Satellites to Submarines: Application of Space Tribology to Terrestrial Industries

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ABSTRACT

The harsh environment of space produces a unique set of challenges, placing specific demands upon lubricants operating in such conditions, and the design of tribological systems in general. This paper shall present and discuss the difficulties faced by the spacecraft mechanism engineer when designing tribological systems to operate under such conditions, and how these lessons learnt and practical solutions can be translated into terrestrial applications. In presenting these examples this paper shall draw from over 50 years of vacuum tribology experience and expertise of The European Space Tribology Laboratory (ESTL) working together with the space mechanisms industry.

1. SPACE TRIBOLOGY

For most applications, the requirement of "good tribology" and effective lubrication is to minimise adhesion, friction, and wear of the contacting surfaces. This is typically achieved through the separation of surfaces in relative motion by imposing a third body with low resistance to shear such that the two surfaces do not encounter severe wear. This third-body lubricating layer can consist of a variety of materials, including solid or fluid lubricants.

Although the subject of tribology is one which is (reasonably) well understood when operating under benign conditions, the harsh environment of space produces a unique set of challenges not often encountered in other fields of tribology. These challenges must be overcome to ensure a successful mission, with the key goals of a tribologist typically being to achieve high efficiency (i.e., low friction) and long lifetimes of the spacecraft mechanisms. This becomes more pertinent as longer and more demanding missions produce ever greater requirements of space engineering, with spacecraft complexity currently growing at a faster rate than our tribological solutions [1], and in recent decades it has been claimed that the limiting factor in spacecraft reliability and performance are these tribological systems themselves [2]. This scenario has produced great emphasis on the development in the field of space tribology.

The specific demands placed upon lubricants operating within space environments shall be discussed, presenting each challenge and the constraints that this enforces upon the tribological solutions in turn.

1.1. Vacuum Environment

In ambient environments metal surfaces are protected somewhat through the absorption and chemical interaction with oxygen and water molecules (as well as other contaminants). From a tribological viewpoint, these layers prevent metal-on-metal contact, and thus reduce friction, wear, and adhesion of the surfaces. However, in the vacuum of space these layers are quickly removed through outgassing or wear and cannot be replenished. This can result in higher friction than one would expect [3]. In addition, adhesion of surfaces can easily occur (often exacerbated through fretting motions induced by launch) resulting in so-called 'cold-welding' of contacts [4]. This is typically avoided through proper attention paid to lubrication, as well as to material treatments (chromes, nitriding, etc.).

If employing a fluid lubricant, the vacuum environment forces engineers to only consider liquids which exhibit exceedingly low volatilities (i.e., low vapour pressure), with the rate of oil evaporation typically being calculated using the Langmuir equation [5], though recent activities have shown this equation to be somewhat inaccurate for non-spherical high molecular weight fluids such as vacuum oils [6, 7]. If a lubricant includes additives, similar consideration must also be given to their individual evaporative behaviours.

$$\frac{dm}{dt} = (P_v - P_p)\left(\frac{M_m}{2000\pi RT}\right)^{0.5} \text{ kg/m}^2\text{s}$$

Where M_m is the molecular weight of the oil (g/mol), R is the gas constant (8.31441 $Jmol^{-1}K^{-1}$), and T is temperature (K). P_p is the partial pressure of the oil molecules in the gas phase. P_v is the vapour pressure at temperature T.

Not only is the evaporative loss of the oil itself a concern, but the potential adsorption of the vapour by surfaces, and the subsequent contamination of optical components, must also be minimised. As such, it is often advised that liquid lubricants are not used within mechanisms incorporating optical devices or, if unavoidable, then measures are taken to mitigate contamination (e.g., appropriate use of anti-creep barriers and/or labyrinth seals).

