Wydział Mechaniczny Energetyki i Lotnictwa
POLITECHNIKA WARSZAWSKA

Interim Engineering Project

Analysis of bearing design solutions in turbine engines

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WARSAW 8 May 2023

Table of contents

1. Introduction

Bearing is a fundamental element in the design of turbine engines. Key engine components such as the rotor and the blades attached to it must be held securely in place, ensuring precision to within tenths of a millimetre, while allowing them to rotate freely with minimal friction. Without proper bearings, vibrations and friction between components can lead to engine malfunction and, consequently, even to its destruction. Various bearing solutions are used in turbine engines, depending on the requirements for loads, rotational speeds and operating temperatures. Therefore, the analysis of bearing design solutions in turbine engines is crucial to ensure engine reliability and performance. This paper will focus on the analysis of bearing design solutions in engines.

turbines, in order to determine their advantages and disadvantages and their impact on engine performance parameters.

2. Types of bearings

The figure below shows the classification of bearings most commonly used in turbine engines or developed for such applications. The vast majority of currently used solutions utilise rolling bearings.

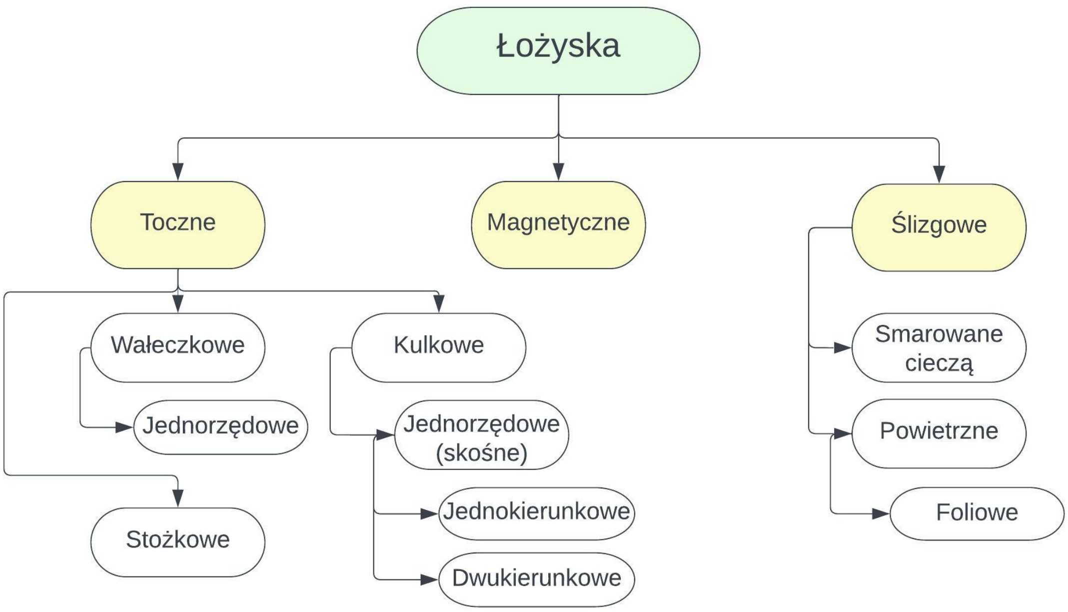


Figure 2.1. Classification of bearings used in aircraft turbine engines

2.1. Rolling bearing design

(a) **Outer ring**: This is the larger of the two concentric rings and is usually attached to the stationary part (housing) of the mechanical system. It is equipped with a raceway (groove), which is essentially machined into the inner diameter to guide the rolling elements.

(b) **Inner ring**: It is the smaller of the two concentric rings and is usually attached to the rotating element (shaft). As with the outer race, it is also equipped with a race on the outer diameter.

(c) **Rolling element**: A set of balls or rollers is placed between two bearing races, and each ball/roller rotates on its own axis while rotating around the bearing axis. These rolling elements transfer the load between the two rings and are the most critical elements in a rolling bearing.

(d) **Cage**: The main function of the cage is to ensure an even angular spacing of the rolling elements so that the load is distributed evenly between them. Another important aspect is that the cage prevents two adjacent balls from rubbing against each other, which could otherwise result in increased friction and wear. The cages of the main rotor bearings are made of brass, aluminium alloy or bearing steel with a coating that reduces the friction coefficient, e.g. a layer of silver, and are centred on the inner or outer raceway.

(e) **Seals/covers**: They prevent external contaminants from entering the bearing during operation and also help to retain the lubricant in the bearing. Both of these aspects are crucial for the service life of the bearing. [1]

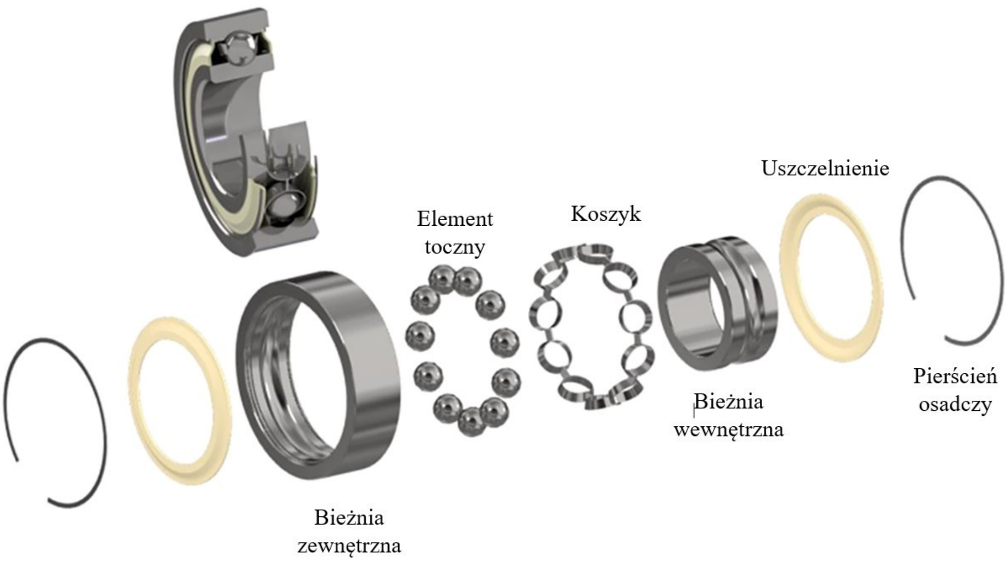


Figure 2.2. Bearing design

2.2. Single row angular contact ball bearings

Angular contact ball bearings have races in the inner and outer rings that are offset relative to each other in the direction of the bearing axis. This means that they are designed to carry combined loads, i.e. simultaneous radial and axial loads.
The ability of angular contact ball bearings to carry axial loads increases with the increase in the bearing contact angle. The operating angle is defined as the angle between the line passing through the points of contact between the ball and the raceways in the radial planealong which the load is transferred between the raceways, and the line perpendicular to the bearing axis.

