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Dropping Knowledge on Space Tribology: Insights into the Effects of Microgravity on Solid Lubricants from the Bremen Tower Drop Experiment

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Abstract

The performance of space mechanisms, such as satellite solar panels, hinges, and robotic arms, heavily relies on the tribological properties of the lubricants used in their design. Their mechanical properties can be significantly affected by the extreme conditions of outer space: including high vacuum, absence of oxygen, and extreme temperatures among others. However, due to technical challenges, the effects of microgravity on these properties are not entirely understood.

The SLuGG PETRI Project (Solid Lubricants in µGravity from Gdańsk) is a student research project from Gdańsk University of Technology, focused on studying the effect of microgravity and air pressure on the coefficient of friction in tribological systems. The project utilised a novel vibrational tribometer that can measure friction with a few orders of magnitude smaller measurement uncertainty compared to classical tribometers. This allowed the team to identify the coefficient of friction in microgravity and analyse the ability of solid lubricants to dampen mechanical vibrations.

Experiment utilised a custom-designed cylindrical vacuum chamber that can simulate microgravity conditions through multiple drops in the Bremen drop tower. They also used a novel vibrational tribometer that can measure friction with a few orders of magnitude smaller measurement uncertainty than classical tribometers. Solid lubricants were applied to the bar, and data was collected from the vibration sensor before and after lubricant application. The PETRI program, in collaboration with ESA, provided support for the project, which introduced valuable insights into the effects of microgravity on tribological systems.

The paper will discuss valuable insights into the effects of microgravity on the damping properties of solid lubricants in tribological systems, which can be useful for designers of space mechanisms, such as hinges, manipulators, drives, and grippers. The findings may also have broader implications for the development of more effective lubricants and tribological systems for use in space exploration.

Keywords: space tribology, microgravity, drop tower, vibration, vacuum, space mechanisms

Nomenclature

μ coefficient of friction

Acronyms/Abbreviations

ESA European Space Agency
HEDGEHOG High-quality Experiment Dedicated to microGravity ExplorationHeat flow and Oscillation measurement from Gdansk
MISSE Materials International Space Station Experiment
PETRI Practical Education in Technology, Research, and Innovation
REXUS Rocket EXperiments for University Students
SLugG Solid Lubricants in μGravity from Gdańsk
ZARM The Center of Applied Space Technology and Microgravity

1. Introduction

One of the most significant challenges that engineers and scientists working in the field of space exploration must face is the issue of space tribology [1]. This branch of the metascience of friction and wear deals with the study of interactions between surfaces under vacuum conditions, high and low temperatures, and in the presence of cosmic radiation—conditions distinct from those encountered on Earth's surface. The complexity of outer space conditions requires a dedicated approach to understand the behaviour of materials, lubrication, and wear in space. The goal of this field is to develop technologies that ensure optimal performance and durability of space components while minimising consumption and avoiding failures. Malfunctioning of even the smallest component can lead to serious consequences, such as the interruption of a space mission or the loss of valuable equipment - a danger and a cost, both to be avoided.

More than 15% of satellite damage and problems are attributed to mechanical issues [2]. Long-term studies of the impact of space conditions have been conducted as part of 14 MISSE missions, mainly focusing on polymers and composite materials [3]. Tribological research has also been conducted on the ISS as part of the TriboLAB experiment, using classical pin-on-disk tribometers [4]. It was impossible to separate the effects of machine bearing wear from the sample experiment wear [5].

These limitations pose serious challenges to understanding of surface phenomena in space conditions and call for a better tribometer for measuring the coefficient of friction μ and how the space environment affects its value in space mechanisms applications.

2. Motivation

Vibrations in space context were already studied within the HEDGEHOG REXUS Project, which aimed to measure the dynamic and thermal environment of a sounding rocket with unmatched quality [6]. Based on this data and numerical simulations, it was possible to characterise the influence of environment and mounting conditions on vibration of objects to be launched into space [7]. One result of that work was a design of a novel vibrational tribometer that is the main topic of this paper.

Microgravity tests have already been performed in Beijing Drop Tower to study the effect of microgravity on the friction behaviour of friction units and to further analyse the influencing mechanism [8]. It was found that microgravity can not only change the value of friction, but also affect its dynamic characteristics. The measured change of that parameter in 3 consecutive trials, where orientation of the friction apparatus was altered, was not consistent. Researchers conclude that relation between friction and gravitational acceleration requires further studies, but also point out weaknesses of their method, and that apparatus of a different type shall be designed to perform appropriate measurements, that "further experiments are needed". Again, limitations of current tribometers prevented from definitive conclusions.

