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Sliding Bearing Applications in Aircraft and Space Engineering

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Examples and prospects of various types of sliding bearings applications in power elements of aircraft engines and in turbopump units (TPU) of liquid propellant rocket engines (LPRE) are discussed in this article.

In the second half of the last century, piston aircraft engines were replaced by turboprop (TPE) and turbojet (TJE) engines. Almost all leading manufacturers of these motors use rolling bearings as rotor supports for the main power units. The use of sliding bearings is extremely rare and is the exception rather than the rule. These exceptions include the company Pratt & Whitney, which has been using sliding bearings since the 1950s (engine PT6A). The sliding bearings are also used in modern turbofan engines Pratt & Whitney PW1000G series. The use of sliding bearings as a support for planetary gearbox elements has a number of advantages over rolling bearings, since under normal operating conditions such supports have a significantly longer service life.

In rocketry, sliding bearings are used as supports for a LPRE TPU. Examples of such supports are hydrodynamic sliding bearings of the first German missiles during the Second World War (one of them was the FAU-2) and Soviet missiles developed by S.P. Korolev and V.P. Glushko. As our analysis has shown, in the 50s the use of sliding bearings in LPRE was abandoned due to a number of advantages of rolling bearings over sliding bearings, especially taking into account the very short service life of these engines (hundreds of seconds). Recently, however, sliding bearings as supports for a TPU have been attracting more attention again due to the development of reusable missile systems with a sharp increase in required service life. Although the results achieved for TPU with rolling bearings still provide the required durability, studies of the sliding bearings for TPU design with increased service life are relevant.

The data obtained as the result of the analysis describe existing practice of using sliding bearings in units of aircraft and rocket engines, as well as the prospects for their further use.

Keywords: sliding bearing, rolling bearings, practice of using, aircraft engines, turbopump units LPRE.

Introduction

It is known, that two main types of bearings for shafts and axles are used. They are: sliding bearings and rolling ones. An attempt to analyze examples and prospects for the use of various types sliding bearings in power elements of aircraft engines and in turbopump units (TPU) of liquid propellant rocket engines (LPRE) was the objectives of this review.

1. Aircraft Engines

Piston aircraft engines, as well as automotive internal combustion engines (piston engines) aren't considered at this section because a lot of the articles should be the subject of separate consideration. The piston engines field of use is light (and ultralight) aviation only.

In the middle of 40s last century, piston aircraft engines were replaced by turboprop (TPE) and turbojet (TJE) engines [1,2]. The leading engine manufacturers have used rolling bearings as rotor ones in the main power elements of the engine (a compressor, a turbine, a gearbox). The usage of the sliding bearings is extremely rare and it is the exception rather than the rule.

Pratt & Whitney company (Canada) is an example of adherence to this type of support. Moreover, this company has been maintaining its commitment to the sliding bearings since the 1950s to the present day.

Let's consider turboprop engine PT6A [3] developed by Pratt & Whitney in the late 50s and early 60s (Fig. 1).

Fig. 1. Turboprop engine PT6A

The PT6 engine appeared in the late 1950s, when it became necessary to replace the popular Pratt & WhitneyWasp radial piston engines with more modern and efficient turbines. Full-scale production of the new engine began in 1963. To celebrate its 50th anniversary, Pratt & Whitney has supplied more than 39,000 PT6A engines of various modifications and is used in more than 100 different aircraft models.

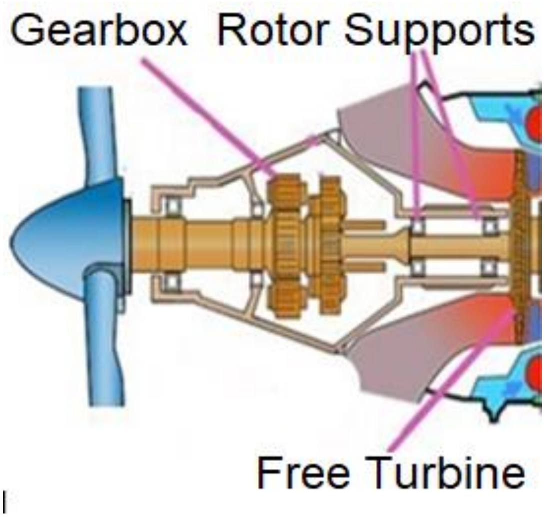

Fig. 2. Scheme of PT6A with planetary gearbox

The engine reducer (Fig. 2) is a two-stage planetary gearbox and it is designed to transfer motion from a free turbine to the propeller [4]. The gearbox has an input of 33 000 rpm, the gear ratio is ***i*** = 15, power 500…550 HP.