2.2.1. One-way bearings

Single row angular contact ball bearings can only carry axial loads in one direction. A single row bearing is usually adjusted in relation to the other bearing. These bearings are non-separable, and their rings have one high and one low flange. Thanks to the low flange, many balls can be placed in the bearing, which allows for a relatively high load-bearing capacity.

The ability to transfer axial loads in only one direction is related to the fact that for the bearing to function properly, it must be "pressed" to ensure good contact between the rolling elements and the raceways. These bearings usually work in pairs. In modern turbofan engines, such bearings are not used. An example of their application is the TRS-18 engine.

Figure 2.3. Single-row, single-direction angular contact ball bearing

2.2.2. Double-direction bearings

Double-row double-direction angular contact ball bearings (four-point contact ball bearings) are transverse single-row angular contact ball bearings.

with raceways designed to carry axial loads in both directions. With a specified axial load, a limited radial load can be transferred. These bearings take up significantly less space in the axial direction than double row bearings. The inner ring is split. This allows a large number of balls to be placed in the bearing, giving it a high load capacity. The bearings are separable, i.e. the outer ring with the cage and balls can be mounted independently of both halves of the inner ring. In addition, the separate design allows the user to disassemble the bearing to inspect its components before and after operation, which is standard practice for many critical aviation mechanisms during ground inspection.

Another advantage is that the design of angular bearings allows the use of single-piece cages (made from a single piece of material), which is beneficial for two reasons: it allows for higher operating speeds than in the case of two-piece riveted cages, and it also helps to minimise the unbalanced forces of the cages, reducing wear in applications with long operating periods.

Currently, these are the most commonly used bearings for transmitting axial forces in turbine engines.

Figure 2.4. Single-row double-direction angular contact ball bearing

2.3. Roller bearings

These bearings have wider grooves in their raceways than ball bearings in order to accommodate the rollers. They also have a higher load capacity than ball bearings because rollers are better at transferring load. The contact between the roller and the raceway is a line, as opposed to a point in the case of ball bearings. The speed capacity of these bearings is lower than that of ball bearings, and they are used in systems where high radial loads exceeding the limits of ball bearings must be transferred. Designers should also take into account the fact that these bearings are susceptible to slippage between the rollers and raceways, and operating conditions must not

cause this phenomenon, as it may lead to bearing degradation.
Roller bearings can only carry radial loads, and most shaft systems using these bearings will have another bearing (usually a thrust bearing) to carry axial loads. The key advantage of these bearings is that they allow axial movement of the shafts, so that thermal expansion/twisting of the shafts does not cause stress in the bearings, which is critical in some designs of turbopumps with longer shafts or turbine engine shaft designs. They cannot accommodate shaft misalignment. [1]

Figure 2.5. Roller bearing

2.4. Tapered roller bearings

Tapered roller bearings consist of two tapered raceways: an outer and an inner one, between which tapered rollers are located. These bearings are capable of carrying axial and radial loads. In tapered roller bearings, as in other rolling bearings, there are high compressive forces that prevent slippage between the raceway and the roller. They transfer radial loads less efficiently than roller bearings and, like roller bearings, are not resistant to shaft misalignment.

Tapered roller bearings are widely used in auxiliary drive shaft bearings in turbine engines, less frequently as main shaft bearings.

Figure 2.6. Tapered roller bearing

2.5. Air bearings

Gas film bearing technology was developed as early as 1960 for high rotational speeds in turbocharger designs for high-pressure engines, auxiliary power units in aircraft (APUs) and selected sections of turbine engines. Gas bearings can often be used where conventional oil-lubricated bearings are not suitable. This is usually due to excessive stiffness, excessive rotational speed and thermal requirements. In general, there is a belief among manufacturers of all kinds of technical equipment such as turbochargers, turbogenerators, turbine engines, spindles, etc. that gas film bearings involve too much risk when attempting to implement them in new applications. Meanwhile, scientists have conducted a series of extensive studies aimed at demonstrating their superiority over conventional bearings in many areas of application, especially in oil-free turbochargers and small gas turbines. In addition, there are many methods for predicting the correct operating time of equipment, for example, based on monitored diagnostic parameters.

Following the achievements of scientists in the field of gas fields, it can be concluded that To date, three generations of gas film bearings have been developed. Generation I designs are characterised by relatively simple flexible elements such as films in bearing shells. They are usually characterised by uniform stiffness properties. Unfortunately, such gas bearings exhibit similar rigidity to rigid gas bearings of the same size (without flexible elements). Second-generation film bearings are equipped with a more complex flexible base (Figure 2.7), in which the stiffness is adjusted to one direction, e.g. axial. This is done in order to adapting the bearing to the environment in which it operates. This applies in particular to the correction of misalignment or the prevention of fluid leakage at the edges of the film. The second generation of foil bearings has a load capacity approximately twice that of the first generation. An example of a design solution is shown in Figure 2.8.

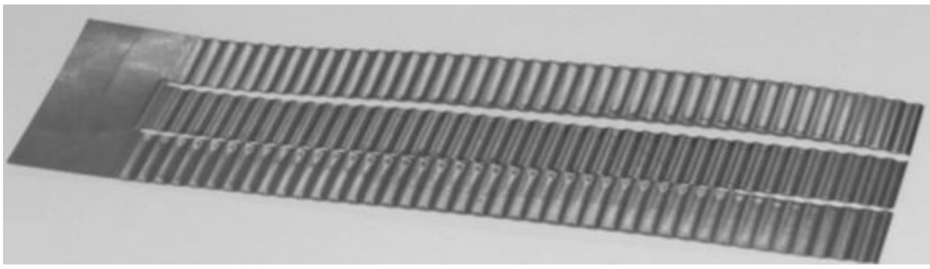


Figure 2.7. Example of a film shaped for a second-generation gas film bearing

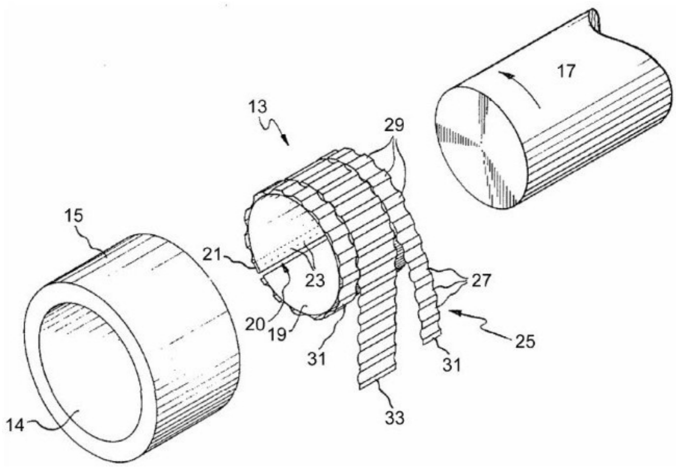


Figure 2.8. An example of a film bearing design

Third-generation gas film bearings consist of advanced, highly complex flexible film bases with stiffness adjusted in two directions (often axially and radially). This level of design flexibility in the bearing's support films allows for the control of edge effects and the optimisation of bearing stiffness for different loads. Third-generation gas film bearings have been found to have a load capacity three to four times greater than first-generation bearings.

