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REVIEW

A Comparative Review of the Lubrication of Bearings in Wind Turbines and Spacecraft to Address Wind Turbine Bearing Failures

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ABSTRACT

Wind turbines have improved in terms of reliability over the past ten years, but they still experience crucial and expensive tribological issues that shorten their intended lifespans. Most turbines require significant repairs or complete replacements of the tribo components in the 5- to 7-year range. The pricey gearboxes have high repair rates, which greatly raises the operating costs for wind turbines and the cost of wind energy. Currently, various bearings in the turbine are lubricated by automatic lubrication systems with the necessary oil filters to ensure cleanliness. The commonly used lubrication methods for wind turbine bearings are centralized lubrication, oil-air lubrication, oil mist lubrication, and oil bath lubrication. There are similarities between wind turbines and spacecraft-moving mechanical systems. Most spacecraft are designed to work for decades in a remote environment without periodic maintenance. Spacecraft use efficient lubrication systems for their moving mechanical systems to provide the required lubricant to the bearings for the required life. Depending on the lubrication requirements, proven active and passive lubrication systems are employed in spacecraft. This paper reviews the lubrication issues of the wind turbine in comparison with the spacecraft and proposes a few lubrication systems that are successfully performing in spacecraft, intending to improve the reliability of wind turbine tribo-systems.

1. INTRODUCTION

With the ever-increasing demand for energy, the threat of climate change, and dwindling fossil fuel reserves, finding sustainable/renewable and affordable energy resources has become a priority for the government of every country. Many countries are now offering industry incentives to allow their governments to reach specific green energy targets that will aid emission reduction requirements and help in achieving the goal of security of energy supply. The European Union (EU), for example, has a mandatory 20% target for energy production from renewable resources for 2020, with United Kingdom's share negotiated at 15% [1].

Renewable energy is vital in every country's future pledged to transition to a low-carbon economy. Currently, renewable energy sources used to generate electricity include hydro, geothermal, biomass, biogas, wind, and solar energy. An estimate of the primary energy available from various sources is depicted in Figure 1 [2,3]. According to Energy Statistics Pocketbook 2022 by the United Nations Department of Economic and Social Affairs [4], the total useful energy consumption from all sources in 2020 is 567 Exajoules (18 TWy/y). Therefore, if only a fraction of the renewable energy from various sources is extracted, alone can meet the world's total energy requirements each year. Renewable technologies, except traditional biomass, are often termed 'modern renewables,' including hydropower, solar, wind, geothermal, and modern biofuel production.

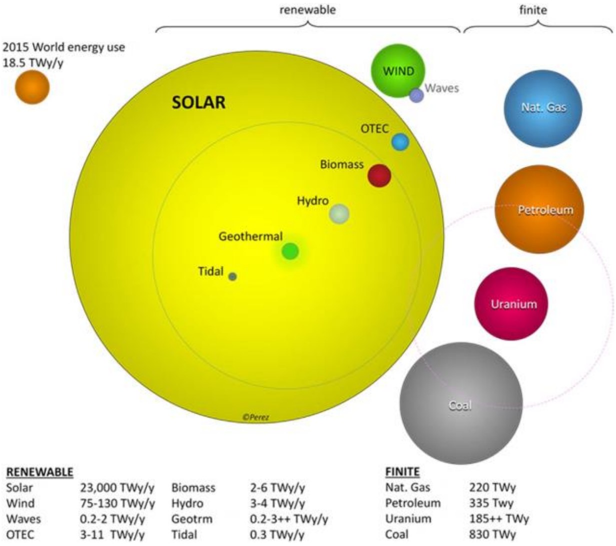

Fig. 1. Comparing the primary energy resources of the planet. The yearly resource is shown for the renewables, and total reserves are shown for the finite resources [2,3].

In 2020, the global energy production from modern renewable sources was 7444 Terawatt-hours, including hydropower [5,6], whereas the total consumption was 154,620 Terawatt-hours which is 4% less compared to 2019 due to the Covid-19 pandemic [7]. By the end of 2026, global renewable generation capacity is forecast to be more than 60% from 2020 levels to over 4800 Gigawatt (GW), which is equivalent to the current total global power capacity of fossil and nuclear combined [8]. To achieve the zero emission milestones 2050 set by the International Energy Agency (IEA), the world would need to add 825 GW of renewables each year until 2050 [6]. This indicates more significant potential for developing efficient systems to extract wind and solar energy. This paper concentrates on wind energy developments.

1.1 Wind energy

The wind is a free, clean, and freely available renewable energy source. Wind power is captured by wind turbines and converting it to electricity. Wind power is the fastest-growing energy sector in the world because of its many advantages, such as unlimited, free, renewable resources, economic value, maintenance cost, and placement of wind harvesting facilities [9]. Unlike traditional power plants, harvesting wind power is a clean, non-polluting way to generate electricity and emits no greenhouse gases.

1.2 Wind turbines

As mighty engineering marvels, wind turbines produce a significant amount of energy at a relatively small cost and with minimal environmental disruption. It is estimated that 72 terawatt (TW) of the earth's wind power is commercially viable for electricity extraction. Currently, the total global power consumption from all sources is about 18 TW [3]. By the end of 2022, all the wind turbines installed worldwide can generate 837 GW, enough to cover 4.65% of global electricity consumption [4]. The wind sector in 2020 had a turnover of $119.2 billion and employed 1.25 million people worldwide. Presently, the industry is undergoing tremendous growth, enjoying high public acceptance and full government support. Figure 2 [10] shows the worldwide total installed wind power capacity. Figure 3 [11] shows the growth of wind turbines in terms of rotor diameter (2R) size and associated power output.