Therefore, an idea for a drop tower experiment was proposed and successfully developed within the European Space Agency PETRI programme [9]. It is potentially possible to use this experiment for vibration research in sensitive structures under extreme conditions e.g. chaotic, externally induced vibration, shock loading.

The test under development joins the subjects of vibration and friction (static/sliding) at simulated space-like conditions. Such scope of factors is rarely observed in current scientific research. Especially in case of tribology related testing. The influence of vacuum on tribological contacts is a well recognised area, however the influence of microgravity is still to be determined in detail. With little evidence published of the possible influence or its lack of the latter factor on the behaviour of bodies in contact with friction, the project offers the capacity to push the boundaries of knowledge in micro-gravity tribology.

The test system, by design, can be used with little modification to study issues like the influence of surface quality and assembly parameters (e.g. linkage pre - stressing) or the combination of materials in contact in friction stabilised connections on the performance of the cargo retention devices or even the components inside the satellite unit (payload).

3. Vibrational tribometer design

The experimental setup is built around the stem of a vacuum chamber mounted to a standard Bremen drop tower capsule support platform. The fully equipped chamber serves multiple purposes: environmental isolation, housing, drive and sensory equipment support. The design was being progressed under the scrutiny of the ESA experts to comply with drop towers' requirements for safety, dimensions, maximum weight, load distribution, interfacing etc.. The general engineering criteria for the system were focused around extensive use of ready – made, standardised components for minimised cost, short delivery time, ease of assembly and maintenance, interchangeability and reliability.

Said chamber consists of three identical six-way DN40CF crosses, substantiating the chamber's modules, each individually rigged with a full set of components for running of the experiment. The modules are hermetically interconnected, but standalone operation of an individual module is also supported. In basic configuration all units are linked to a common vacuum manifold, designed to operate with turbomolecular pumps. If required, additional units and pumps can be linked.

Each experimental unit (a single six-way cross) contains a cantilever oscillator assembly as depicted in Fig. 1.

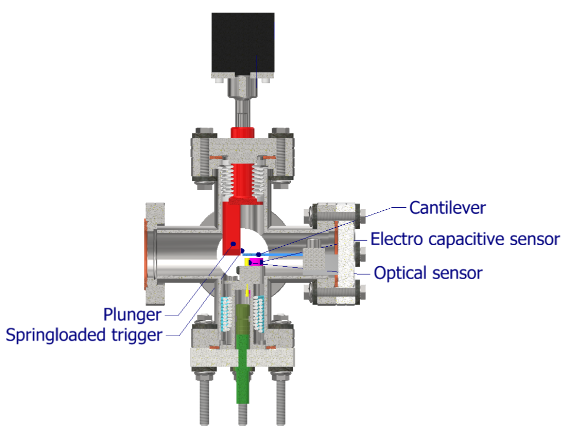

Fig. 1. Complete assembly cross section, side view

The oscillator assembly is composed of a motorised triggering mechanism, (depicted in Fig. 3.) cantilever beam mount (Fig. 4.) and sensor mount (Fig. 2.). The sensor mount (depicted in Fig. 2.) carries two displacement sensors: one electro capacitive and one optical. The arrangement allows for additional insight into measurement quality and comparability between two types of sensors with the benefit of redundancy added to the system. Each sensor is connected via a hermetic feedthrough to a signal processing unit located outside the chamber. Both sensors are screw set at a designated distance from the oscillator's surface. The distance can be adjusted as required.

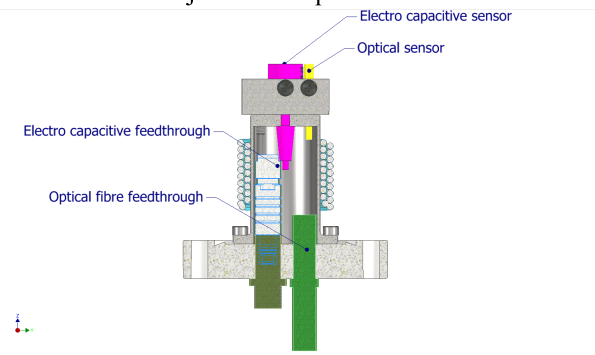

Fig. 2. Sensor mount assembly cross section

The cantilevers are bolted to mounting blocks at set tightening torque and clamped down by U shaped brackets. The trigger is motorised and can be controlled remotely in a pre-programmed mode, with time or acceleration triggering as well as by manual override to the program. The trigger operates on the principle of a threaded bolt linear actuator with a flexible, corrugated bellow air/vacuum separator, welded to both the plunger and the flange. Exact geometry is depicted in the figure below.