The hydrodynamic bearings are used as satellite supports in the first gearbox stage. Also, such bearings operate as supports for the satellites housing.

Usually, the central links of the planetary gear transfer are unloaded from the radial forces, but the bearings into sattelites are loaded with significant tangential forces from the mating wheels.

The satellites of both gear stages are mounted on axles fixed in the casing of the satellites. The satellites are supported by hydrodynamic bearings.

In addition, the casing of the first stage satellites locates on the gear casing through a hydrodynamic bearing made in the form of a sleeve, which inner surface is coated with an anti-friction alloy.

To lubricate the hydrodynamic bearings of the satellites and the wheels of the first stage of the gearbox, oil from the gearbox oil system is used.

Some decreasing of radial dimensions and weight of the gearbox has been achieved due to the use of hydrodynamic bearings.

Sliding bearings have found application in modern turbofan engine designs [5].

A turbofan engine in popular literature is usually called as turbojet bypass engine (turbojet engine) with high bypass ratio (more than 2) [6, 7].

Typically, in a turbojet engine, a fan and a turbine that rotates it are connected by a common shaft and, therefore, have equal rotational speed. This scheme is structurally simple, but at the same time the fan limits the turbine rotational speed because great centrifugal forces are produced by the fan big size and transonic flows should be avoided at the periphery of the fan thirst blades. The sound barrier transition is fraught with a number of negative effects, which result in a decreasing of the fan efficiency to an unacceptable level. The problems described above may be solved by means of gearbox be installed between a fan and LP compressor [8]. The planetary gearbox used in the Pratt & Whitney PW1000G series motors [9] allows the fan and the low-pressure parts to rotate independently of each other at the most efficient speed for them.

In the PW1000G (Fig. 3) the fan rotates more slowly, allowing engineers to increase its diameter. Increasing the size of the blades increases the amount of air passing through the fan, resulting in improved engine efficiency as well as noise reduction.

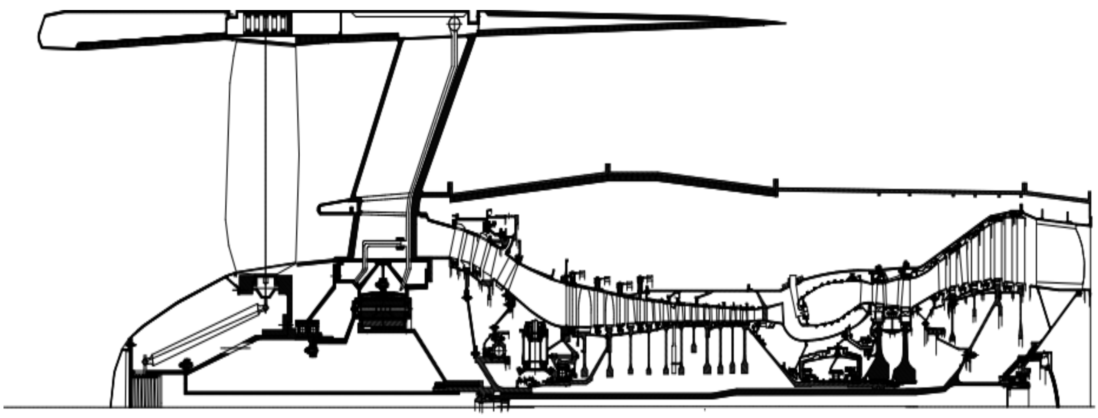

Fig. 3. PW1000G cross section

The external view of the engine, its main components and the gearbox are shown in Fig. 4 [10].

The bypass ratio of the PW1000G can be increased not only by increasing the fan, but also by reducing the internal circuit. The fact that the compressor and low-pressure turbine rotate at an increased speed (independently of the fan), makes their parts more compact and lightweight. As a result, the bypass ratio of the new PW1000G increases up to 12:1.