The vacuum environment also poses problems for solid lubrication. One of the more common terrestrial solid lubricants is graphite, but this is impractical for space applications as the material displays an elevated wear rate when shearing in an environment devoid of water vapour [8]. As such alternative solid lubricants must be selected, with arguably the two most common for space applications being molybdenum disulphide (MoS_2) and lead (Pb), both of which perform very well in low moisture, high vacuum environments.

Spacecraft mechanisms also typically operate in environments where they do not experience a G-force (although spin-stabilised spacecraft such as Meteosat Second Generation (MSG) can experience acceleration greater than 1G in a radial direction). Although usually not a significant factor, clearly any system in which lubricant is transported via gravity cannot be employed. Lubricant migration must also be considered as this can occur against the force of gravity and is typically addressed through the use of anti-creep barriers to modify the surface energy of any adjacent substrate.

1.2. Power Requirements

Typically, spacecraft applications have extremely limited power availabilities, with little margin for increases. At a tribological level this results in very stringent restrictions on torque margins compared with terrestrial applications, as well as requirements for low and consistent torque noise (as significant torque deviations may introduce vibrations impacting any optical devices, and even impact the stability of the spacecraft as a whole). As a result, tribological solutions which provide low and consistent torques over the lifetime of the application are required.

In addition, it is usually the case that failure of the lubricant equates to failure of the mechanism itself, with the typical fatigue-type failure mode of mechanical systems not being encountered within space applications. According to The European Cooperation for Space Standardisation (ECSS) guidelines for spacecraft mechanism design, a qualification test is deemed to have failed once "an unacceptable level of wear" is produced [9]. Typically, this means that any degree of substrate-on-substrate contact, or plastic deformation, is considered a failure in eyes of ECSS.

1.3. Temperature Extremes

Spacecraft engineers will go to lengths to ensure that their flight mechanisms operate in a temperature window close to ambient temperatures (-40 to +80°C). However, this is not always possible due to the specific mission, or the hardware requirements on-board. Thermal environments may exceed several hundred degrees Celsius, such as is the case for the joint ESA-JAXA BepiColombo spacecraft, launched in 2018 to survey the planet Mercury. In such a scenario the evaporation rate of a liquid lubricant would be prohibitively high for the mission duration, and as such cannot be selected. Conversely, near and mid-infrared instruments on-board the 2021-launched James Webb Space Telescope (JWST) require cryogenic operation temperatures, achieved through a combination of a sunshield and passive cooling system. Such temperatures are significantly below the pour point of all space fluid lubricants (e.g., the common space perfluorinated polyether (PFPE) fluid Fomblin Z25 has a pour point of -75°C), again precluding their use, and necessitating dry/solid lubricants as a solution. Even whilst above their pour points, space fluid lubricants display significantly higher torques due to increases in fluid viscosity resulting in greater frictional losses [10].