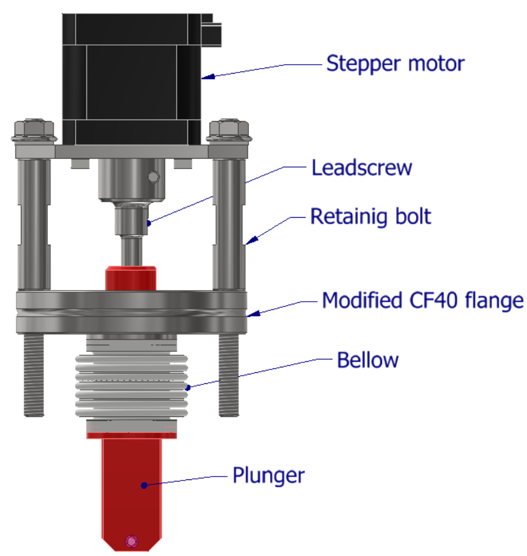

Fig.3 a). Trigger assembly, rear view

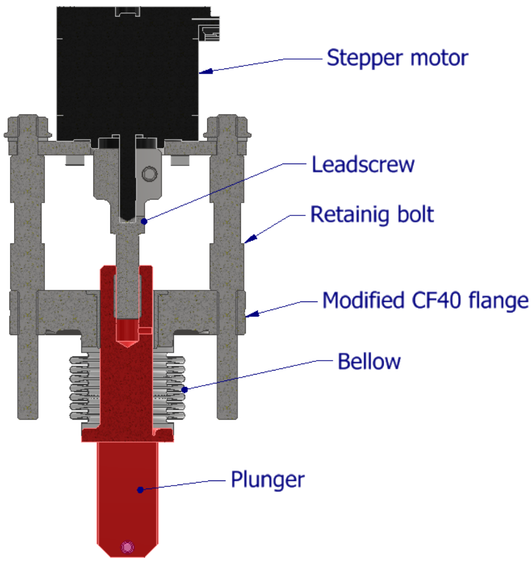

Fig. 3 b) Trigger assembly cross section, rearview

The major advantage of the modular design is the ability to conduct individual trials in each of the modules without any changes to its internal configuration. The intended use of the system is to measure the impact of microgravity on solid state lubricants under vacuum conditions, which makes it, in principle, a highly specialised tribometer. The system is expected to provide a minimum of stable vacuum of 10^{-5} Pa.

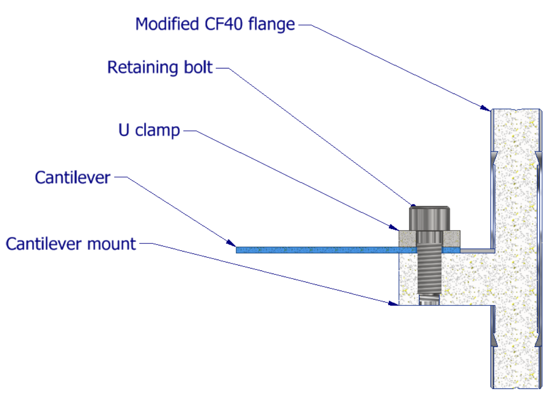

Fig. 4. Cantilever assembly, cross section

The experiment will be conducted under a vacuum of 10^{-5} Pa with a cantilever made out of 6061 aluminium with a natural frequency of approximately 450 Hz. The test begins when the plunger starts to lower, this in turn causes the spring loaded trigger to interlock with the edge of the cantilever. Once a sufficient force is developed at the contact the cantilever is released and begins to vibrate. The amplitude and frequency of these vibrations will be measured by the electro - capacitive and optometric sensors. This process will repeat regardless of the direction in which the plunger is moving, as the trigger can also engage and release the beam on the reverse stroke. For proper measurement it is essential that the cantilever is released only under microgravity conditions.