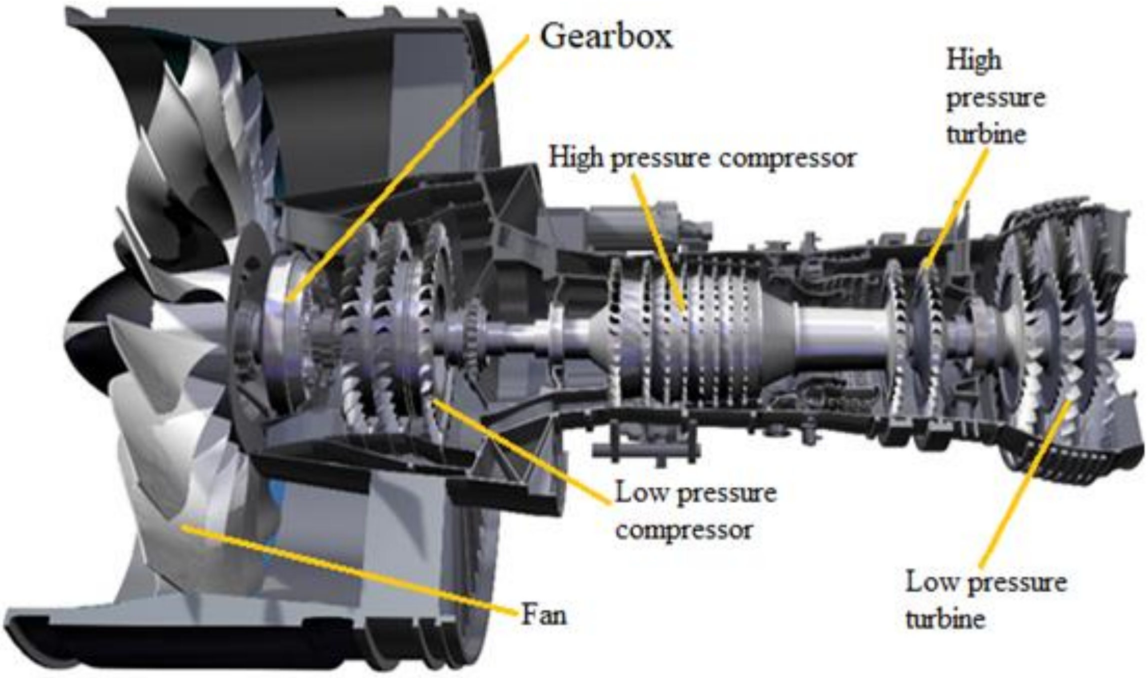

Fig. 4. PW1000G main components

The gearbox (Fig. 5, 6) is a planetary gear made according to the scheme $\overline{AI}$, which consists of driving central wheel 4, satellites 2, mounted on hydrodynamic bearings 3, and wheel 1 with internal teeth. Oil for lubrication of bearings and gears is supplied from the engine oil system through oil supply holes and channels.

The performed analysis has shown that, although sliding bearings are used in modern aircraft engines, they are very rare.

Fig. 5. Scheme of $\overline{AI}$ planetary gearbox

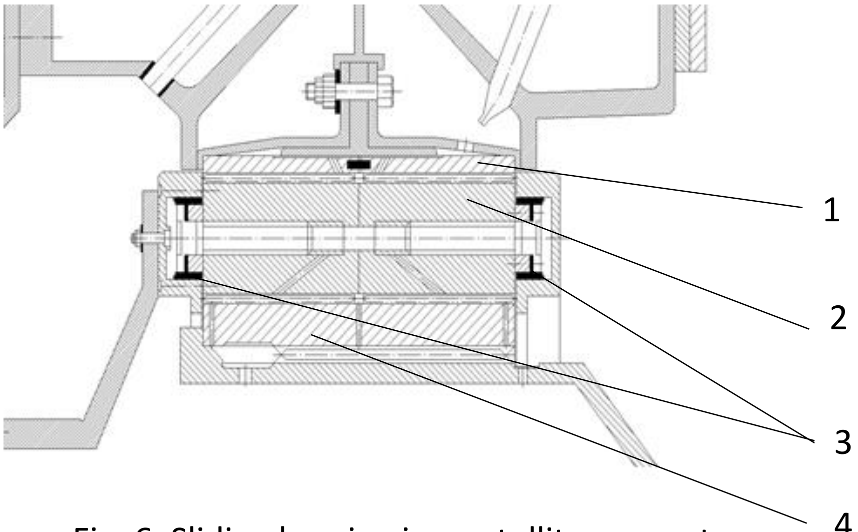

Fig. 6. Sliding bearing in a satellite support

2. Rocket Technology

Let us consider the supports of TPU of LPRE as an example of the sliding bearings usage in a rocket technology.

