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Investigating lubricants behaviour in microgravity for vibration damping purposes.

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Abstract

Vibration is one of the harshest environments an object is exposed to during and after launch into space on a launch vehicle. Such vibrations should be damped to avoid destruction of the spacecraft or its elements. Currently, active and material damping is used. A possibility of using lubrication as the damping factor is suggested by some research. MoS_2 is a typical solid lubricant used in space applications. Its properties vary heavily with environmental conditions and have been tested on ground. Recent research proves that dynamic characteristics of other lubricants are significantly affected by microgravity regime.

This research proposes characterisation of mechanical damping properties of MoS_2 in microgravity. For that reason a drop tower experiment is designed with a cantilever beam (a tuned vibration amplifier-filter). The cases of dry and wet (lubricated) vibrations will be tested. The beam will be triggered by an electromagnet and a set of sensors: accelerometers, strain gauges and capacitive displacement sensors will measure its vibrations. Computer analysis of the results will allow us to determine the damping coefficient of the lubricant in microgravity conditions.

Knowledge of this parameter will determine if damping properties of the MoS_2 lubrication (useful for tribological reasons) could be applied for damping of vibrations in spacecraft. This could possibly decrease the need for active vibration control and lower costs of future space missions.

Keywords: lubricant vibration damping, vibrations in weightlessness

Nomenclature

This section is not numbered. A nomenclature section could be provided when there are mathematical symbols in your paper. Superscripts and subscripts must be listed separately. Nomenclature definitions should not appear again in the text.

Acronyms/Abbreviations

ADC - analog to digital converter
AIT - Assembly, Integration and Test
CCS - Capsule Control System
DGT - Polish electronics manufacturing company
DYT - Drop Your Thesis
ECG - electrocardiography
ECTS - European Credit Transfer System points
ELGRA - European Low Gravity Research Association
EMC - electromagnetic compatibility
ESA - European Space Agency
ESTL - European Space Tribology Laboratory
FEM - finite element method
FSI - fluid-structure interaction
GUT - Gdańsk University of Technology
I2C - Inter-Integrated Circuit communication bus
IF - impact factor
IRS - individual research studies
JCR - Journal Citation Review
LV - launch vehicle
NASA JPL - National Aeronautics and Space Administration Jet Propulsion Laboratory in Pasadena, California
S/C - spacecraft
SimLE - Simply Learn and Expirience, GUT student science club
POLSA - Polish Space Agency in Gdansk, Poland
PC - personal computer
PCB - printed circuit board
ZARM - Center of Applied Space Technology and Microgravity in Bremen, Germany

1. Introduction

In this paper authors propose a research to study effect of lubricants on vibration damping in weightlessness conditions. Envisioned project is preceded by other projects examining vibrations, performed by the duo of authors of this article. These projects include:

- **HEDGEHOG REXUS Project**, a study of dynamic and thermal conditions inside a sounding rocket during its flight, performed within the REXUS/BEXUS programme;
- **GDArms Spin your Thesis Project**, demonstrating possibilities of recreating

thermal and dynamic conditions of sounding rocket flight within a Large Diameter Centrifuge, performed within ESA Education Spin your Thesis programme;

- Adam Dąbrowski's PhD project studying effect of different environmental parameters on vibration damping properties of lubricants.

Having the experience within the domain vibrations in astronautical applications we perceive great importance of utilising novel vibration damping technologies.

2. Scientific background and objectives of the project

2.1. *Scientific objectives of the project*

The scientific objective is to quantify the mechanical damping properties of MoS2 lubricant in space-like conditions.

Vibration is one of the harshest environments an object (such as a satellite or a spacecraft - S/C) is exposed to during and after launch into space on a launch vehicle (LV). The propulsion forces, the aerodynamic forces, the acoustic and shock loads during launch of the S/C strongly interact with the low- and medium frequency dynamic characteristics of the LV and will introduce mechanical vibrations throughout the LV and also at the interface with the spacecraft.

These mechanical vibrations are generally categorised as follows:

- sinusoidal vibrations, 5-100 Hz;
- random vibrations, 20-2000 Hz;
- shock loads, accelerations, 100-5000 Hz.

The spacecraft will encounter severe vibrations during launch and later less severe vibrations when the spacecraft is placed in orbit and the deployable appendices are released and latched. Structural engineers designing and analysing spacecraft structures, solar arrays, antennae, instruments, equipment, etc., have to investigate the structural responses (e.g. accelerations, forces, stress) of the spacecraft and its components to mechanical vibrations and acoustic loads. Damping of these vibrations is a crucial aspect to ensuring the safety of a S/C [1].