2.6. Magnetic bearings

An active magnetic bearing is a rotor support that uses magnetic force to hold the rotor in place, as opposed to the forces acting in a rolling or air bearing. Like other types of bearings, magnetic bearings can be characterised in terms of stiffness, damping and load capacity, and therefore the forces that give these properties are, in a sense, analogous for each bearing.

Figure 2.9. Installed foil bearing

2.6.1. Principle of operation

As shown in Figure 2.11, a magnetic bearing consists of multiple electromagnetic coils attached to a ferromagnetic stator. The coils are arranged so that opposite poles are adjacent to each other, maximising the magnetic flux passing through the rotor. The ferromagnetic, laminated rotor "stack" is attached to the shaft to provide a path for the flux and attractive magnetic forces while minimising the formation of eddy currents. This "stack" is essentially a series of laminated plates with thin insulating layers between them. Position sensors are mounted at a certain distance from the shaft. The output voltage from the position sensors transmits position information to a microprocessor controller, which uses this information to generate a control signal. The control signal is converted to the desired intensity by amplifiers and transmitted to magnetic coils, ensuring that the magnetic force is attracted to the rotor. Typically, control algorithms treat the rotor assistance system as a mass/spring/damper interaction on two axes, usually vertical and horizontal. The controller sends signals proportional to the displacement of the shaft from the centre.

2.6.2. Advantages and disadvantages

The use of magnetic bearings in turbine engines offers three main technological advantages: oil-free operation without the need for air, the ability to operate in extreme temperatures, and active control. These advantages result in a growing list of desired improvements to the turbine engine. These include reduced weight; no contact with bearings, no wear and tear and lower maintenance requirements; operation at high altitudes; placement of the bearing in the hot sector of the engine; shorter, thicker

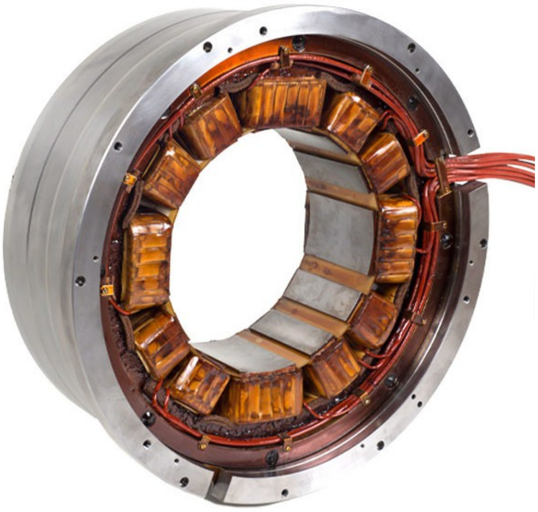


Figure 2.10. Magnetic bearing

and highly damped shafts; blade tip clearance control; shaft imbalance control; and dynamic stiffness and damping.

The magnetic bearing also enables the use of integral starter-generator (ISG) technology, which could replace the conventional generator driven by the main shaft via a gearbox and thus eliminate the need for lubrication and cooling, not to mention the additional complexity of the system.

Fig. 2.12 shows a comparison of three types of bearings in terms of specific "limiting factor" characteristics. Rolling, air film and magnetic bearings have real applications in gas turbine engines depending on size, speed and desired smart capabilities.

The undisputed advantage of rolling bearings, however, is their thorough understanding, as well as the fact that they offer significantly higher load capacity in relation to the bearing sleeve surface. Unfortunately, rolling bearings are currently very close to their technological limits in terms of temperature and DN, or have already reached them, and have a relatively short service life under higher loads. It cannot be ruled out that in order for engines to run hotter and faster with a long service life, they will ultimately have to be redesigned around foil (air) bearings or magnetic bearings.

The different load-bearing characteristics of foil and magnetic bearings make it possible to use them in separate engine operating ranges. Magnetic bearings are better suited for large motors operating under high loads and at relatively low rotational speeds (compared to foil bearings). Air film bearings, on the other hand, do not have a high load capacity at lower rotational speeds and, at present, have not been demonstrated in a size suitable for large motors.

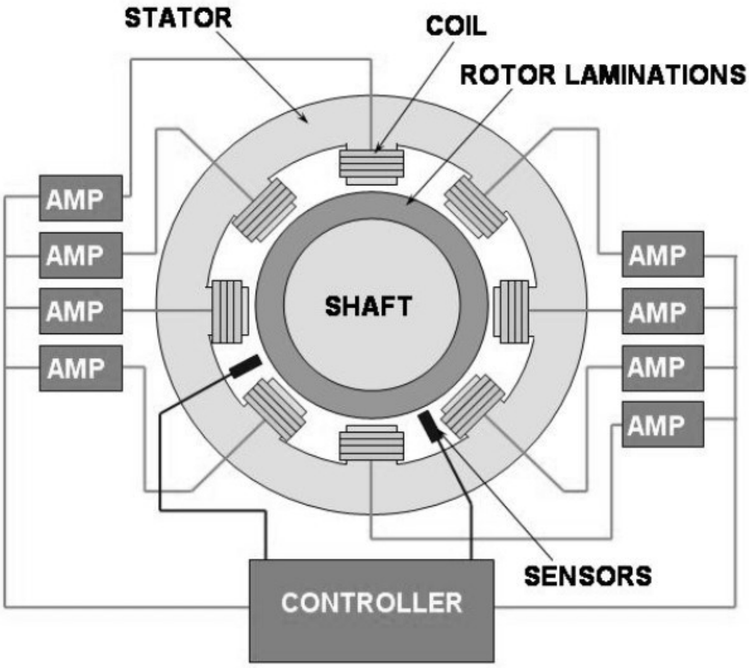


Figure 2.11. Magnetic bearing design

There are three frequently mentioned disadvantages of the current magnetic bearing technology, which are considered fundamental:

1. Lack of viable backup bearing technology – how to design a system that is resistant to magnetic bearing failure
2. Insufficient heat dissipation from the bearing
3. Deficiencies in load capacity and dynamic stiffness

Ways to counteract these disadvantages are currently being developed, and it is possible that in the near future the use of magnetic bearings will expand to the aerospace sector. [3]

	Rolling Element	Foil Bearings	Magnetic Bearings
Max Operating Temp.	350–500 °F (180–260 °C)	1200 °F (650 °C) *Ref (2)	1000 °F (540 °C) *Ref (4)
Documented Operating Speed (DN) (Speed*ID)	Less than 2 million DN (RPM*mm)	2 million DN (2" dia.) *Ref (2) *theoretically limit is unknown	2.25 million DN (3" dia.) *Ref (5) *theoretically limit is unknown
Documented Load Capacity	Varies: wear, heating, lube breakdown Highest load capacity per square inch (~300 psi)	Proportional to rotation speed 0 to ~1000 lbs (4"dia.) max range for largest bearing size (~100 psi) *Ref (2,3)	For entire speed and temperature range 1000 lb/axis (116 psi) (3" dia.) *Ref (4,5)
Energy/ Power Consumption	6-8 kW @12krpm 7-11 kW @ 17krpm (4.7" dia) *Ref (7)	No data	2.1 kW @ 1000 °F, all speeds *Ref (4,6)

Figure 2.12. Comparison of the properties of conventional, foil and magnetic bearings

3. Bearing configurations and examples of applications

In most turbine aircraft engines, each shaft is supported by two or three bearings. One of these supports must be axially non-movable, i.e. a bearing (or pair of bearings) that transmits axial forces.