Rocket A-2 created by German engineer Wernher von Braun [11, 12] was successfully launched In Germany in 1934 year. It was a small model that worked on ethanol (ethyl alcohol) and liquid oxygen. The military was most interested in the possibility of using ethanol as one of the fuel components at the time of a constant shortage of petroleum products for Germany. Ethyl alcohol was produced in large quantities as a result of processing potatoes and by hydrolysis of wood. This kind of fuel was used by the Germans throughout the Second World War.

Liquid oxygen was used as an oxidizing agent.

Having achieved success with the A-2, the von Braun group moved on to develop rockets A-3 and A-4 (future "FAU-2"). The rockets were single-stage and had liquid propellant rocket engine. Fig. 7 show the prepared TPU of the FAU-2 rocket. Hydrodynamic sliding bearings were used for the oxygen pump.

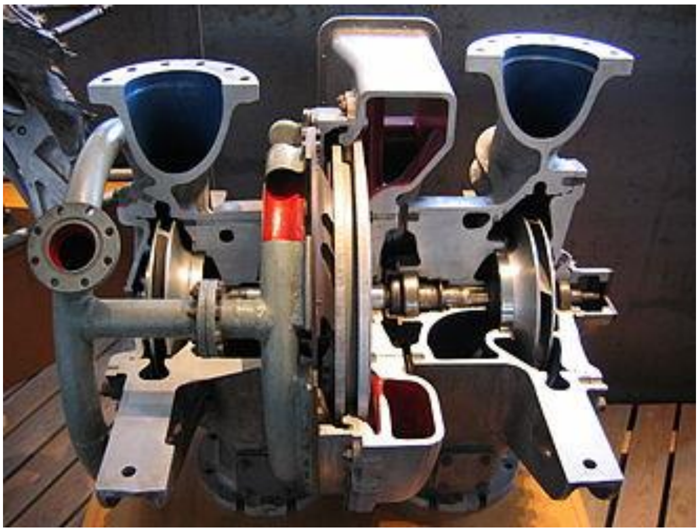

Fig. 7. TPU of the FAU-2 rocket

After the end of the Second World War, the American occupation authorities took out from Germany to the United States together with Wernher von Braun about 100 ready-made missiles in the disassembled form.

The Soviet Union got production without technical documentation, individual parts of missiles without drawings and calculations. The search for the complete rocket lasted for about a year.

When it became clear that these efforts would lead nowhere, they focused on self-restoration of FAU-2 as a basis. The R-1 rocket was the first large ballistic missile created in The Soviet Union. It had certain design differences from the prototype, due to the lack of solid samples of the FAU-2 and the difference in the material and design base.

For several years, these works under the direction of Sergei Korolev have been successfully completed [13]. Korolev realized the first launch of the R-1 rocket on October 10, 1948. Oxygen-alcohol engines RD-100 (as well as subsequent RD-101 and RD-103) were developed by V.P. Glushko.

R-1 rocket turbopump unit (Fig. 8) of the RD-100 engine was not much different from the TPU of the FAU-2 engine. The supports of the oxygen pump were also hydrodynamic (Fig. 9), as in the prototype. Fig. 8 shows the turbopump assembly of the R-1 (8A11) rocket at the stand of the Kapustin Yar test site museum, Znamensk.

Fig. 8. R-1 rocket turbopump unit

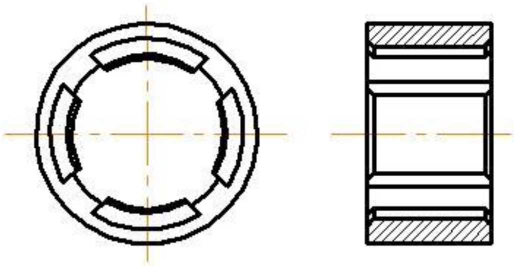

Fig. 9. A hydrodynamic support

Later the fuel components liquid oxygen-kerosene instead of ethyl alcohol were used.