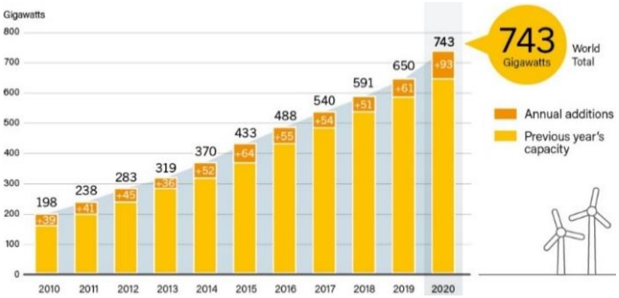

Fig. 2. Wind Power global capacity and annual additions, 2010-2020 [10].

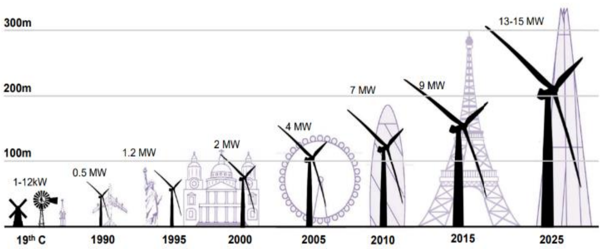

Fig. 3. Evolution of wind turbine heights and output power [11].

Structurally, a wind turbine consists of a rotor with a wing-shaped airfoil attached to a hub. The rotor hub is directly attached to the nacelle, which houses the gearbox, connecting shafts, support bearings, and a generator (Figure 4) [12]. The turbines sit on towers 60 to 120m above the ground to take advantage of the low turbulent but faster wind, with rotor diameters often reaching more than 75m. In a typical horizontal axis wind turbine design, the rotor blades are attached to a low-speed shaft that connects to the gearbox. The gears in the gearbox connect the low-speed shaft with the high-speed shaft and increase the speed of the rotor hub from about 20-60 rpm to 1,000-1,800 rpm to match the rated speed of most generators used to produce electricity. The high-speed shaft of the gearbox is coupled to the generator shaft, which turns inside the generator, producing AC electricity. Although wind turbines are gaining wide acceptance and being increasingly installed worldwide, some of the moving mechanical components in a wind turbine have tribology-related challenges that can drastically reduce their expected lifetimes [13].

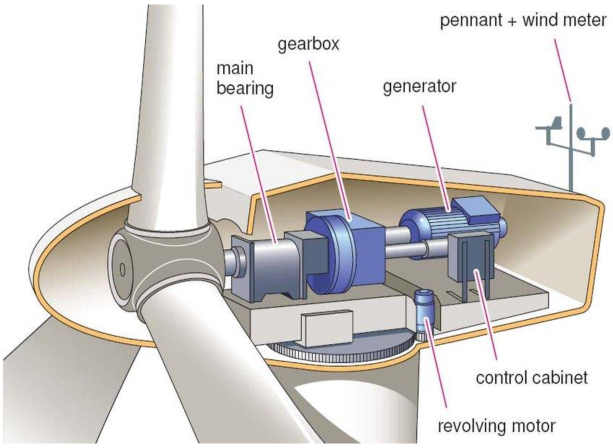

Fig. 4. Internal details of a typical horizontal axis wind turbine (HAWT) [12].

1.3. Gearbox and bearings

The gearbox in a wind turbine system typically employs three stages of gear enhancements to provide the required speed ratio between the low- and high-speed shafts. Each stage is designed either as an epicyclic or parallel arrangement, with one or two intermediate shafts transmitting power between the low-speed and high-speed shafts. The low-speed stage of the gearbox is generally a planetary configuration with either helical or spur gears. The sun pinion in the planetary configuration drives a parallel intermediate shaft that, in turn, drives a high-speed stage. Both the intermediate and high-speed stages use helical gears. A generalized schematic of a wind turbine gearbox is shown in Figure 5 (a) and (b) [14].

Several rolling bearings support a wind turbine's main shaft, intermediate shafts, and gears. There are low-speed bearings and high-speed bearings. Low-speed bearings are used in the main shaft, blade pitch control, and yaw control. In comparison, the gearbox and generator bearings are designated as high-speed bearings. Also, several different types and sizes of bearings are used at various locations. Ball bearings are used in yaw control, pitch control, and generators. Most modern turbines use four-point contact bearings or ball-bearing slewing rings for pitch operation. Depending upon the size of the rotor blades, either single-row or double-row four-point bearings are used. Yaw bearing configurations are often single-row, four-point contact ball bearings, although double-row, eight-point contact ball bearings are also used. Roller bearings (cylindrical, spherical, or tapered) are used in the main shafts and gearbox. One of the significant features of wind turbine bearings is that they operate in a wide range of loads, from light to heavy loads (when exposed to gusts) [15]. The rotor shaft bearings repeat start, acceleration, deceleration, and stop operations irregularly as they are exposed to the fluctuation of load. Therefore, the optimal specifications for various parameters such as bearing type, clearance, number of rolling elements, crowning, and retainer must be examined for each condition (minimum, average, maximum load).

