for extreme conditions.

Common Lubricants Used

1. **Mineral Oils**: Derived from petroleum, commonly used due to their good lubricating properties and cost-effectiveness.
2. **Synthetic Oils**: Engineered lubricants offering superior performance in extreme temperatures and conditions.
3. **Greases**: Semi-solid lubricants composed of oils thickened with soaps, suitable for applications where oil leakage is a concern.
4. **Solid Lubricants**: Materials like graphite or molybdenum disulfide used in environments where liquid lubricants are unsuitable.

Plain Bearings can operate under different lubrication systems:

- **Type A (Manual/Drip)** applies oil manually at intervals.
- **Type B (Bath or Disk)** uses a sump of oil that lubricates through disk rotation.
- **Type C (Circulating)** uses a pump for continuous lubrication flow.

The overall reliability and performance of bearing systems depend heavily on appropriate design, retention, sealing, material selection, surface finish, and lubrication strategies.

Sommerfeld Number

The Sommerfeld Number, also known as the Bearing Characteristic Number is a dimensionless number that is used for analysis of hydrodynamic lubrication. Page 305: Design of Machine Elements 4th Edition by Virgil Faires.

$$S = \frac{\mu N}{P}\left(\frac{r}{C_d}\right)^2 = \frac{\mu N}{P}\left(\frac{D}{C_d}\right)^2$$

Where: P = Unit Loading on Bearing or Bearing Pressure, psi

Heat Dissipation in Journal Bearings: empirical formula that is used to estimate how much heat the bearing housing can dissipate due to friction between shaft and bearing.

$$Q = \frac{C_h LD}{778}$$

Where: Q = heat dissipated, Btu/min

C_h = heat dissipation coefficient, $\frac{lb - ft}{min - in^2}$

Heat absorbed by Lubrication Oil: provides information about how much the oil temperature actually rises in operation.

$$Q = mC\Delta T$$

Where: m = mass flow rate of oil, lb_m

C = specific heat of the oil, $3737 \frac{in - lb_f}{lb_m - {}^oF}$

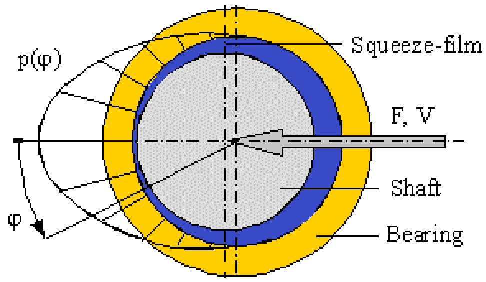
ΔT = change in oil temperature

Sliding Bearing Maintenance:

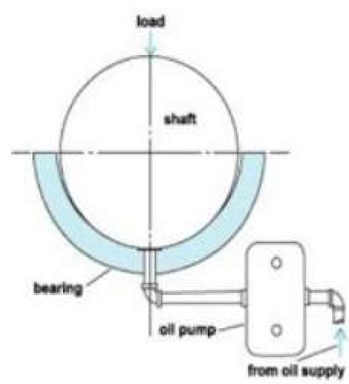
1. Lubricate properly – Clean oil minimizes friction and temperature rise.
2. Control operating load – Avoid overload and shock loading.
3. Ensure cooling and circulation – Proper oil flow removes frictional heat.
4. Inspect alignment and balance – Reduces uneven wear and torque.
5. Monitor temperature trends – Rising temperature indicates friction increase or cooling inefficiency.

Hydrodynamic Lubrication or Thick-Film Lubrication

When a thick film of lubricant completely separates the moving surfaces, the bearing operates under hydrodynamic or full-film lubrication. In this condition, there is no metal-to-metal contact, and the load is supported by pressure generated within the lubricant film. In hydrodynamic lubrication, the pressure within the lubricant film is generated by the relative motion of the surfaces.



No external pump is needed — the rotation or sliding of the shaft drags the lubricant into a wedge-shaped gap, creating a self-acting pressure that supports the load.

Hydrostatic bearings are employed in applications requiring extremely low friction, high load capacity, and high stiffness. These bearings maintain full-film lubrication through an externally pressurized lubricant supply, making them ideal for slow-speed, heavily loaded systems such as rolling mills and machine tools. In contrast, guide bearings serve primarily as positioning devices in machine tools, supporting linear motion. These typically operate within the boundary lubrication region using dry films (e.g., MoS_2 or TFE), grease, or oil, and often utilize pressurized air or fluid pockets to maintain separation between surfaces. In hydrostatic lubrication, pressure is generated by an external pump that forces lubricant into the bearing clearance before motion starts.	