New rocket motors developed in the 1950s don’t use sliding bearings. They have been completely replaced by rolling bearings.

Here are several reasons of this choice:

– rolling bearings are easy to install,
– they have stable design parameters,
– have a lower coefficient of friction,
– provide the required load capacity,
– have smaller axial dimensions.

Moreover, the service life of the units of the LPRE power systems is at least several thousand times lower than the service life of aircraft engines. For example, the operating time of some TPU are: for engine RD-103 is 115…120 s; RD-105 – 130 s; RD-106 – 330 s; RD-107 – 140 s.

The RD-107 engine, developed in the 50s for the first famous ballistic missile R-7 (it launched the first artificial satellite in 1957) had a TPU, which rotor was supported by rolling bearings [14].

Lubrication and cooling of ball bearings in TPU of RD-107 was carried out as follows: in the oxidizer pump – with a small consumption of liquid oxygen from the high-pressure cavity, in the fuel pump – with the help of a special grease which is resistant to fuel.

The question of replacing rolling bearings with sliding bearings arose in connection with the development of reusable motors, where the service life of TPU and bearings should be significantly increased.

For the bunch of four engines in the LV "Energia" central block of space system "Energia-Buran" [15,16] liquid-propellant rocket reusable rocket engine RD0120 was developed according to the technical assignment of NPO Energia (now – RSC Energia, Korolev, Moscow region) at the Khimavtomatika design bureau (KBKhA) in the period from 1976 to 1986.

The RD0120 oxygen-hydrogen rocket engine was designed and manufactured in a reusable version, which makes it possible to reuse the engine without bulkheads.

Subsequent developments of such engines were oxygen-hydrogen LPRE RD-146, RD-146D (operating time 560 s and 1350 s, respectively) [17].

In LPRE used in the upper stages of the rocket, the durability of the bearings was about one hour at their rapidity $\boldsymbol{d_m}$ $\boldsymbol{n}$ = $(2...3)\cdot 10^6$ mm·rpm ($\boldsymbol{d_m}$ is the mean bearing diameter). According to the TPU developers information, they managed to achieve the level of durability of rolling bearings of about 1 hour at the rapidity parameter of $(3{,}1...3{,}6)\cdot 10^6$ mm·rpm.

Therefore, the results achieved for TPU with rolling bearings still satisfy the required durability, and replacing them with sliding bearings is not urgent [18,19]. Especially, if the reasons as follows are taken into account: the flow quantity through the sliding bearings is much greater than through the rolling bearings, axial fixation of the shaft is absent, and the volumetric efficiency of the pump decreases.

However, the investigations deal with the possibility of sliding bearings application in the TPU liquid-propellant engine to increase their resource have been and are being carried out over the last decades [20].

At the end of the 80s KBKhA with the participation of the author of this article, carried out work to extend life of hydrostatic bearing supports for an oxygen-hydrogen rocket engine. To test it in an experimental set the turbopump unit was created.

The part of this TPU, which includes turbine 1, pump impeller 2 and support unit 3, is shown in Fig. 10. Bearings 2 of rotor 1 (Fig. 11) were installed on elastic elements 3 (see invention certificate No. 1700003 "Sliding support with lubricant supply under pressure"). The lubrication of the bearings with fuel components was envisaged. A pneumo-hydraulic test scheme for liquid hydrogen was developed, and the stand systems in Zagorsk were being prepared. But the situation dramatically changed with the collapse of the Soviet Union, and these works were stopped.