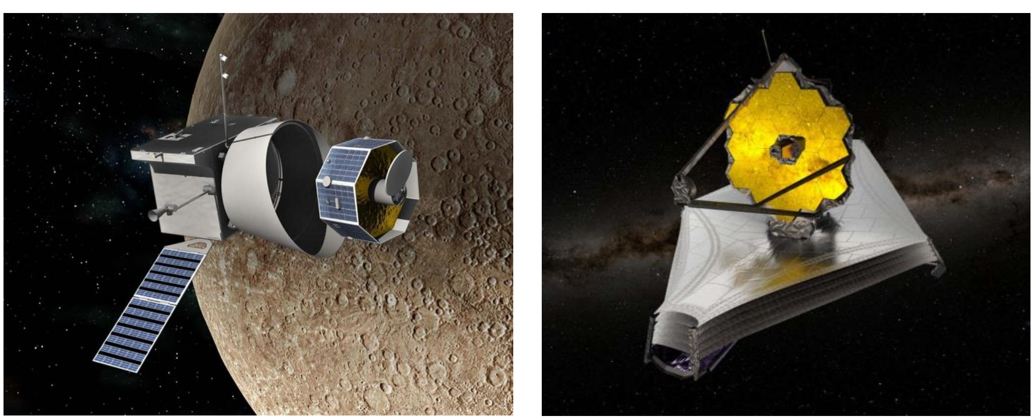

Figure 1. Artist impressions of BepiColombo (left) and JWST (right) spacecraft

1.4. Launch

Spacecraft launch introduces extremely harsh vibrations to the mechanism, necessitating robust and stiff design. The impact of this vibration on the mechanism elements must be carefully considered, and detailed on-ground vibration testing is mandated by ECSS for qualification of a new mechanism. Clamping and hold-down mechanisms can be considered as a solution for particularly vulnerable systems. It is also often attractive to increase the preload on bearings to reduce the risk of gapping and mechanical damage, but this introduces elevated torques which may cause issues against the stringent available torque margin. An elegant solution can be achieved through the application of a higher preload during launch, with is then reduced for lower-torque operation on orbit, as employed by the Alphasat spacecraft utilising a Bearing Active Preload System (BAPS) within its optical Coarse Pointing Assembly (CPA) [11].

1.5. Storage

Storage must also be carefully considered for spacecraft mechanisms, with these commonly stored before or after spacecraft integration for a considerable time. Such storage can occur prior to launch (on-ground storage), or in-flight where a mechanism remains dormant but exposed to the flight environment potentially for some years prior to operation. Whilst the "ideally benign" on-ground storage conditions for the most sensitive lubricants (e.g., sputtered MoS_2) are typically considered as dry nitrogen (DN_2) of 1%–3% ppm moisture, for practical reasons some relaxation of this criteria is commonly followed. Extended on ground storage at spacecraft level is often under a continuous long-term purge of semi-dry nitrogen (~10%–20% relative humidity (RH)), with periodic "exercising" of the components under DN_2. For in-flight storage, mechanisms are exposed to the thermal vacuum conditions of space, but usually without any possibility for "exercise". Storage periods can continue for months and occasionally for many years both before and after launch.

The general consideration is that this storage period under "benign" conditions will have a negligible impact on the tribological behaviour of the employed lubricants (assuming they are correctly applied). However recent activities [12] have cast some doubt onto this understanding, for both storage and operational environment conditions.

1.6. Nature of Space

The holistic nature of working within the space industry cannot be ignored. Spacecraft mechanisms are traditionally high value, extremely difficult to service/maintain, offer limited options for inspection and relubrication, and may be subject to uncompromising timescales if specific launch windows are required. Operational lifetimes can also be extremely long, with (for example) reaction wheels requiring over 10^9 bearing revolutions over the lifetime of the spacecraft with no opportunity for relubrication (Figure 2). This issue is compounded by the fact that mechanisms are often single-point-failures of their parent spacecraft, with mechanical failure potentially compromising the entire mission.