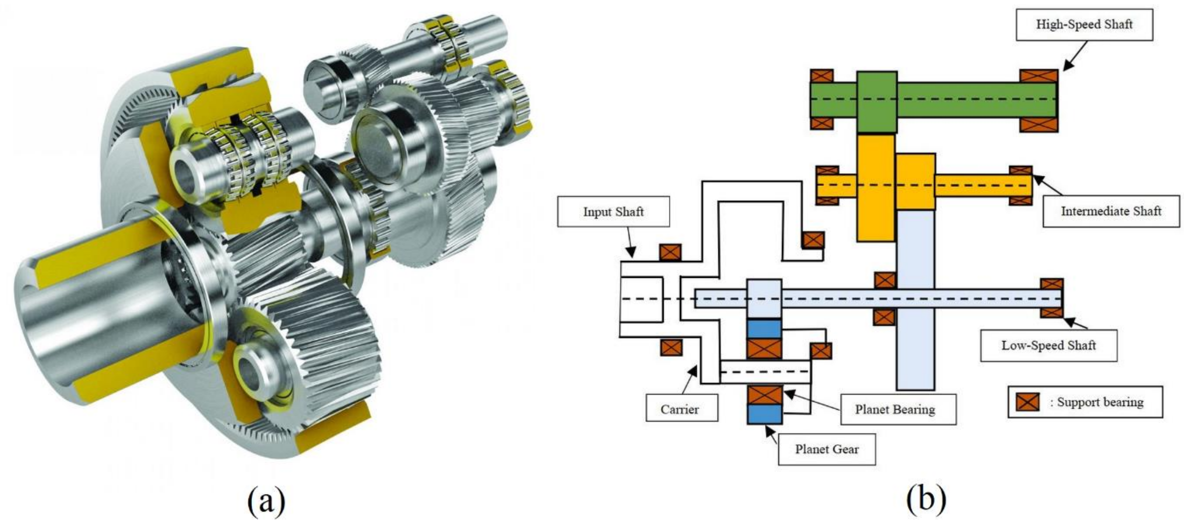

Fig. 5. Schematic of a typical gearbox arrangement [14].

The gears and bearings of a wind turbine system are subjected to both rolling and sliding contact under varying loads. These are lubricated with suitable lubricants to reduce friction and associated wear. Grease lubricant is generally used to lubricate blade root bearings, main shaft bearings, and yaw bearings. The gears and high-speed bearings are typically lubricated using liquid lubricants. The lubricating oil creates a thin film between the mating gears, allowing for elastohydrodynamic lubrication (EHL) between the mating surfaces.

Statistical reports from wind turbine manufacturers and the literature show that 25-70% of wind turbine downtime is due to significant component failure [1]. Gearboxes are not the only major component in a wind turbine; therefore, gearbox failures are below these figures. 60-85% of wind turbine gearbox failures are due to bearing failures. Rolling-element bearings are incorporated to support the rotor and rotor shaft, the gearbox shafts, and the generator input shaft, with the bearing arrangement depending heavily on the drivetrain layout. Rotor shaft bearings support the main shaft and the rotor blades, operating under dynamic axial and radial loads and slow speeds (approximately 20–30 rpm). The wind turbine gearbox bearings are designed to take extremely high loads, and the bearing performance criteria will be different throughout the gearbox. In some operating conditions, the requirement is to carry medium-sized loads at low speeds, while in some other conditions, the bearings need to carry much lower loads at far higher speeds [16].

2. LUBRICATION OF WIND TURBINES

There are a number of components in a wind turbine that demands flawless lubrication, such as the gearbox, open gear, pitch gear, pitch bearing, rotor shaft, yaw bearing, yaw gear, and generator bearings. These points require various types of lubricants, such as gear oils, hydraulic oils, and greases [17]. Wind turbine gears have relatively low pitch line velocity and high gear tooth loads. These conditions require either synthetic or mineral gear oil with antiscuff additives and the highest viscosity that is practical. Too low a viscosity can cause micro pitting, macro pitting, adhesive wear, and scuffing [18]. Gear oil is used in lubricating gearboxes, and grease is typically used on the main rotor shaft and yaw bearing, pitch drive gears, blade bearing, and generator bearing. In the hydraulic systems for the blade pitch control, hydraulic fluid is used. It is estimated that more than 80% of the lubricants used within the wind turbine industry are synthetic [19]. Synthetic lubricants such as PAOs (Poly Alpha Olefin), PAO/ester Blend, and PAGs (Polyalkalene Glycol) are typically used for the wind turbine. These can be further subdivided into hydraulic fluid, grease, and gear oil, considered the most essential synthetic lubricant for wind turbines [20]. Synthetic oils offer longer life, reducing the need for oil changes. A detailed study about degradation and condition monitoring of various lubricating oil for wind turbine gearbox appear in [21].

Several publications have already focused on grease composition for wear reduction of oscillating rolling element bearings [22,23].

Greases comprise base oil, which lubricates the contact, and a thickener to increase the consistency. Commonly used thickeners can be metal soaps, e. g., Lithium (Li), Calcium (Ca), complex, e.g., Lithium Complex (LiX), Calcium Complex (CaX), or non-soap like with Polyurea [24]. The base oils can be Mineral, Synthetic, or Ester oils with added additives. The contacts are lubricated by the base oil bleeding from the thickener. The assurance of an adequate lubricant film is critical to the reliability and longevity of tribo-components such as the roller bearings, gear teeth, etc., to operate in the elastohydrodynamic regime, in which significant elastic deformations of lubricated surfaces occur. Typical elastohydrodynamic film thickness would be within the surface roughness of the interacting surfaces, which is of the order of 0.01 -10 μm [25,26].