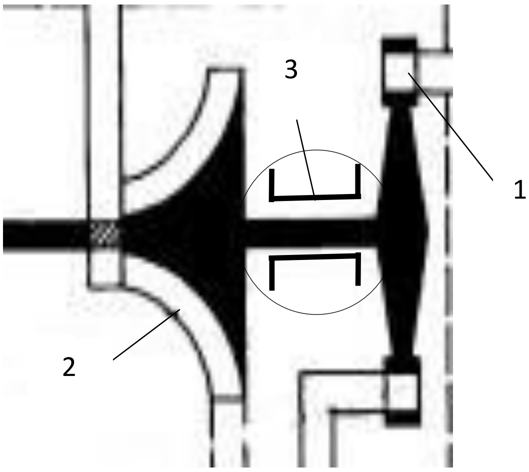

Fig. 10. TPU scheme

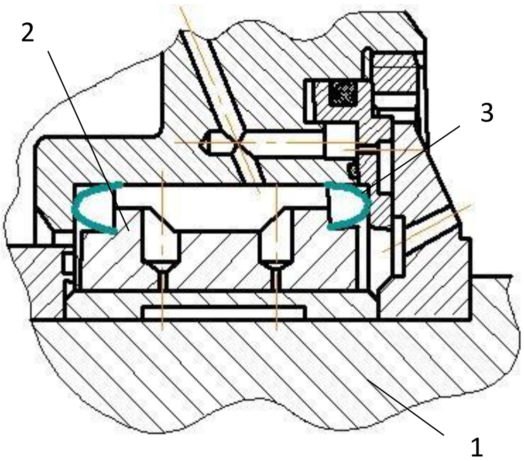

Fig. 11. Sliding bearing on elastic elements

Thus, at present, the existing designs of rolling bearings cope with the tasks set, i.e. without sliding bearings, the development and refinement of which as part of the TPU liquid-propellant engine requires significant efforts, until it is possible to do without.

Conclusion

Thus, if we trace the history of the use of bearings in technology, including in various types of transport devices, we can note the initial widespread use of sliding bearings, which were then replaced by rolling bearings in many machines for various purposes.

However, in recent decades, there has been some recovery of sliding bearings in their positions. This is due, first of all, to an increase in the rotational speed of modern machines and the need to increase their resource.

In addition, there is a fairly large number of areas of technology where sliding bearings (liquid and gas) are traditionally used: automobile transport, power plants of water transport, powerful turbines of nuclear power plants, chemical engineering, etc.

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Використання підшипників ковзання у авіаційній та космічної техніці

В статті розглянуті приклади і перспективи застосування підшипників ковзання різних типів в силових елементах авіаційних двигунів і в турбонасосних агрегатах (ТНА) рідинних ракетних двигунів (РРД). З другої половини минулого століття на зміну поршневим авіаційним двигунам прийшли

турбогвинтові (ТГД) і турбореактивні (ТРД) двигуни. Практично усі провідні виробники цих двигунів використовують в якості опор роторів основних силових вузлів підшипники кочення. Використання підшипників ковзання вкрай обмежено, і це швидше виключення, ніж правило. До таких виключень відносяться двигуни фірми Pratt&Whitney, яка використовує підшипники ковзання з 50-х років минулого століття (двигун PT6A) до теперішнього часу. В сучасних розробках компанії Pratt&Whitney підшипники ковзання знайшли застосування в турбовентиляторних двигунах серії Pratt&Whitney PW1000G. Використання підшипників ковзання для опор елементів планетарних редукторів має ряд переваг перед підшипниками кочення, оскільки при забезпеченні нормальних умов роботи такі опори мають значно більший ресурс.

У ракетній техніці підшипники ковзання використовуються як опори ТНА рідинних ракетних двигунів. Приклади таких опор – підшипники ковзання гідродинамічного типу перших німецьких ракет часів другої світової війни (однією з них була ФАУ-2) і радянських ракет розробки С. П. Корольова і В. П. Глушко. Як показав аналіз, в 50-х роках від використання підшипників в РРД відмовилися в силу ряду переваг підшипників кочення перед підшипниками ковзання, особливо з урахуванням дуже малого ресурсу роботи цих двигунів (сотні секунд). Проте останнім часом у зв'язку з розробкою ракетних комплексів багаторазового використання, де різко зростає необхідний ресурс, знову спостерігається інтерес до повернення підшипників ковзання у склад турбонасосного агрегату. І хоча досягнуті результати для ТНА з підшипниками кочення доки забезпечують необхідний ресурс, актуальними є дослідження підшипників ковзання для створення ТНА підвищеного ресурсу. Отримані в результаті аналізу дані дають уявлення про існуючу практику використання підшипників ковзання у вузлах авіаційних і ракетних двигунів, а також про перспективи їх подальшого застосування.

Ключові слова: підшипники ковзання, підшипники кочення, практика використання, авіаційний двигун, турбонасосний агрегат РРД.

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