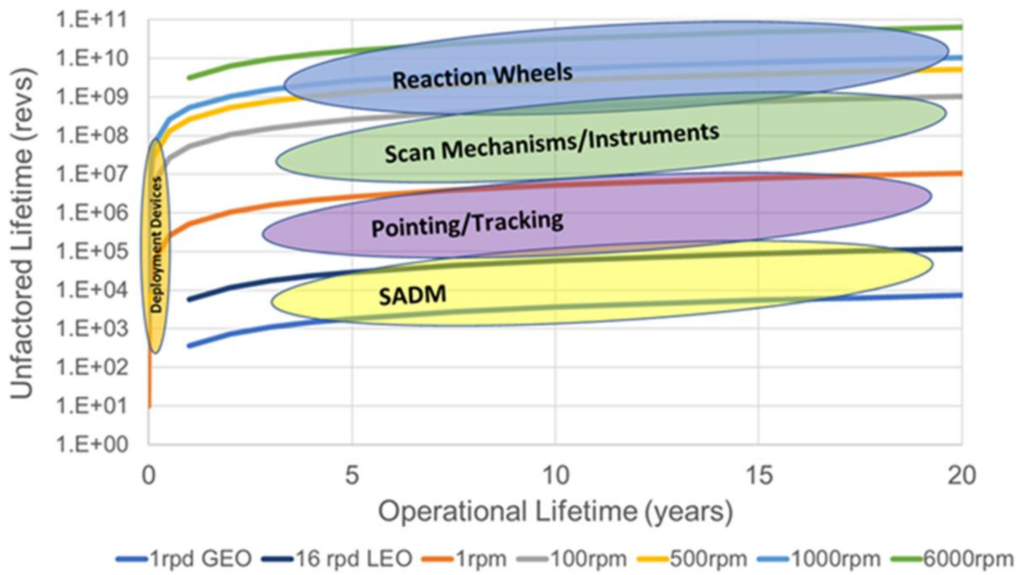

Figure 2. Typical bearing lifetimes for spacecraft mechanism applications

The solution to these factors is usually the implementation of a rigorous and comprehensive testing, qualification, and validation procedure to demonstrate the performance of the lubricant solution under representative thermal vacuum conditions.

Given the unique circumstances of space mechanism operation, there is usually no ideal lubricant for all applications. Often one must carefully consider the individual operational conditions and select the best (or least worst!) lubricant for the specific application.

2. TERRESTRIAL APPLICATION FOR SPACE TRIBOLOGICAL KNOW-HOW

Despite these complications, solutions for space mechanism lubrication do exist (although somewhat limited in choice). The European Space Tribology Laboratory (ESTL) have been working with the European space mechanisms community for +50yrs to provide lubrication solutions for space, and many of the lessons learnt over these decades also have applicability towards terrestrial applications. We now present case studies of example terrestrial applications which benefit from, or may benefit from in the future, space tribology technological know-how.

2.1. Lubricants for Extreme Bearing Applications

Many terrestrial bearing applications operate in similar “extreme” environmental conditions to space. For example, high-speed bearings employed in motor racing (e.g., Formula 1) experience high temperatures, and consequently employ similar technologies of high precision, well-adhered thin film solid lubricant coatings, originally developed for space applications. These coatings may be applied to hybrid ceramic bearings of high-hardness steel raceways and ceramic balls to reduce adhesive wear and provide high mechanical stiffness.

The high value and competitive nature of motor racing also draws parallels with the space industry, leading to an emphasis on reliability and quality control. Other examples of this derisking philosophy which may drive the technical solution towards space-developed and qualified hardware include the nuclear industry, with concerns around temperature and accesses of the lubricated parts.

This lubrication technology is also employed in certain aspects of the medical industry, where particular bearings may operate at high temperature, under vacuum, with a desire to reduce vibrations, and torque (and audible) noise to improve patient comfort. Again, thin film solid lubricants are typically employed, applied via controlled Physical Vapour Deposition (PVD) technologies transferred directly from space.

2.2. Fusion Reactor Applications

Technologies and lubricants originally developed for space can be considered for use within Fusion Tokamak reactors, particularly for use with the blanket modules used to cover and protect the inner walls of the vacuum vessel. A lubricant within this application would see high temperatures (~250°C) under vacuum, be exposed to neutron-irradiation (~1-10 Mev) from the exposure to tritium, but must maintain low friction. Given the nature of the application there would also be significant concerns regarding material wear and debris production between sliding interfaces, as well as issues of accessibility should relubrication be required. Given that these concerns are very similar to those experienced by high temperature spacecraft mechanisms, or those with contamination concerns (such as optical applications), the technical solution is often found in the same family of thin-film solid lubricants.