2.1 Tribological issues

Wind turbines have had several limitations to their mechanical system reliability due to tribological problems over the past few decades [27,28]. While several studies show that turbines are becoming more reliable, they are still not at an overall level acceptable to operators on their current business models. Experience shows that the electrical components are the most problematic; however, the parts are small and thus easy and inexpensive to replace in the nacelle on top of the tower. Tribological issues receive the most attention since they have higher costs associated with repair or replacement. These include the blade pitch systems, nacelle yaw systems, main shaft bearings, gearboxes, and generator bearings [29]. Of these, gearbox failures are regarded as one of the most severe breakdowns caused in a wind turbine for two reasons: first, the high cost of repairing or replacing the gearbox, and second, the resulting downtime. Due to these reasons, the wind turbine gearboxes have yet to achieve their original design life goals of 20 years. Most turbines require significant gearbox repairs and/or replacements in the five to seven-year range during the 20 years lifetime. A gearbox failure typically causes two to three times more downtime than any other component failure. Replacing a wind turbine gearbox primarily involves the gearbox cost, typically representing around 10% of the total wind turbine cost. On top of this expense, its transportation to the site, crane rental, mobilization cost, and the man-hours spent on the replacement [30].

The majority of wind turbine gearbox failures originate in the bearings. Recent studies show that bearings cause around 70% of gearbox downtime and 21-70% of generator downtime (21% on small generators ($P < 1$ MW), 70% on medium generators ($1 \text{ MW} < P < 2$ MW) and 50% on large generators ($P > 2$MW)) [31]. Unlike general-purpose industrial bearings, wind turbine bearings' loads and rotation speeds change considerably because of dynamic wind flows. In extreme operating conditions, large-scale wind turbine bearings experience excessive loads, and they can be potentially damaged [32]. Studies show that high-speed bearings in a wind turbine are most susceptible to failure [33,34]. These failures occur even though most gearboxes have been designed and developed using the best bearing-design practices. This points out that the issues are with the supplementary lubrication.

According to a reliability-centered maintenance (RCM) study by Katharina et al. [35], overloading, ineffective lubrication, and corrosion are the primary reasons of bearing failure that were discovered throughout the examination. It is known that inadequate lubrication of the bearing surfaces is the main cause of corrosion in bearings. A typical failure mode for wind turbine gearbox bearings is known as white etching cracks (WEC), which are subsurface fracture networks surrounded by microstructural changes [36,37]. WECs often begin below the surface of the bearing material and progressively rise to the top. Leaving them unattended could result in catastrophic failure by pitting or spalling the bearing surface. There is currently no commercial remedy for WEC, which is regarded as the most expensive failure mode for all wind turbine components [38]. Researchers have put out a number of theories as to why WEC forms, including sub-surface inclusions [39,40], hydrogen embrittlement [41–44], frictional energy or frictional power intensity [45], and the amount and direction of sliding [46,47]. Therefore, WECs can be avoided by using the proper materials, designing the bearing system to minimize stress concentrations, and providing adequate lubrication and maintenance.

It is also well known that wind turbines are installed offshore and onshore, and the turbines are located at a height up to 100m above sea or ground level. Therefore, frequent maintenance becomes more expensive. Today, as a renewable energy source, one of the concerns of using wind turbines is its high cost, especially the operation and maintenance costs. It is estimated that these costs represent 10-15% and 20-25% of the overall cost for onshore and offshore wind turbines, where the cost of unscheduled maintenance is about 30-60% of the total [1].

2.2 Lubrication systems

The lubrication methods used for various bearings also have major impact on the life-cycle. The majority of current lubrication methods are timed and quantified, which is highly likely to result in under or over-lubrication of bearings, thereby leading to wear or non-ferrous metal reactions and lubricant spillage contamination [48]. Currently, various bearings in the turbine are lubricated by automatic lubrication systems with necessary oil filters to ensure cleanliness. The commonly used lubrications methods for wind turbine bearings are centralized lubrication, oil-air lubrication, oil mist lubrication, and oil bath lubrication [49-51]. The main shaft bearings are generally lubricated either by pressure-fed oil lubrication or grease lubrication. The pressure lubrication method uses a circulating oil delivery system that involves the use of pumps, valves, and pipes to supply oil to the bearing. The gearbox bearings are generally lubricated using gear oil using oil-splash or circulating oil (pressure-fed) lubricant delivery system [52].

According to Rensselar [53], “The similarities between the gearboxes used in wind turbines and the gearboxes used in aerospace applications allow some research crossover. Gearboxes in both industries operate under extremely demanding conditions. However, one of the major differences is that wind turbines are subjected to larger varying and cyclic stress loadings during wind gusts than jet engines, helicopter blades, or spacecraft moving mechanical systems. Researchers are encouraged by the progress the aerospace industry has made in reducing or eliminating the same gearbox problems that persist in wind turbines.”

From the above, it is understood that the tribological failures pose a severe threat to the future of wind turbines as promising renewable energy generators. The tribological failures can be overcome only through concentrated research on tribological issues, thus developing efficient lubrication systems that continuously supply the required lubricant for more than 20 years. The following sections introduce some lubrication systems developed for spacecraft moving mechanical systems and proven in various spacecraft subsystems.

3. LUBRICATION OF SPACECRAFTS SYSTEMS

Regardless of size, type and purpose, spacecraft usually contain several moving mechanical systems (MMS). These MMS are classified as high-speed systems (gyroscopes, momentum wheels, reaction wheels, control moment gyros, etc.) and low-speed systems (hinges, scanners, solar array drive, etc.). Continual performance of these systems can only guarantee the intended functions essential for the successful operation of the spacecraft. Most of the problems encountered with these moving systems pertain to tribology. Lubrication of space systems is still a challenging task before the tribologists due to the unique factors encountered in space, such as near-zero gravity, hard vacuum, weight restriction, and attention-free operation. Ever since space exploration, several mission failures have been reported to emanate from a bearing system malfunction. A bearing in a rotating mechanical system may fail for multiple reasons, such as degradation of the quality of the lubricant, loss of lubricant from the working zone by evaporation and surface migration, and retainer instability [54-57]. Unlike yesteryear, today's space missions are planned to last for 30 years or more [58].