Retaining methods ensure that bearings remain properly positioned within their housings. The most common method is a press or shrink fit, which creates an interference fit. Shrink fits are achieved by cooling the bearing or heating the housing to allow insertion. Additionally, mechanical keying methods—such as set screws, Woodruff keys, dowel pins, and flanged bolts—are used to resist rotational or axial motion. Sealing is crucial to prevent lubricant escape and contamination ingress. Static seals (e.g., gaskets, O-rings) are used where no relative motion occurs, while dynamic seals are required for rotating or sliding applications, including positive contact seals and controlled-clearance noncontact seals.

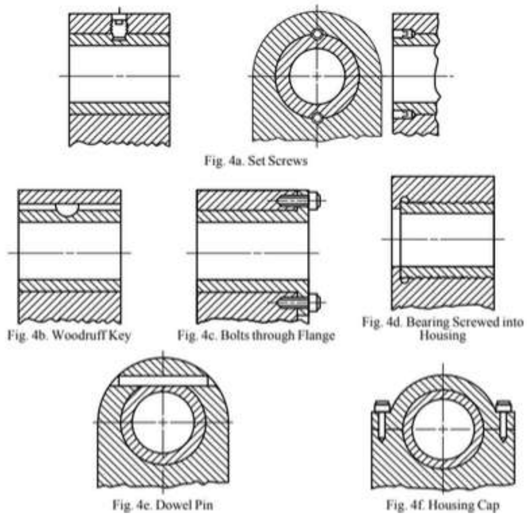


Fig. 4a. Set Screws
Fig. 4b. Woodruff Key
Fig. 4c. Bolts through Flange
Fig. 4d. Bearing Screwed into Housing
Fig. 4e. Dowel Pin
Fig. 4f. Housing Cap

Surface finish is another critical consideration. Full-film lubrication requires smoother surfaces compared to mixed or boundary lubrication, as shown in the recommended roughness values. Surface finish affects friction, wear, and load-carrying capacity. Journals must be harder than the bearing material to reduce wear and scoring. Materials like high-leaded bronzes and aluminum bronze are selected based on load and alignment conditions.

PLAIN BEARING MATERIALS

Plain bearing materials must exhibit specific mechanical and chemical properties to function effectively. These properties include fatigue resistance, embeddability, compatibility, conformability, thermal conductivity, corrosion resistance, and load capacity. Each property contributes to a bearing's ability to withstand repeated stresses, embed contaminants without damage, work smoothly with mating components, and adapt to misalignment. High thermal conductivity aids in dissipating heat, while corrosion resistance and high load capacity ensure durability under harsh operating conditions.

Babbitt or white metal alloys remain a standard for plain bearings due to their excellent embeddability and compatibility. They contain elements like tin, copper, antimony, and lead in varying proportions depending on performance requirements. Babbitts are commonly used in automotive, household, and industrial machinery applications. Tin-based babbitts are ideal for fatigue and strength, while lead-based versions provide cost-efficiency and castability. Cadmium and copper-lead alloys also improve load performance, with the latter being used in high-speed, high-load applications.

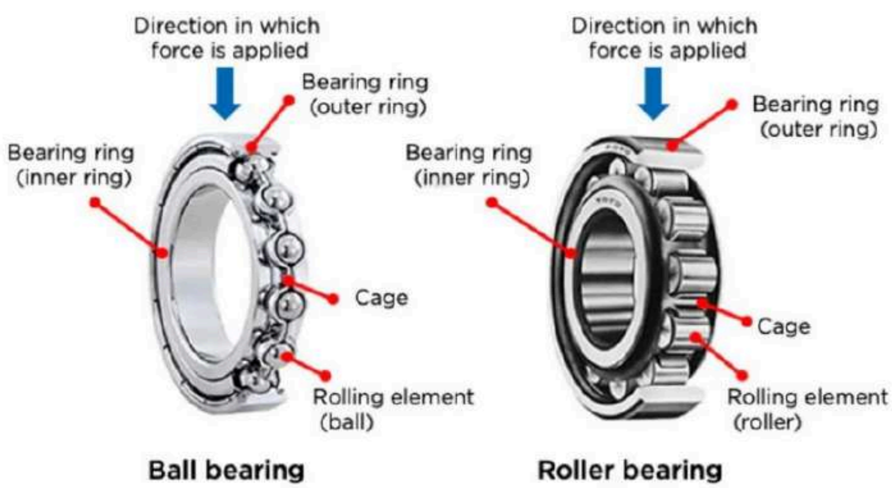
Bronze bearings offer superior strength and are used in heavy-duty applications. Leaded bronzes are easier to embed dirt and operate under inadequate lubrication. Tin bronzes are stronger but require better lubrication conditions. **Aluminum bearings**, often alloyed with silicon or copper, are used in light to medium-load scenarios but require tighter clearances due to their thermal expansion. **Silver bearings** provide excellent load-carrying capacity and are used in high-speed diesel engines and aerospace applications.