The use of single ball bearings along the main shaft instead of tandem pairs improves maintainability, reduces engine complexity, costs and the frequency of damage caused by slippage. A single bearing allows the use of a resistance balancing system that reduces the minimum load required to prevent bearing slip. This allows for an appropriate reduction in the maximum load carried by the bearing. In some designs, such as the JT9D engine, this reduction can be so large that the fatigue life is greater than that of a pair of bearings. [4]

For these reasons, the most commonly used bearings for absorbing axial forces in modern engines are double-sided angular contact ball bearings (usually with a split lower raceway). Tapered roller bearings are also sometimes used.

Due to the thermal expansion of engine components during operation, the shaft cannot be placed on two non-movable supports. Consequently, the rest of the supports are roller bearings, ensuring freedom of axial movement.

The bearing configurations of some turbo-ventilator engines are shown below.

3.1. RR Trent 1000

The configuration of the Trent 1000 engine is unusual compared to its competitors due to the fact that it has three shafts. For this reason, the engine has three ball bearings (one for each shaft). In addition, the high-pressure shaft is supported by a single roller bearing, while the medium- and low-pressure shafts are supported by two roller bearings. [5]

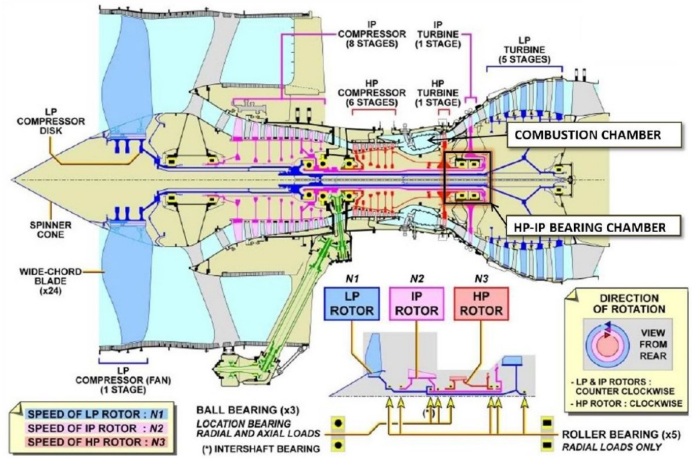


Figure 3.1. Bearing configuration of the Rolls Royce Trent 1000 engine

3.2. PW 1000

An example of an engine that uses tapered roller bearings is the PW1000 engine family. The two-shaft engine with a gearbox uses two ball bearings (one per shaft) and one roller bearing used to support the high-pressure shaft, two roller bearings supporting the low-pressure shaft, and a tapered roller bearing to support the fan shaft (to which torque is transmitted from the low-pressure shaft via a planetary gearbox).[6]

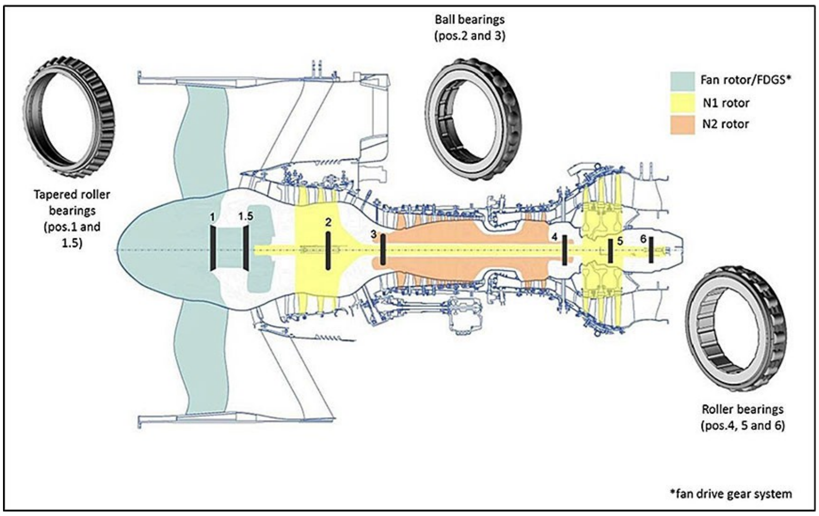


Figure 3.2. Bearing configuration of the Pratt & Whitney PW 1000 engine

3.3. CFM56

The CFM56 engine can undoubtedly be called the most "classic" engine among those mentioned so far in terms of bearings. It has a two-shaft design, with the high-pressure shaft supported by a ball bearing and a roller bearing, and the low-pressure shaft supported by one ball bearing and two roller bearings. [7]

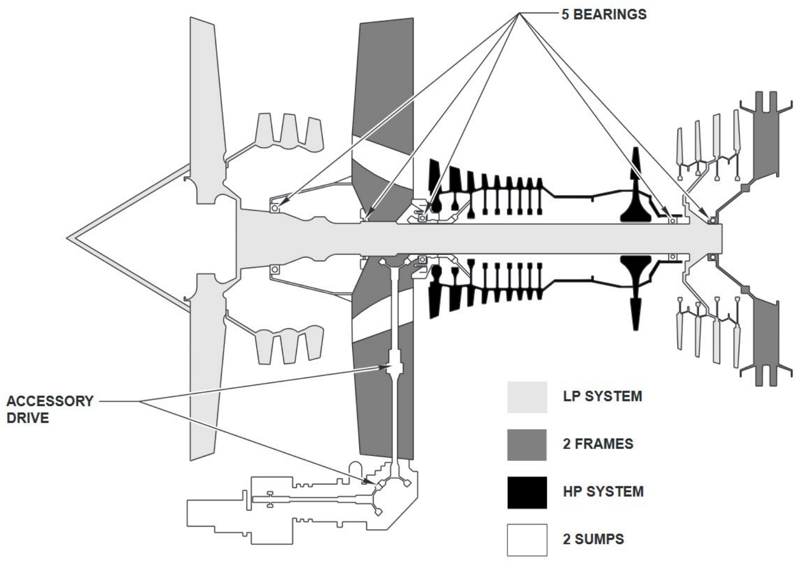


Figure 3.3. Bearing configuration of the CFM56-5A engine

4. Materials technology

Main shaft bearings in aircraft engines represent state-of-the-art design and material solutions, but the requirements associated with these bearings are also directly relevant to other critical bearing applications. As can be seen in Fig. 4.1, the rotational speeds of aircraft engine shafts (characterised by the bearing speed index (dm*n), which is the average bearing diameter dm in [mm] multiplied by the rotational speed of the shaft n in [r/min]) have steadily increased over time, and there is no reason to believe that this trend will not continue in the future to further improve the performance, reliability and economy of future aircraft engines.