Currently, the tribological failures of spacecraft systems seldom occur because of efficient lubrication methods and systems. There are a number of various types of lubrication systems for the MMS developed by researchers from various spacecraft system manufacturers. According to the nature of the operation, the supplementary lubrication systems used in momentum/reaction wheels can be broadly classified as active and passive systems [59]. The active lubrication systems, known as positive lubrication systems, supply a controlled amount of lubricant to the bearings when external commands actuate it. Positive commandable lubricators, remote in-situ systems, etc., are examples of active lubrication systems. Passive lubrication systems, also known as continuous systems, supply lubricant continuously to the bearings. These are driven by centrifugal force and or by surface migration force. The centrifugal lubricators, wick-feed systems, oozing flow lubricators, porous lubricant reservoirs, etc., are examples of passive lubrication systems. Some of these systems suitable for wind turbine bearings and gearboxes are presented here.

3.1. Active lubrication systems

The active lubrication systems supply the required quantity of lubricant when needed. Various active lubrication systems are in use, some of which are briefed here.

Positive Lubrication Systems: In this system, a known quantity of lubricant is delivered to the bearings when external commands actuate the system. The signal to actuate the lubricator is executed when demand for lubricant arises. The demand is indicated either by a fall in the thickness of the lubricant film or by an increase in bearing temperature due to an increase in bearing friction torque. Several designs of positive lubrication systems are available, which use different actuators such as stepper motors, solenoid valves, etc. In the commandable oiler developed by Hughes Aircraft Company [60], a solenoid-operated piston moves inside a reservoir chamber, one end of which acts as a cylinder. During every operation, a quantity of oil equal to the cylinder volume is discharged. The oil discharges from the cylinder and is directed to the bearings through stainless-steel tubing. This system had been used in the Intelsat IV satellites. The positive lubrication system (PLUS) developed by Smith and Hooper [61] is another kind of solenoid-operated lubricator. In PLUS, the lubricating oil is stored in a metallic bellow and is pressurized by a compression spring. The high-pressure oil is delivered to the bearings by actuating the solenoid valve connected to the reservoir. The quantity of oil delivered depends on the valve's opening duration, the reservoir pressure, oil temperature, plumbing resistance, and the oil viscosity. The positive-pressure feed system (Figure 6) proposed by James [62] consisted of spring-loaded metallic bellows in which oil is stored under pressure, a release valve, metering bellows, a metering valve, and a lubricant feed line. When the release valve is actuated, the oil flows out through the metering bellows and the metering valve into the feed line. The metering bellows control the quantity of oil delivered to the bearings. The lubricant feed line reaches up to the bearing and delivers oil directly to the bearing balls, which transfer it to the contact surfaces.

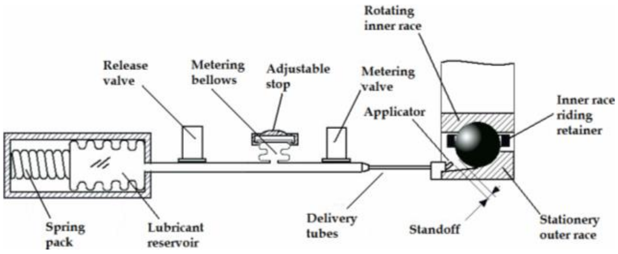

Fig. 6. Positive commandable lubricator for satellite bearing application [62].

The command lubrication system (CLS) [63,64] is another active lubrication system with flexible metallic bellows, a micro-stepping motor, frictionless ball screw, injection nozzle, and capillary tubes. The stainless-steel bellows act as the oil reservoir in which the oil is stored under ambient pressure. A compression type bellows, having a swept volume (i.e., the difference between the normal and fully compressed states) required to hold the oil for the service life, is selected. The micro-stepping motor, which is the actuator, is a geared motor driven through the drive electronics. The precision ball screw connects the reservoir bellows with the motor shaft. A nozzle attached to the delivery end of the bellows connects the capillary tubes that run up to the bearings, as shown in Figure 7.

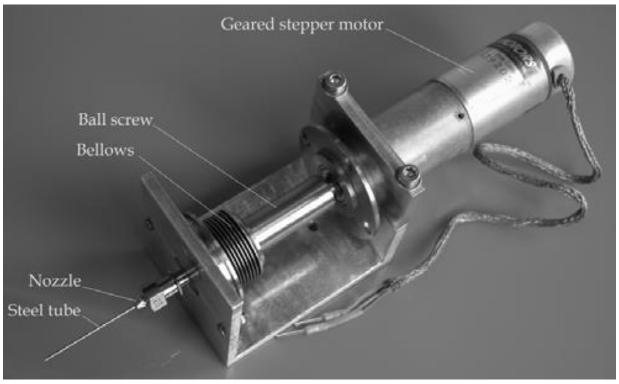

Fig. 7. Command lubrication system [63].