Porous metals, such as sintered bronze or iron, allow for self-lubrication by retaining oil within their structure. These bearings are suitable for applications requiring minimal maintenance. A wide variety of nonmetallic materials are also used, including **plastics** like nylon and Teflon, which offer low friction and good corrosion resistance, and **rubber**, which excels in vibration damping for pumps and rudders. **Wood**, once widely used, is now rare due to modern alternatives.

Carbon-graphite bearings operate well in high-temperature environments and are self-lubricating. They are used in applications involving acids or where conventional lubrication is not possible. Their composition resists chemical attack, and they are dimensionally stable across a wide range of temperatures.

ROLLING BEARINGS

Rolling-contact bearings, such as ball and roller bearings, are widely used in mechanical systems due to their key advantage: they exhibit low starting friction, which is only slightly higher than their operating friction. This contrasts sharply with sliding-contact bearings, where metal-to-metal rubbing creates significant friction at startup. The coefficient of friction for rolling-contact bearings remains relatively stable with changes in load and speed, making them especially useful for applications involving frequent starts and stops under load, such as in railway axle bearings.



These bearings also offer low maintenance, require less axial space, and can handle both radial loads and axial thrust. However, they have trade-offs. For example, they tend to be noisier, more expensive, and typically have a shorter lifespan compared to journal bearings. This limited life is due to the high stress experienced by the raceways each time the shaft rotates, which can lead to fatigue failure over time.

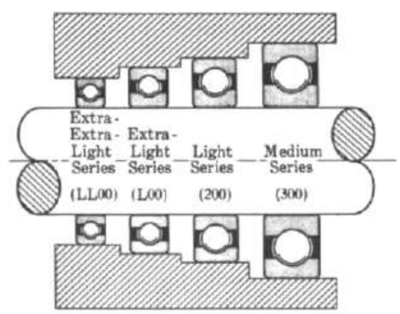
While rolling-contact bearings and sliding-contact bearings each have their advantages, the choice between them depends on the specific engineering application. Rolling bearings are standardized components, meaning that engineers do not design them from scratch but instead select a type, size, and configuration from a catalog based on the system requirements.

To make a good bearing selection, the designer must understand the basic performance factors such as load capacity, lifespan, speed capability, and operating conditions. Rolling-contact bearings are preferred where predictable performance, ease of replacement, and compact design are needed—especially in systems where efficiency and frequent cycling are critical.

SIZING OF BEARINGS

Bearings are available in a range of standardized **series sizes** that determine their dimensions and load capacities. These size series help engineers and designers select the right bearing for a given application based on load, speed, and space requirements.

Extra-light series	100 series
Light series	200 series
Medium series	300 series
Heavy series	400 series



These classifications refer to how heavy-duty the bearing is. For instance, a 200 series bearing is considered *light*, while a 300 series is *medium*, and 400 series is *heavy*. Bearings heavier than the 400 series, and lighter than the extra-light series, are often developed for special applications such as rolling mills or precision instruments.

The heaviness or load capacity of a bearing in a given series is increased by increasing the outside diameter, while the bore size (inner diameter) remains the same. The selection of bearings will depend on the type of load, size of shaft, space limitation of the housing and other design considerations.