2.3. Optics and Semi-Conductor Industries

The optics and semiconductor industrials also have many parallels with the space industry, with these industries featuring operation of high-value machinery in vacuum environments. Cost and reliability concerns are also prominent, with extreme financial impacts if the mechanical hardware experiences prolonged down-time. Contamination concerns typically reject thin-film solid lubricant options, but modest temperature ranges can lead to the selection of low vapour pressure fluid lubricants (such as perfluorinated polyether oils (PFPEs)) as the technical solution.

However, despite their good evaporative lives, PFPE oils are susceptible to chemical degradation which tends to limit their operational lives [13]. Typically, the oil degrades to a form of fluorocarbon polymer which provides poor tribological behaviour due to worsened shear properties. Current theory states that this degradation occurs initially through a reaction between the fluid and residual iron oxides in the surface (Fe_2O_3) as a result of shearing of the polymer chains [14]. As the polymer chains break the corrosive Lewis acid COF_2 is released, which reacts with metal oxide to yield FeF_3, itself highly reactive and resulting in further and self-propagating degradation of the polymer at a more rapid rate.

Therefore, much of the tribological effort focuses upon extending the lifetime of these shear-induced tribo-chemical degradation sensitive fluids through the restriction of their interaction with steel substrates. This can be achieved through either the use of bulk ceramic substrates (such as silicon nitride balls in hybrid ceramic bearings [15]), hard ceramic coatings (such as Titanium Carbide), or through the use of thin film solid lubricants as degradation barriers

2.4. Mechanical Watches and High Precision Engineering Applications

Luxury mechanical watches are an application which one would not naturally assume to be comparable to space mechanisms, but several parallels do exist. Besides the requirement for precision engineering and manufacture, low power requirements lead to a need for low and consistent friction within the tribological contacts, maintained for long life (at a practical level, a longer duration before mechanical failure allows the manufacturer to provide a longer warranty period on the product). Low wear is also desired to reduce the risk of visible debris within the mechanical elements of the watch.

In many instances the mechanical elements within the watch are sealed to operate within a dry inert cover gas environment (such as DN_2). Whilst this sealing is done principally to remove the risk of external contamination, the dry environment allows the use of low friction moisture-sensitive lubricants, originally developed for space. One such lubricant is PVD MoS_2, the tribological performance of which is highly dependent upon environmental moisture [16].

2.5. Condition Monitoring of Vacuum Tribo-Systems

Condition monitoring technologies are utilised to some degree in spacecraft mechanism applications. The ability to detect the onset of lubricant failure before significant and catastrophic mechanical wear, and potentially to modify the operational paramaters of the mechanical elements, is highly advantageous in an environment where maintenance access is severely limited. A high-profile example of such analysis was the bearing failure of the Solar Alpha Rotary Joint (SARJ) onboard the International Space Station, which was detected in part due to increased structural vibrations experienced by the spacecraft [17]. Other spacecraft have utilised onboard accelerometers to detect and analyse vibrations suspected to be resulting from misbehaving bearings, including recently the Rosetta spacecraft where accelerometers mounted to the Philae lander were used to evaluate the fluid lubricant status within the spacecraft's reaction wheels by examining the microvibration signature of the wheels and comparing the data with ground-based test results [18].

Condition monitoring-style analysis can also be used for spur gear applications. The in-orbit lifetime of spacecraft spur gear units is clearly limited by lubricant failure, which in vacuum is immediately followed by scuffing and subsequently severe wear of tooth faces. Such failure will result in a sharp increase in gear torque eroding margins or causing mechanism failure. Analysis work has shown that, at least at test-rig level, several frequently used frequency- and time-domain condition monitoring indicators (waveform observations, FFT, envelope analysis, noise-based indicators etc.) can detect the onset of gear lubrication distress and imminent wear-out prior to an increase in torque for solid and fluid lubricated spur gears [19]. This observation raises the possibility that by extension from torque to motor current monitoring, such techniques may ultimately be used for in-situ monitoring of flight hardware and could be translated to terrestrial vacuum applications.