To supply lubricant to the bearings, the drive motor of the CLS is actuated for a predetermined period. When the motor is powered, the shaft and the ball screw attached to it rotate. The housing of the ball screw, which is rigidly connected to the bellow, moves linearly and presses the bellows. As a result, oil in the bellows gets compressed and flows through the capillary tubes. The delivery tip of the capillary tube is placed adjacent to the bearing race. A set-off distance, i.e., the distance between the nozzle's tip and the bearing's moving element, is provided, preventing the nozzle tip from touching the bearing surface. Generally, the set-off distance is approximately equal to the diameter of the oil droplet. Depending on the design of the bearing unit, the nozzle tip can be conveniently located near the bearing to ensure an oil supply. The amount of oil delivered is proportional to the duration of the motor actuation, which can be precisely controlled. In this system, the chances of leaks are absent since the oil is stored at ambient pressure.

In-situ Lubrication Systems: The lubricating oil is stored in a cartridge containing a porous sleeve and is placed adjacent to the bearings. When the porous sleeve is heated up by some means, the oil stored in its pores comes out due to differential thermal expansion. The oil oozes out of the cartridge and migrates into the bearing surfaces due to the low surface tension of oil compared to the bearing metal. The lubricator is actuated when the bearing temperature increases due to higher friction, demanding lubricant.

3.2. Passive lubrication systems

Passive lubrication systems supply lubricant continuously at a controlled rate irrespective of the requirement. These systems work on centrifugal force and are attached to the bearing assembly. Several designs of passive lubrication systems are used today by different manufacturers of moving mechanical systems for spacecraft. The centrifugal lubricators [64 – 66], oozing flow lubricators [67-70], wick feed systems [71], porous lubricant reservoirs [66], etc., come under this classification. Passive systems are generally simple in construction, but it is difficult to control the flow rate to the required level. Different techniques are used to control the flow rate in these types of lubricators. In the centrifugal lubricators studied by Sathyan et al., the flow rate from the lubricator was controlled to the lowest level by introducing a block of microporous material along the flow path. The flow rate in the oozing flow lubricator [67] is controlled by specially made constrictions along the flow path.

The Centrifugal Lubricator: The centrifugal oil lubricator [72,73] was developed keeping in mind various lubrication issues related to the development of momentum/reaction wheels required for future long-term space missions. It is designed to suit a rotating housing–type bearing unit. However, it can also be used for rotating shaft-type bearing units with slight modifications.

The centrifugal lubricator consisted of an outer cup and an inner sleeve made of aluminum. When the outer cup and inner sleeves are assembled, the space between the two becomes the reservoir space for the lubricant. Both ends of the assembly are sealed using a space-proven adhesive to make the reservoir leakproof. Electron beam welding or other metal joining methods are preferred for long-term reliability. On one of the faces of the outer cup, a small hole is provided to fill the reservoir with the lubricating oil. After oil filling, this hole was plugged and sealed with adhesives. A small hole (called the main orifice) of 150 µm diameter is drilled on the periphery of the outer cup through which the lubricant flows out. Figure 8 shows the centrifugal lubricator.

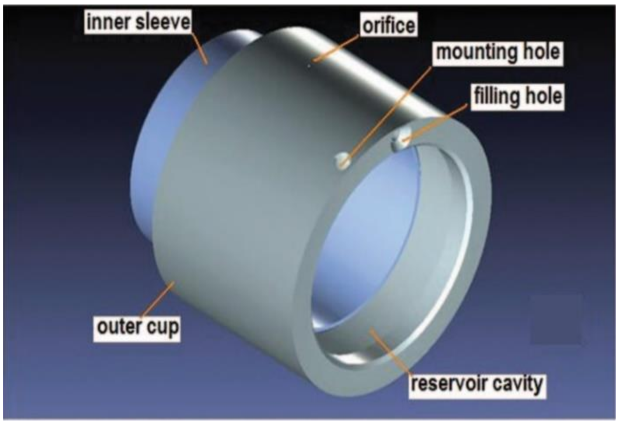

Fig. 8. Features of the lubricator [72].

As the lubricant goes out of the reservoir space, it may create a vacuum inside the reservoir, and this negative pressure can reduce the flow rate by reducing the net pressure head acting at the orifice. This is avoided by providing a vent hole on the wall of the inner sleeve (Figure 9). The diameter of this hole was approximately 10 µm. The size is determined to ensure no lubricant exits the lubricator when the differential pressure is zero; this help to store the lubricator when not in use.

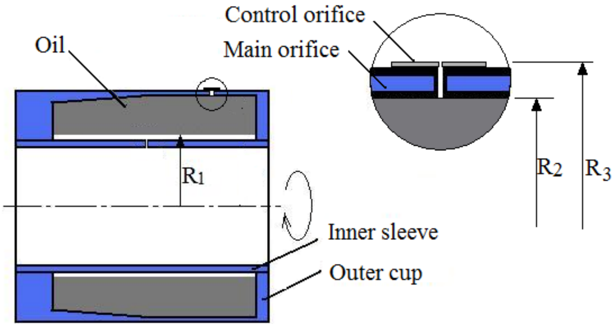

Fig. 9. Lubricator assembly showing the orifice details.

In centrifugal lubricators, the centrifugal force due to the rotation of the bearing unit is utilized to supply lubricant to the bearings. When the bearing rotates, the lubricator attached to the rotating part of the bearing unit also rotates. The rotation causes centrifugal force, which increases the pressure head of the oil filled in the reservoir. This pressure varies along the radial direction and is the maximum at the outer oil layer closest to the orifice. A flow restrictor was incorporated at the orifice to reduce the flow rate to the required value. Different mechanisms can be used to restrict the flow, such as a piece of isotropic porous material [65, 66, 74]. Also, the flow rate is controlled to the required level by using an additional micro/nano-orifice called a control orifice [72, 73, 75]. The control orifice was created on a copper foil of a thickness of 50 µm, using a pulsed laser system [76]. The control orifice plate was mounted over the 150-µm orifice, as shown in Figure 10. The centrifugal pressure caused the oil to flow through the control orifice. The oil particles from the orifice are thrown into the spacer to which the lubricator is attached. From the outer spacer, the lubricant flows into the bearings on its side. The diameter of the control orifice is determined depending on the flow rate required.