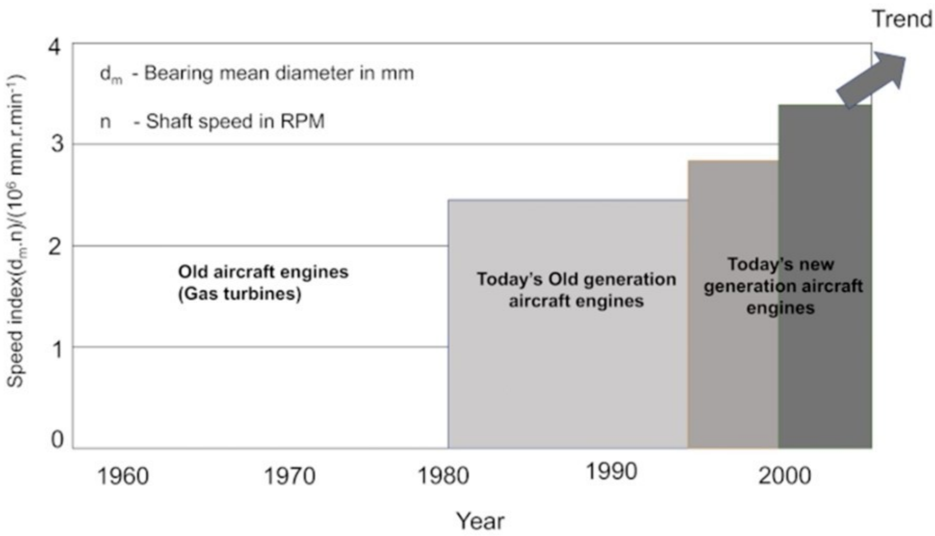


Figure 4.1. DN in turbine engine bearings over the years

In the early 1940s, aircraft bearings were made of high-chromium steel (SAE 52100), which was the first grade of steel commercially developed for bearings and is still the most commonly used material for bearing production. During this period, bearings were frequently replaced in engines to prevent failure, and it should be noted that the operating conditions of the bearings, such as speed and temperature, were within the limits of the properties of SAE 52100. In later stages, corrosion-resistant steel grades such as AISI 440C and BG42 were also developed and implemented for use in aircraft bearings. However, with the development of aircraft engine technology towards engines with higher thrust and better efficiency, operating temperatures began to rise in addition to speeds, and bearings had to meet these requirements. To achieve this, a family of molybdenum-based tool steels such as AISI M50 (AMS 6491) was introduced in the 1960s, which could maintain sufficient hardness and strength up to 315 (°) C, and were further developed for use in aircraft turbine engine bearings. To this day, M50 material, after hardening treatment, is the most commonly used steel for aircraft engine bearings.

Higher DN values indicate centrifugal forces acting on the bearing elements. Centrifugal forces increase circumferential stresses on bearing rings, and the presence of tensile stresses leads to the initiation and propagation of fatigue cracks, which in turn leads to premature failure. To solve this problem, continuously carburised steels such as M50NiL (AMS 6278) were developed and introduced in the 1980s. The composition of M50NiL is based on M50 alloy, but has a reduced carbon content (0.12%) and modified nickel content (3%, 5%). M50NiL is a carburising grade characterised by a hard outer layer resistant to fatigue and wear and a ductile core. With proper carburising and heat treatment, M50NiL creates residual compressive stresses (400 MPa) in the housing, which increases speed and service life. The surface layers of the bearing rings are critical fatigue zones.

Thanks to new material developments, it has become possible to overcome performance barriers and significantly increase the operational capabilities of rolling bearings in aviation applications.

Bearing corrosion has been diagnosed as one of the main causes of premature bearing failure in many aviation applications, particularly in aircraft engines. Furthermore, new high-temperature oils developed specifically for future aircraft engines caused corrosion of the then-dominant bearing steels, such as 52100, M50 and M50NiL. In order to achieve increased durability and reliability, and even the goal of designing a bearing that would not require replacement or repair during engine operation, it was necessary to minimise or completely eliminate all possible types of failure, including corrosion. Classic "stainless" bearing steels, such as AISI 440C, BG42 offer a certain resistance to corrosion, but their fatigue properties are insufficient due to their unfavourable microstructure with large carbides and carbide stratification at the grain boundaries. Therefore, these materials are used only in a very limited number of applications in aircraft bearings.

The latest developments focus on improved, corrosion-resistant bearing steels offering increased fatigue life. Cronidur 30 (AMS 5898), a unique nitrogen-alloyed martensitic steel, has been a great success. Cronidur 30 offers excellent corrosion resistance, good hot hardness and significantly increased service life. Cronidur 30 can be used in place of conventional, through-hardened (not just surface-hardened) bearing steels such as 52100, M50, BG42, 440C, etc., in order to practically eliminate corrosion problems, increase durability and improve bearing reliability, resulting in lower operating and maintenance costs.

To conclude, it should be mentioned that ceramic materials, specifically silicon nitride, have been accepted and widely used in bearing applications. Super-precision bearings used in machine tool spindles are prime examples of "hybrid" bearings (i.e. steel races combined with ceramic balls).

which are currently considered the "standard" in high-performance spindles. There is also a steadily growing number of applications in the aerospace industry.
- starting with ball screws used to activate flaps and slats in aeroplanes, through applications in cryogenic rocket turbines, to aircraft main shaft bearings, where ceramic balls and rollers combined with steel races are successfully used or tested, showing significant performance improvements. The special properties of ceramic materials – high strength, high hardness, high corrosion resistance and low density – allow for an increase in the speed and operating temperature of bearings and a reduction in their weight. At the same time, increased durability can be achieved because heat generation, material stress and bearing wear are reduced, and corrosion can be completely eliminated (Fig. 4.2).

	100Cr6	440C	M50	M50NiL	Cronidur 30	Silicon nitride* (Ceramic)
Microstructure	Basis	–	=	+	++	++
Fatigue life						
-Low temperature (<150 ℃)	Basis	–	=	+	++	++
-Medium temperature (<180 ℃)	Basis	–	+	++	+	++
-High-temperature (>180 ℃)	Basis	–	++	+++	+	++
-Mixed fiction operation	Basis	=	+	++	++	+++
Corrosion resistance	Basis	+	=	=	++	+++
Contamination resistance	Basis	–	=	+	++	++
Hot hardness/strength	Basis	=	++	++	+	+++
High-speed capability	Basis	–	+	+++	++	+++

* for rolling elements (used with steel races)
Definitions: "–" worse than "Basis"; "=" comparable with "Basis"; "+/++/+++" better to much better than "Basis"

Figure 4.2. Comparison of materials used in bearing production

For these reasons, the use of ceramic rolling elements, especially in combination with advanced corrosion-resistant steel such as Cronidur 30 or surface-hardened steel such as M50NiL, will become increasingly widespread. whereas fully ceramic bearings will only find very specific and therefore limited applications in the aerospace industry in the foreseeable future. It is becoming clear that combinations of Cronidur 30 or M50NiL with ceramic rolling elements are very advantageous material combinations.[1][8][9][10][11]

The following describes the methods of hardening and remelting steel for the production of bearings for aerospace applications and how they affect the steel.