Research within the space mechanisms industry is also committed towards technologies providing the detection of degradation and indication of imminent failure of a vacuum fluid lubricant, prior to its tribological failure, based upon sensitive detection of volatile species produced during the incipient failure stage. This methodology was identified and understood during tests carried out to assess space lubricant performance and degradation using a specialized space tribology instrument (the Spiral Orbit Tribometer) [20], but is under consideration as a means of detecting incipient failure of space lubricants in space hardware during life test and even ultimately in-flight.

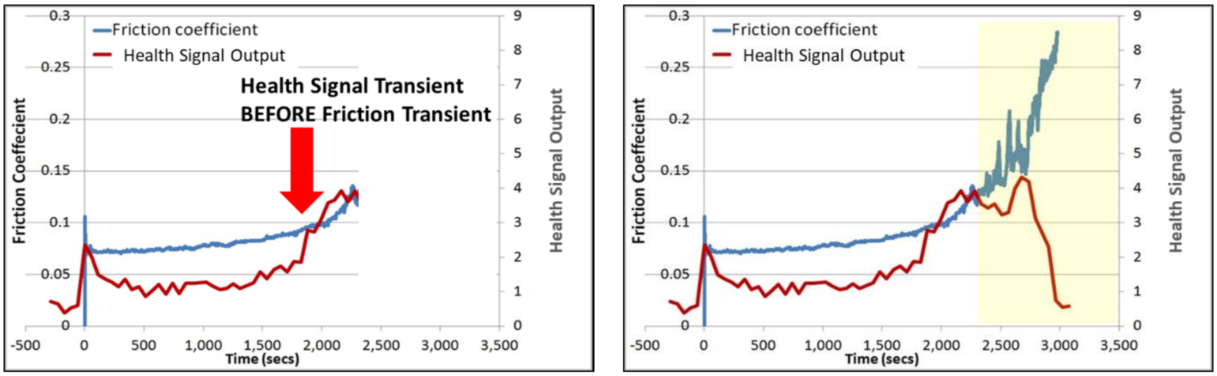

Figure 3. Early detection of lubricant failure via monitoring of volatile gas species (during tribological test)

Given that this technology allows early detection of degraded lubricant within a vacuum system before the lubricant undergoes tribological failure (see Figure 3), it may also provide a valuable tool for on-condition monitoring of terrestrial vacuum applications, including industrial vacuum pumping systems, to identify pump failure, permit potential extension of maintenance periods and minimise warranty costs associated with tribological failures Ultimately the technology foreseen could sense species associated with incipient failure within the pump cavity using an appropriate sensor principle and indicate the need for maintenance intervention to prevent catastrophic pump failure/downtime or warranty claims.

2.6. Modelling of Ball Bearing Dynamic Behaviours

Developed by ESTL for ESA, the rolling element bearing analysis software CABARET provides a tool for the design and analysis of bearing systems [21]. Though originally developed for the analysis of ball bearings in high-speed rocket engine turbopump applications, the software has since been maintained, generalised for other space applications, and extended under various ESA contracts. Key features of CABARET include dynamic cage modelling, fluid traction calculations and power losses, columbic torques, flash temperatures, stiffness calculations, thermal and centrifugal strain effects, vibration analysis, multi-bearing assemblies, and fatigue life. Whilst other bearing analysis software exists, both specific to space applications (SHABERTH, RBSDYN) and generalised to terrestrial applications (ADORE, COBRA, MESYS, SKF SimPro), CABARET offers superior capability in tribological modelling terms with respect to torque/power and cage dynamics modelling, but also matching the common set of features the alternative software solutions have to offer.