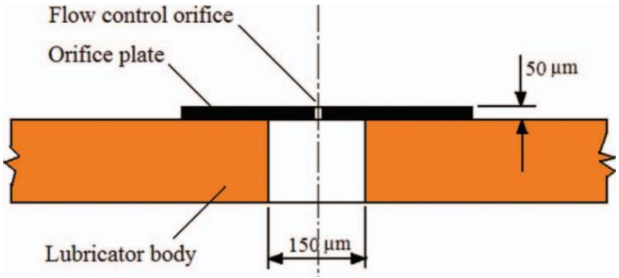

Fig. 10. Arrangement of flow control orifice.

The equation for mass flow rate from the lubricator is [72].

$$q = K \frac{\pi \rho^2 \omega^2 r^4}{8\eta}\left[\frac{R_3^2 - R_1^2}{R_3 - R_2}\right] \tag{1}$$

where K is the flow coefficient (0.326), ρ is the density of the lubricant in kg/m3, η is the dynamic viscosity of the lubricant in kg/m-s, ω is the angular speed in rad/s, r is the radius of the orifice in m, R_1 is the instantaneous radius of inner oil layer in the reservoir in m, R_2 is the radius at which oil enters the orifice in m and R_3 is the radius at which oil leaves the orifice in m. In this case, R_2 and R_3 are constants, and the difference between the two gives the flow length (Figure 9), and q is the mass flow rate in kg/s. Thus, if the required flow rate is finalized, the flow area (or diameter of the orifice) can be calculated. Figure 11 depicts the operation of a typical centrifugal lubricator with an orifice diameter of 0.48 mm and a rotating speed of 5000 rpm.

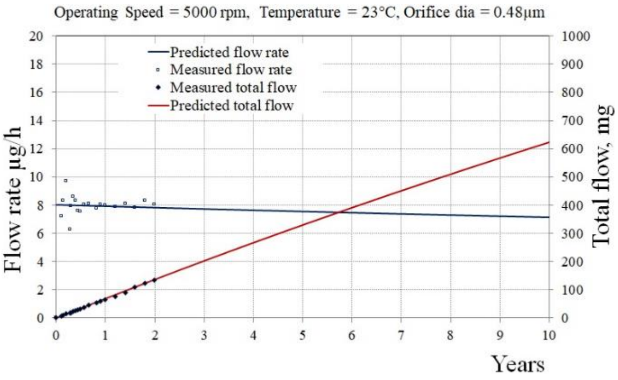

Fig. 11. Performance of a centrifugal lubricator at 5000rpm.

The flow rate and total flow data for a two-year period are compared in Figure using theoretical and experimental data. This lubricator has a total capacity of 5000mg. The measured flow rate is around 8µg/hour, which enough to support efficient lubrication. The entire flow in two years is just 130mg, as shown in Figure 11. This demonstrates that the lubricator's expected lifespan of 30 years or more.

4. SUGGESTED LUBRICATION FOR WIND TURBINES

Bearings and braking systems are particularly vital parts of wind turbine systems since faults in these parts can result in catastrophic failure of the wind energy conversion systems [77]. It is estimated that only 10% of bearings are appropriately functioning without any failure till their life cycle, while 90% of bearings failures include insufficient lubrication (30%), poor installation (40%), and manufacturing defects (20%) [78]. Figure 12 [79] presents the most frequent failure modes leading to different bearings wear in wind turbines. It is understood that the second main factors influencing the appearance of wear types are: poor design, overload, and oil supply problems.

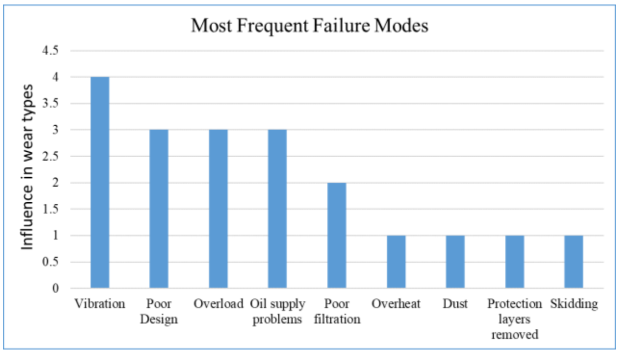

Fig. 12. Most frequent failure modes in bearings [77].

Bearings are used in various mechanical systems of a wind turbine, such as the main shaft, pitch system, yaw system, gearbox, and generator, to provide physical support to the drivetrain and allow it to rotate with minimum friction and wear. Commonly used bearings types are self-aligning roller bearing, cylindrical roller bearing, full complement cylindrical roller bearing, single-row tapered roller bearing, double-row tapered roller bearing, and four/eight-point contact ball bearing [15,80]. The high-speed shaft makes 1500 to 1800 revolutions per minute during power generation. This high-speed shaft is supported by the high-speed stage bearings located on the front and back sides of the shaft. The various types of bearings used at different locations and lubrication of large-capacity wind turbines are given in Table.1.

From the Table, it is understood that the bearing at different locations of the turbine rotates at different speeds. Also, grease and oil are used to lubricate these bearings according to their operating speed. Therefore, compared with the spacecraft moving mechanical systems, the following lubrication methods/systems are proposed, which may increase the reliability of wind turbine bearings used in the gearbox. The proposed lubrication systems are well proven in various spacecraft with a design life of 30 years.