4.1. Hardened steels

4.1.1. Secondary hardened steels

Bearing steels must maintain a hardness above 58 HRC under operating conditions, and any deviation from this value may lead to the formation of pitting in the raceways and subsequent degradation of the bearings. Steels for secondary hardening can maintain their hardness at elevated temperatures up to 300 (°)· C·Tool steels such as M50, which contain alloying elements such as molybdenum, belong to this class of steel, and among secondary hardening steels, M50 is the most commonly used steel for aircraft engines. The ability of this steel to maintain high strength and hardness is attributed to the formation of molybdenum carbides at higher temperatures. T1 (18-4-1) steel was developed for bearings used in gas turbines and contains tungsten as the main alloying element. Similar to M50, T1 steel forms tungsten carbides when tempered at higher temperatures.

Extensive research has been conducted on the evolution of microstructure in M50 steel in response to heat treatment, retained austenite content, and the correlation between microstructure and fatigue life. New heat treatment processes other than the traditional quenching and tempering (Q-T) sequence have also been developed for this steel grade. Although M50 steel with a martensitic structure is traditionally used in bearings, a bainitic structure can also be achieved for these steels. Double hardening of M50 steel by plasma nitriding has been investigated and it has been found that the nitriding process introduces further secondary hardening by precipitating fine secondary carbides. Another important aspect is the dimensional stability of M50 under operating conditions, as a change in the fit of the bearing rings to the shaft can affect the performance of the bearing and even reduce its service life. A relatively newer class of bearing steels with a high nitrogen content, such as cronidur-30, also exhibits a secondary hardening effect when tempered at 475 °Cand is becoming the preferred candidate for use in high-performance aerospace systems. [1]

4.1.2. Steels with increased strength

Hardened steels such as M50 or AISI 440C are not suitable for applications where bearings are exposed to impact loads during operation. These steels are characterised by a fracture toughness of 20-30 MPa. Another application in which these steels cannot be used is in applications requiring the bearing rings to be pressed onto the shaft, which causes tensile stresses on the rings. To solve these problems, steels with increased strength have been developed. The above-mentioned M50NiL steel, a derivative of M50 with a lower carbon content and a higher Ni content, was developed for the production of carburising steel. These steels can be surface hardened, with the outer layer being carburised (temperature range from 840 to 950 (°) C)to achieve high hardness, while [illegible]remains soft and ductile. This feature makes

The bearings can withstand impact loads thanks to the greater hardness of the material, and the hard housing minimises friction and wear at the points of actual contact. Further hardening of the housing introduces residual compressive stresses on the surface, which improves fatigue life and also helps to mitigate the harmful effects of circumferential stresses on the inner rings at very high rotational speeds. [1]

4.1.3. Continuously hardened using the "Duplex" method

Duplex hardening is a process used to obtain the unique properties of bearing steels used in the aerospace industry, in which conventional heat treatment methods, such as secondary or surface hardening, are followed by a surface nitriding process to obtain better properties

. During this process, nitrogen diffuses into the outer layers to a depth of 0.2 mm and additionally increases the hardness of the surface layer. M50NiL contains a significant amount of alloying elements such as Mo, V and Cr, which form carbides during carburising, and during surface nitriding, these carbides dissolve in the matrix and then form nitrides of these alloying elements.

Two key advantages over carburised steels are the higher hardness of the nitrided layer and the greater residual compressive stresses on the surface, which cause these steels to have better properties than carbon steels when it comes to bearing operation in demanding conditions, such as lubricant shortage and contaminated environments. The improved durability of bearings made of duplex hardened steel compared to steel hardened only by conventional methods or surface-hardened steel has been well documented. [1]

4.2. Powder steels

The concentration of alloying elements in bearing steels determines the volume percentage of precipitates formed during hardening, and therefore the limit of mechanical properties is determined by the concentration of alloying elements. Another aspect to note is that if the concentration of alloying elements is increased above a certain threshold, it will cause microsegregation during solidification, which will result in composition gradients in the remelted elements, leading to poorer mechanical properties. Therefore, in the case of conventional alloy steels for bearings, the maximum achievable hardness was limited to the range of 62-64 HRC. With the advent of hybrid bearings, steel became the weaker element in the bearing contact and intensive efforts were made to further increase the mechanical strength of bearing steels. These efforts resulted in the development of metallurgical steels with a higher content of alloying elements, in which chemical segregation cannot exceed a scale longer than the size of the powder, and REX20 and CRU20 CRU80 and CRU20 are among the most commonly used powder steel grades. CRU20 achieves hardness of 66-67 HRC (yield strength of 4000 MPa), which, when used in hybrid bearings, can increase fatigue life up to six times compared to SAE 52100 steel. [1]

4.3. Steel smelting

It is well known that alloy inclusions (impurities) negatively affect the fatigue strength of bearing steels, which is why advanced steel smelting practices are used for bearing steels in aerospace systems in order to increase the reliability and durability of these bearings. Bearing steels can be divided into three broad classes depending on the smelting sequence. The critical role of steel purity levels in the fatigue life of bearings is well established, and Figure 4.3 clearly shows the improvement in bearing life due to multiple levels of vacuum refining of steel.