Rolling element bearings are widely used across many terrestrial industries where rotating machinery is used. Bearing performance is critical to both safety and reliability and is a determining factor in the periodicity of downstream activities, such as inspection and maintenance, and hence in operating costs of many forms of industrial equipment. Thus, CABARET presents an ideal solution for addressing applications where precise control of bearing operation is required, for reasons of reliability and/or efficiency, especially where the fundamental tribology of the contacts or the cage behaviour is important. Additionally, there is intense competition within the rolling element bearing market, and any new advances in bearing technology provide bearing suppliers with a competitive edge. However, new or modified products are often met with uncertainty or risk aversion, especially if the existing product is performing to an acceptable standard. Therefore, there is a strong requirement to obtain independent quantitative analysis of bearing systems using software.

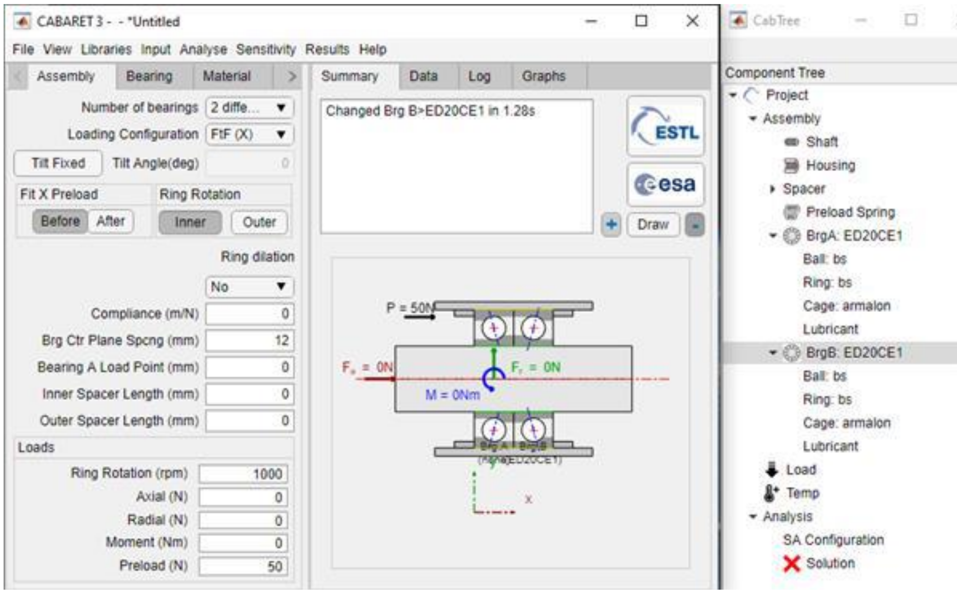

Figure 4. CABARET User interface

An example terrestrial application of CABARET (and one being actively explored at present) is the rail industry, where bearing failure provides a real safety critical concern. Although it is possible to ascertain the failure mode (fatigue, lubrication failure, design and manufacture, contamination, assembly etc.), the root cause is often subjective. Bearing failure analysis is reactive and bearing refurbishment or replacement is actioned on a run time basis. The bearing replacement interval is provided by the bearing manufacturer, who have a vested interest in providing an overly pessimistic appraisal of bearing life, and it is therefore in the interest of the customer to obtain an independent estimation. The effect of design variations, instances of cage failure and inner ring fracture are of particular interest within the railway industry, as these result in non-standard failure modes that cannot be predicted by normal analysis models. It is hoped that CABARET can provide a better understanding of the bearing, cage and lubricant behaviour to minimise premature and unexpected bearing failure and optimize bearing performance.

3. CONCLUSION

Space tribology brings with it unique complications which must be solved in order to achieve long and reliable mechanical life whilst reducing the risk of mechanism failure. However, many of these complications are also encountered within specific terrestrial applications, particularly those which either operate under vacuum or dry cover gas, or whose holistic nature requires high precision engineering and risk mitigation processes. Therefore, there is potential for cross-pollination of space know-how into these terrestrial industries, with lubricant solutions and products developed explicitly for the space industry being translated across into non-space. ESTL has experience in this form of technology transfer, with successful implementation into many terrestrial fields.

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