Types of Rolling Bearings

Ball Bearings		Roller Bearings	
Deep Groove Ball Bearings: Versatile and widely used, suitable for high-speed applications.		**Cylindrical Roller Bearings:** Suitable for high radial loads and moderate speeds.	
Angular Contact Ball Bearings: Designed to handle combined radial and axial loads, commonly used in pairs.		**Tapered Roller Bearings:** Capable of handling large radial and axial loads, commonly used in automotive applications.	
Self-Aligning Ball Bearings: Feature two rows of balls and a common spherical raceway, accommodating misalignment		**Spherical Roller Bearings:** Designed to accommodate misalignment and heavy radial loads.	
Thrust Ball Bearings: Specifically designed to handle axial loads in one direction.		**Needle Roller Bearings:** Contain long, thin rollers, ideal for applications with limited radial space.	
		Thrust Roller Bearings: Engineered to support high axial loads.	

In practice, ball bearings are chosen for high-speed and light-load applications (like electric motors), while roller bearings are preferred for heavy-load and low-speed conditions (like gearboxes or truck axles).

Designations and Identification

1. Basic Numbering System (e.g., "6204")

This typically consists of four digits, each carrying a specific meaning:

- First Digit (6): This indicates the bearing type or series:
  - 1 – Extra light series
  - 2 – Light series
  - 3 – Medium series
  - 4 – Heavy series
  - 6 – Single-row deep groove ball bearing (most common)
  - 7 – Single-row angular contact ball bearing
  - N – Cylindrical roller bearing (in some systems)

- Second Digit (2): This signifies the bearing series, which gives information on width and height proportions. It's used to define the cross-section of the bearing.
  - Higher numbers indicate heavier-duty bearings with thicker walls.
- Last Two Digits (04): These represent the bore size (inside diameter of the bearing):
  - Multiply this number by 5 to get the bore diameter in mm.
  - So "04" means 4 × 5 = 20 mm bore diameter.
  - For 00, 01, 02, and 03:
    - 00 = 10 mm
    - 01 = 12 mm
    - 02 = 15 mm
    - 03 = 17 mm

2. Suffixes (e.g., "ZZ")

These letters indicate special design features such as seals, shields, internal clearances, cage types, and more.

- ZZ: Double metal shields on both sides. Prevents dust from entering but does not retain lubricant like a seal.
- 2RS or RS: Rubber seals (contact type) on both sides (2RS) or one side (RS).
- C3: Greater internal clearance than normal—used in high-speed or high-temperature applications.
- NR: Snap ring groove and ring.
- K: Tapered bore.
- M: Machined brass cage.
- TVP, J, etc.: Denote cage materials or designs.

Complete Example: "6204-ZZ C3"

- 6 = Deep groove ball bearing
- 2 = Light series
- 04 = 20 mm bore
- ZZ = Double metal shields
- C3 = Increased internal clearance

This bearing is a light-series deep groove ball bearing with a 20 mm bore, shielded on both sides, and suitable for higher thermal expansion or rotational speed.

Specialized Bearings

Several special bearing types exist for unique applications. These include pillow blocks and flanged housings, non-separable or fully self-aligning types, and those designed for extreme temperatures, misalignment, or corrosive environments.

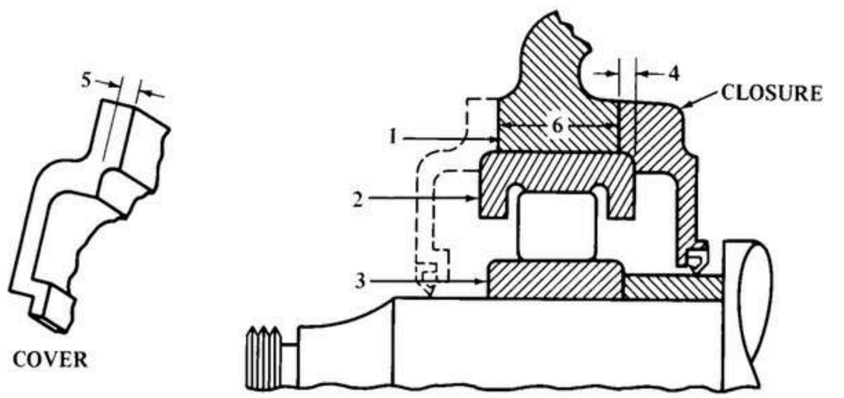
			
Pillow blocks	Flanged housings	Non-separable	Self-aligning

Tapered roller bearings, needle roller assemblies, and machined race bearings are used in high-performance or heavy-duty applications where standard bearings may fail.