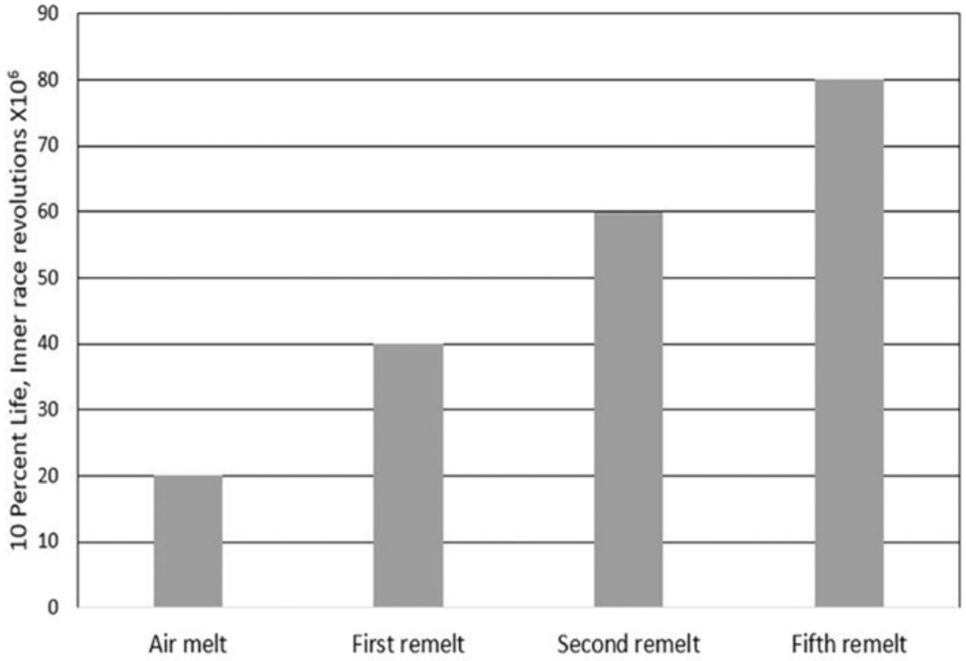


Figure 4.3. Relationship between bearing service life and type of steel smelting

4.3.1. Vacuum-smelted steels (individually)

These steels are produced using vacuum induction melting (VIM) and, as the name suggests, they are melted in a vacuum in an induction-heated crucible. Vacuum melting is an advanced melting method in which it is possible to achieve a chemical composition close to the target composition. This process helps to eliminate the porosity observed in conventional steels smelted in air and significantly reduces the level of oxygen and nitrogen. The vacuum atmosphere also helps to eliminate most trace impurities such as arsenic, antimony, selenium, bismuth and copper. In addition, the absence of oxygen eliminates the formation of oxides by impurities such as aluminium and calcium. This is the most widely accepted method of refining steel used in aircraft bearings. [1]

4.3.2. Double vacuum-smelted steels

These steels are produced using the VIM (vacuum induction melting) process, followed by the VAR (Vacuum Arc Remelting) process. The VIM process is used to produce the consumable electrode, and in the VAR process, the consumable electrode is melted by creating an electric arc between the electrode and the molten metal in a water-cooled copper crucible. Metal droplets are carried by the arc, which is generated in a vacuum chamber. As a result, the metal undergoes additional refining. Due to the complexity of the process and the resulting high cost, it is only used in critical applications requiring bearings with a long service life, such as spacecraft bearings.

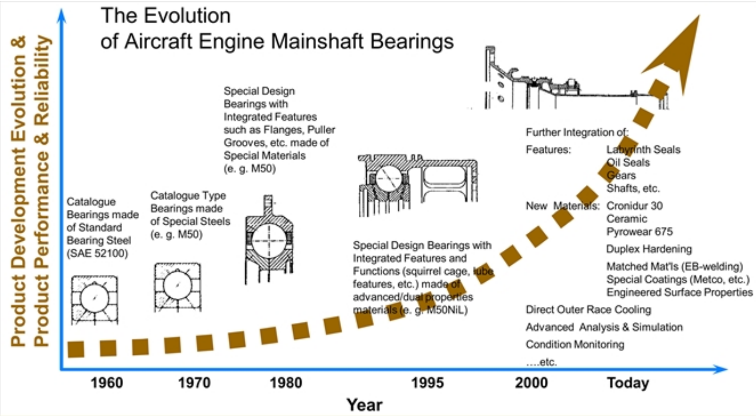
4.3.3. Continuously triple vacuum melted

This process produces steels with the lowest alloy content and, as the name suggests, the steels undergo three levels of vacuum melting (VIM) + electric arc remelting (ESR) + VAR. These steels have the most homogeneous and pure microstructure. In the ESR process, alternating current is passed through a steel electrode, one end of which remains in contact with refractory slag. The molten metal passes through the slag and is collected underneath it, while the chemically active slag removes non-metallic oxides, free oxygen and sulphur. This is the most expensive type of bearing steel, used exclusively in critical applications at high speeds.

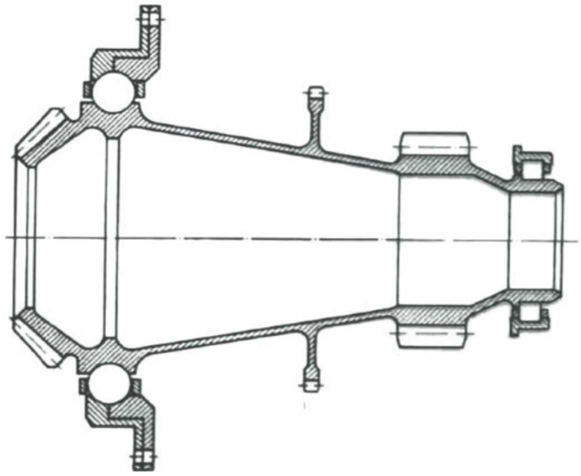
5. Integration of structures

Another design concept currently used in aircraft bearings is an integrated design approach, in which one of the bearing rings or races is integrated into the mechanical system. Weight reduction equals cost reduction. This principle is particularly applicable in the aerospace industry. Integrated bearing designs offer significant advantages in this respect. The technical advantages of an integrated bearing design are obvious: reduced number of components, lower tolerance stack-up, smaller and more compact design, and overall weight savings for the system. The resulting benefits for the user are: fewer tight tolerances to manufacture and control, ease of installation, increased efficiency and reliability, and reduced system cost. Examples of such advanced, integrated bearing design concepts are shown in Fig. 5.1.

It is clear that such an integrated design, comprising bearing races, gear wheels, shafts and structural parts, requires the combination of different material properties within a single component, i.e. hard functional surfaces for good resistance to fatigue and wear, and greater plasticity in structural areas. [8]

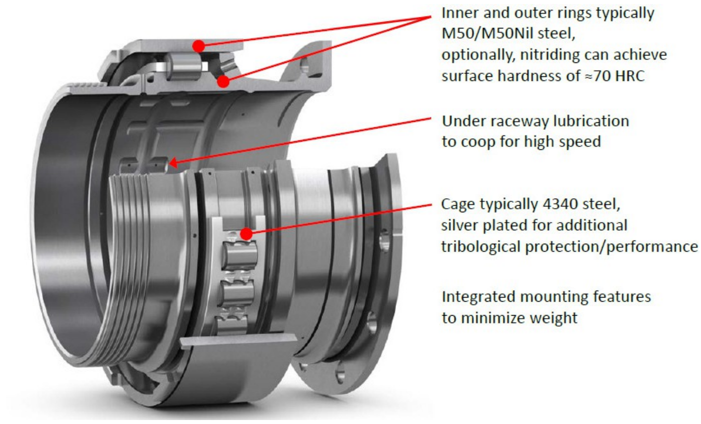


(a) Evolution of motor shaft bearings



(b) Example of bearing integration 1

(c) Example of bearing integration 2



(d) Example of bearing integration 3

Figure 5.1

6. Vibration damping

Longer periods between overhauls, as required by airlines, have prompted the introduction of dampers to reduce vibration stresses caused by rotor imbalance. Reducing vibration levels makes it possible to increase the service life of rotors, bearings and many other components to meet the requirements of longer periods between overhauls. In addition to the possible excitation of the rotor itself, the unbalanced loads transmitted by the bearings cause vibrations in the motor housing and supporting structure. These unbalanced loads are mainly transmitted by roller bearings. Vibration dampers have been developed to counteract these undesirable phenomena.

6.1. Oil dampers

Due to the fact that most vibrations are transmitted through roller bearings, the logical solution was to install a shock absorber in series with this bearing and its support, as shown in Fig. 6.1. Hydraulic dampers, in which the vibration energy is dissipated in a viscous oil film, proved to be a good solution.