Table 1. Bearing types, speed range, and lubrication.

Shaft/ Location	Bearing Type	Speed Range, rpm	Lubrication
Pitch	Four-point Contact Ball Bearing	< 1	Grease
Yaw	Four-point Contact Ball Bearing.	< 1	Grease
Main Shaft	Self-aligning Roller Bearing, Taper Roller Bearing	10 - 30	Grease
Planetary	Full Complement Cylindrical Roller Bearing, Self-aligning Roller Bearing, Taper Roller Bearing	20 - 30	Oil
Low Speed	Full Complement Cylindrical Roller Bearing, Self-aligning Roller Bearing, Cylindrical Roller Bearing.	50 - 160	Oil
Intermediate	Four-point Contact Ball Bearing, Self-aligning Roller Bearing, Cylindrical Roller Bearing, and Taper Roller Bearing.	240 - 600	Oil
High Speed	Four-point Contact Ball Bearing, Self-aligning Roller Bearing, Cylindrical Roller Bearing, Taper Roller Bearing, Ball Bearing	1200 - 1800	Oil

4.1. For planetary and low-speed bearings

Since these bearings are running at a slower speed, an active lubrication system (e.g., command lubrication system (CLS), Figure 7) is suitable. The lubrication system can be appropriately designed to hold the required quantity of liquid lubricant. The system can be installed at a suitable location, and oil can be delivered to the bearing surfaces through steel tubes. This system can be completely automatic by including necessary control electronics and algorithms. It requires a series of sensors and actuators. The electronic circuits in the film thickness sensor issue the signal to actuate the active lubrication system. The lubricant film thickness sensor monitors the real-time thickness of the lubricant film and generates the appropriate commands when the film thickness at the interacting surfaces falls below the prescribed value. There are many different lubricant film thickness sensors available such as eddy current sensors [81]., ultrasound transducers [82-84], relative optical interference intensity (ROII) [85] etc. Ultrasound reflectometry is the most common use of ultrasound transducers in lubrication film monitoring. Detecting lubrication conditions like fully flooded or partially starved can also be done using piezoelectric transducers [86]. Bearing temperature also indicates the presence of lubricant film at the contact surfaces. There are several types of sensors commercially available that can be used for temperature measurement. However, the most commons are resistance temperature detectors (RTDs), optical pyrometers, and resistant thermometers.

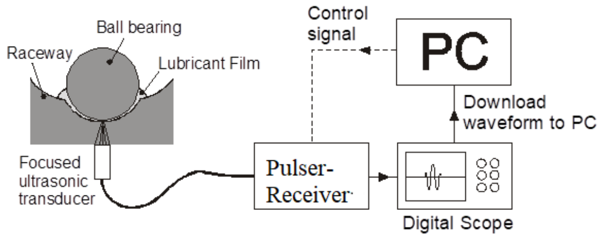

Fig. 13. Schematic representation of ultrasonic pulsing and receiving system [84].

4.2. For intermediate and high-speed bearings

Passive lubrication systems are the best option for these bearings since the rotational speed is sufficient to generate a centrifugal force to squeeze the lubricating oil out. The centrifugal lubricator mentioned above [72,73] using pure oil can be used, but with some modification because it is designed for housing rotation. In the case of wind turbine gearbox bearings, the shaft is rotating, and therefore to guide the oil to the outer race, a suitable arrangement must be made. A layout of the system is shown in Figure 14.

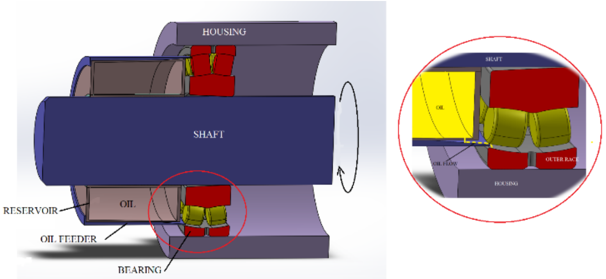

Fig. 14. Schematic of centrifugal lubricator integrated to the highspeed shaft bearing.

The centrifugal oil reservoir is mounted on the rotating shaft and in contact with the bearing inner race. The oil reservoir rotates with the shaft and develops the required centrifugal force to throw the oil out through the micro orifice, which is made on the outer cup of the reservoir. As shown in the Figure, a feeder cup is mounted over the reservoir. This feeder has a tapered surface on the inner side, directing the lubricant to the outer raceway and lubricating the bearing surfaces. The size of the flow control orifice can be calculated from Eq. (1) if the lubricant viscosity and flow rate are known. The reservoir cartridge can be instantly replaced once it is emptied. This lubricator can be designed to store sufficient oil for 5 to 10 years. Therefore, only two-three replacement is needed to serve the entire service life of the gearbox.

5. CONCLUSION

A detailed review of the tribological requirements of the wind turbine bearings has been done. A comparative study of wind turbine bearing with the spacecraft moving mechanical systems shows that both systems have similarities such as long-life requirements with very high reliability, low-speed and high-speed bearings, maintenance accessibility, cost, etc. Based on the study, the following suggestions are made for the lubrication of wind turbine bearing:

1. Active lubrication systems are suitable for low-speed bearings such as planetary and low-speed shafts. These systems can be designed fully automatically, which ensures long-term unattended service.
2. Passive lubrication systems, such as the centrifugal lubricator, are suitable for high-speed bearings. This system can supply lubricants continuously for many years and thus reduces the maintenance intervals and lubrication failure of such bearings.

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