Bearing Mounting Practice

Proper mounting is crucial to bearing longevity. Misalignment, poor surface finish, or incorrect preload can cause premature failure. Bearings should be mounted with consideration to housing and shaft tolerances, with alignment checks for runout, squareness, and parallelism. Preloaded bearings must meet exacting standards, especially in high-speed or precision applications.

Feature	Location	Tolerance
Housing Face Runout	1	Square to shaft center within .0004 inch/inch of radius full indicator reading.
Outer Race Face Runout	2	Square to shaft center within .0004 inch/inch of radius full indicator reading and complementary to the housing runout (not opposed).
Inner Race Face Runout	3	Square to shaft center within .0003 inch/inch of radius full indicator reading.
Cover and Closure Mounting Face Parallelism	4 and 5	Parallel within .001.
Housing Mounting Face Parallelism	6	Parallel within .001



Shaft and Housing Design

Shaft shoulders should be square and wide enough to support bearing inner races. Housing bores must be properly machined to avoid stress risers and eccentric loads. Undercuts and fillets must be designed to avoid fatigue. Where possible, mounting should allow axial preload and avoid overhangs that could cause misalignment. Vibration-sensitive applications may require elastomeric or spring supports.

Seals, Closures, and Fits

Seals and shields protect the bearing from contaminants and retain lubricants. Shields may be metal or rubber and are usually fitted to the outer race. Bearing fits—whether loose or press—must prevent slippage under load while allowing thermal expansion. Proper shaft tolerances and mounting temperatures ensure secure assembly.

Design Considerations

Friction in rolling bearings is minimal, but heat generation, preload, and lubricant selection are critical for performance. Preload affects stiffness, fatigue life, and load distribution. System-level factors such as vibration, housing stiffness, and misalignment must be evaluated in the design. Rolling bearings are precision components, and their selection must be based on load, speed, mounting constraints, and desired service life.

Proper handling and care of bearings are essential to ensure their longevity, reliability, and optimal performance. Mishandling during transport, storage, or installation can introduce defects that lead to premature failure. Bearings should always be kept in their original packaging until use to prevent contamination from dirt, moisture, or corrosive agents. They must be handled using clean, dry gloves or tools to avoid transferring moisture or particles. Dropping or striking bearings can introduce brinelling (indentations on the raceways) or internal cracking, which might not be visible but can later result in vibration, noise, or complete failure during operation.

During installation, using hammers or applying force improperly can misalign races or damage rolling elements. Bearings should be mounted using proper tools like bearing heaters or press-fit sleeves, ensuring even load distribution. Cleanliness is paramount; even minute contaminants can act as abrasives, accelerating wear and generating excessive heat. Lubricants must be selected carefully and applied properly—under-lubrication causes dry friction, while over-lubrication can lead to seal failure and overheating.

Common Bearing Failures, Deficiencies, and Their Origins

1. **Contamination** – Caused by dust, dirt, or debris entering the bearing due to poor sealing or improper handling. Results in abrasive wear and shortened bearing life.
2. **Improper Lubrication** – Too little lubrication causes metal-to-metal contact; too much can generate excessive heat. Incorrect lubricant type may not withstand temperature or load conditions.
3. **Misalignment** – Occurs when the shaft and housing are not properly aligned. This causes uneven load distribution, resulting in edge loading, excessive vibration, and eventual fatigue.
4. **Overloading** – Bearings subjected to loads beyond their rated capacity suffer from plastic deformation of raceways or rolling elements, leading to surface spalling and failure.
5. **Improper Installation** – Forcing a bearing into place or using incorrect tools can cause raceway dents, cracked rings, or misalignment that accelerates failure.
6. **Corrosion** – Moisture or chemical exposure leads to rust or pitting, weakening the bearing surfaces. Often caused by improper storage or inadequate sealing.
7. **Fatigue Spalling** – Caused by repeated stress cycles. Tiny cracks form below the surface and eventually cause flaking of the raceway or rolling elements.
8. **Brinelling** – Permanent indentations caused by static overload or shock loads, such as hammering during installation or mishandling during shipping.
9. **Creep and Fretting** – Creep refers to the movement of the bearing ring relative to the shaft or housing, often due to poor fit. Fretting is corrosion caused by this relative motion, leading to wear at the interface.