The basic viscous damper acts as a non-rotating hydrodynamic bearing and is shown in Fig. 6.2. As a result of the rotation of the shaft transmitted by the roller bearing in the oil layer in the damper ring, a hydrodynamic compressive force occurs. The subsequent viscous shear causes damping, which reduces the transmitted amplitudes and forces. [4]

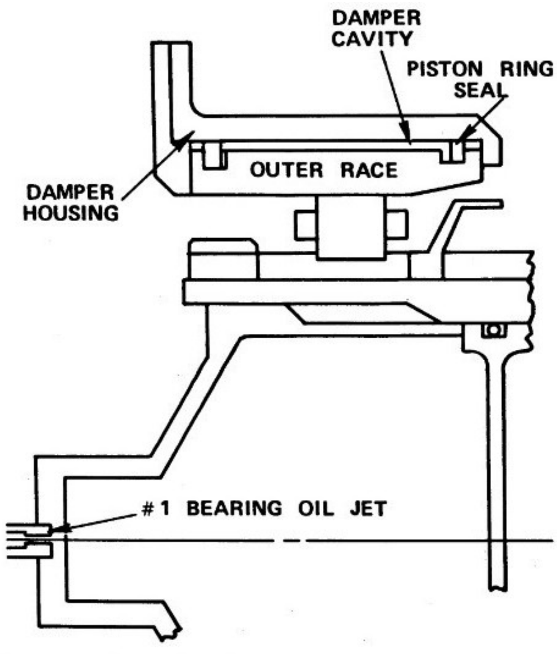
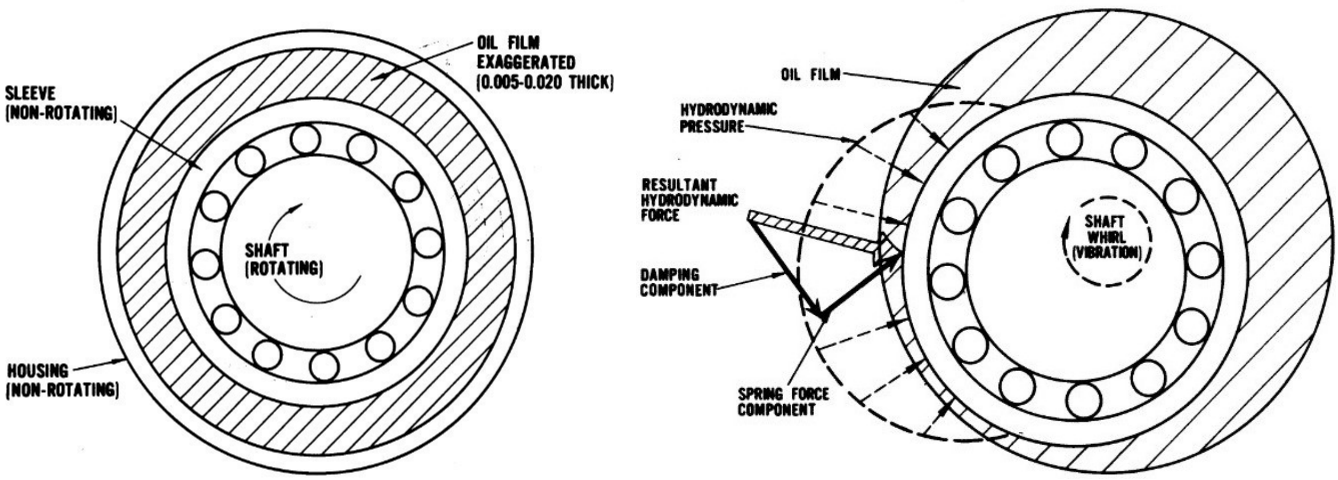


Figure 6.1. Schematic diagram of the oil damper design



(a) Oil damper operating diagram

(b) Forces acting on the oil damper

Figure 6.2

6.2. Mechanical dampers

Another method of vibration damping is mechanical damping. The design of these dampers (springs) resembles that of a cage (hence the English name – squirrel cage).
"squirrel cage"). It is a thin-walled cylinder with milled holes around its circumference, which makes it sufficiently flexible to undergo elastic deformation and thus dissipate the vibration energy transmitted from the rotor through the bearing. As a rule, solutions of this type are used for high-pressure compressor bearings.

This type of damper must be tuned to a specific engine, because in order for it to be effective, the forces acting on the engine must be sufficient to deform it. Before installing the bearing in the engine, calibration is performed using strain gauges mounted on the spring centres. An axial load corresponding to the maximum pressure exerted by the engine is applied to the device and the corresponding deformation values are measured. [12][11]

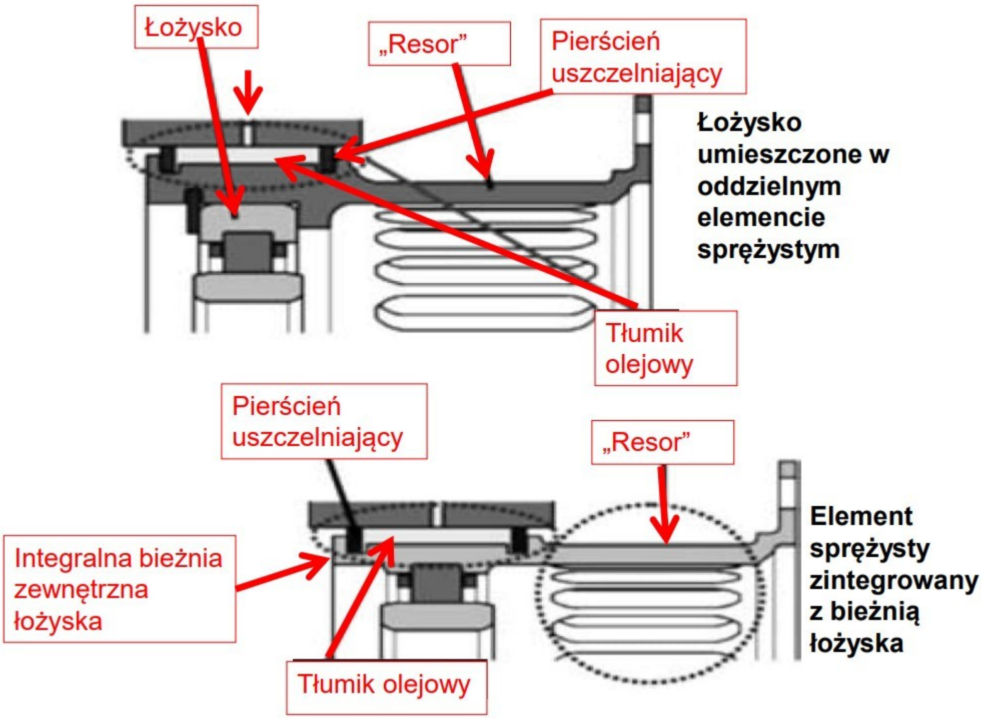


Figure 6.3. Description of the components of a mechanical vibration damper

Figure 6.4. Example of a mechanical vibration damper

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