Varying factor between each of the levers is the type of lubricant for each of the cantilever. So, with three modules available, a set of three tests on different lubricants can be performed simultaneously. Said lubricant/lubricants will be applied to the contact surfaces on the mounting stand. The impact of every type of lubricant will be compared based on the damping coefficient derived from the observed vibration. These measurements will be used to determine the friction coefficient with and without lubrication. The friction is achieved when a vibrating cantilever starts to bend near the edge of its mounting, at the beam's support surface. This causes incremental cyclic changes in the length of the cantilever and results in repeated friction by micro slippage. That friction, influenced by the performance of the lubricant, is expected to cause a change in the damping of vibrations. That method allows for research into space conditions tribology without resulting in a major degradation of the vacuum quality, like a conventional tribometer would. In this setup the micro debris is entrapped in the space between the mount and the beam, preventing vacuum degradation.

4. Experiment design

Most important experiment parameters were presented in Table 1.

Table 1. Experiment parameters

parameter	value	unit
gravitational acceleration	10^{-6}	[g]
vacuum level	10^{-5}	[Pa]
beam deflection measurement:		
- inaccuracy	$2\cdot10^{-7}$	[m]
- frequency	$4\cdot10^{3}$	[Hz]
experiment time	9.3	[s]
coefficient of friction measurement inaccuracy	10^{-3}	[-]

5. Results

Results will be available after a drop tower experiment campaign scheduled in ZARM Bremen Drop Tower in December 2023.

6. Conclusions

An idea for a vibrational tribometer (a device for measuring the coefficient of friction) was proposed. The design is simplified and ruggedised as compared to tribometers used in Earth-based laboratories, making it ideal for use in space. The invention is characterised by:

1. Radically reduced number of moving parts (ease of fabrication, assembly and maintenance).
2. One degree of freedom (limiting the parasitic friction in structural nodes, such as bearings, springs, mechanical interfaces present in classical tribometers).
3. Mechanical signal amplification (making it more accurate than devices with similar power requirements and dimensions).

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References

[1] E. W. Roberts, Space tribology: its role in spacecraft mechanisms, *J. Phys. D: Appl. Phys.* **45** (2012) 503001. DOI: 10.1088/0022-3727/45/50/503001

[2] R. P. Perumal, H. Voos, F. D. Vedova, H. Moser, Small Satellite Reliability: A Decade in Review, SSC21-WKIII-02, *Small Satellite Conference*, Logan, Utah, USA, 2021.

[3] K. K. deGroh, B. A. Banks, J. A. Dever, D. A. Jaworske, S. K. Miller, E. A. Sechkar, S. R. Panko, NASA Glenn Research Center's Materials International Space Station Experiments (MISSE 1-7), *International Symposium on SM/MPAC and SEED Experiments*, Tsukuba, Japan, 2008.

[4] M. Brizuela, A. García-Luis, J. I. Oñate, I. Garmendia, TriboLAB: an experiment on space tribology. In-orbit data at the ISS, *13th European Space Mechanisms And Tribology Symposium*, Vienna, Austria, 2009.

[5] J. Łubiński, The influence of chosen research device parameters on the result of a tribological experiment with sliding friction, Gdańsk University of Technology, Gdańsk, Poland 2017. ISBN 978-83-7348-703-1

[6] A. Dąbrowski, K. Pelzner, S. Krawczuk, J. Goczkowski, A. Elwertowska, Preliminary results from HEDGEHOG REXUS project – A sounding rocket experiment on accelerations, vibrations and heat flow, *Acta Astronaut.* **177** (2020) 80 – 85. DOI: 10.1016/j.actaastro.2020.07.016

[7] A. Dąbrowski, The influence of environment and mounting conditions on vibration of objects to be launched into space, Doctoral Thesis in Mechanical Engineering, Gdańsk University of Technology, Faculty of Mechanical Engineering and Ship Technology (WIMiO), 2022.

[8] Y. Duan, S. Qu, C. Yang, X. Li, F. Liu, Drop Tower Experiment to Study the Effect of Microgravity on Friction Behavior: Experimental Set-up and Preliminary Results, *Microgravity Sci. Technol.* **32** (2020) 1095 – 1104. DOI: 10.1007/s12217-020-09838-4

[9] H. Marée, P. Galeone, A. Kinnaird, N. Callens, The ESA Education Programme and its ESA Academy, *Proceedings of the 3rd Symposium on Space Educational Activities*, Leicester, UK, 2019, 16 – 18 September, p.251 – 257. DOI: 10.29311/2020.62