It has been recently suggested that a lubricant film can be used to dampen mechanical vibrations in case of a deep groove ball bearing [2]. Studies of dynamics of mechanical systems with lubrication have been extensive in recent decades, as described by Flores et. al. [3], however, only recently dampening properties of lubricants were studied [4].

Space tribology is a recent field of study describing the frictional behaviour of space systems [5]. It encompasses the friction, wear and lubrication of mechanical components such as bearings and gears. Tribological practices are aimed at ensuring that such components operate with high efficiency (low friction) and achieve long lives. On spacecraft mechanisms the route to achieving these goals brings its own unique challenges. A review by Roberts [6] describes the problems posed by the space environment, the types of tribological components used on spacecraft and the approaches taken to their lubrication. He shows that in many instances lubrication needs can be met by synthetic oils having exceedingly low volatilities, but that at temperature extremes the only means of reducing friction and wear is by solid lubrication. As the demands placed on space engineering increase, innovatory approaches will be needed to solve future tribological problems. Much of the knowledge on the topic is provided in the Space Tribology Handbook maintained by the European Space Tribology Laboratory (ESTL) [7].

Molybdenum disulfide (MoS_2) is a typical solid lubrication used in space applications due to its great lubricating properties at various temperature ranges [8]. However, oxidation and moisture is known to affect its performance [9] which is crucial while on-ground environmental testing of space systems. Long time tests have been performed by the ESTL to determine various properties of the MoS_2 [10]. However, ESTL professionals in a private conversation with the Science Coordinator of this project during the Space Tribology Course, revealed that the damping properties of the lubricant have not been studied yet.

Science Coordinator's PhD thesis is based on determining the effect of the environmental variables (such as air pressure and temperature) and mounting properties (mounting torque) on the dampening properties of the MoS_2 lubrication. This has already been tested and proved to be an interesting topic. A test rig with a cantilever beam in a vacuum chamber has been proposed with a manual triggering system. The cantilever vibrations were measured by a piezoelectric distance sensor and an optimization algorithm on a supercomputer was matching an FEM simulation with measured data to identify damping coefficient.

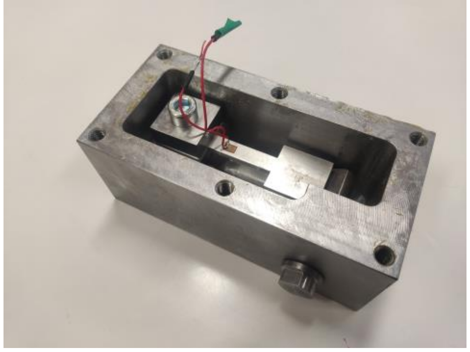

Fig. 1. Part of a test rig to measure vibration [12].

By performing tests with and without the lubricant layer at various air pressures, it has been shown that air presence seems to have a significant influence on damping properties of MoS_2 [11]. However, no tests in microgravity conditions have been performed.

The authors of the research proposal have substantial experience in measuring signals, especially vibrations in space-like conditions. Especially HEDGEHOG experience enabled us to create, test and analyse behaviour of a novel tunable mechanical vibration amplifier/filter system [12] (patent-pending).

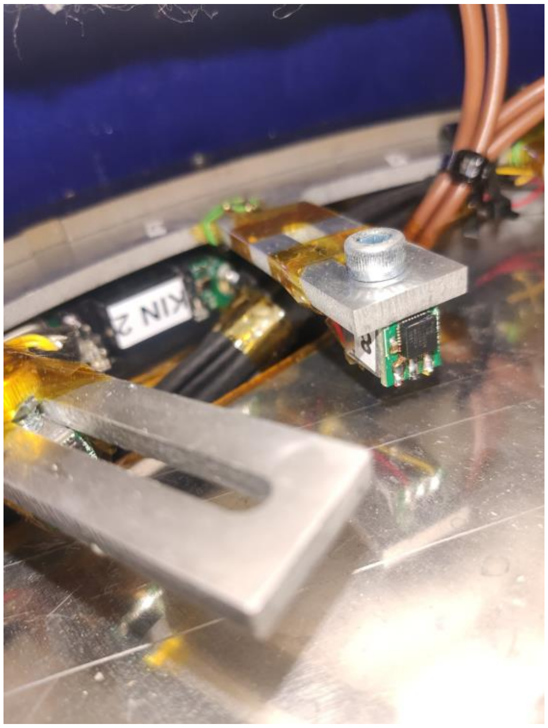

Fig. 2. The vibrational part of HEDGEHOG REXUS Project

The first part of the experiment focused on vibrational phenomena. A system of 10 cantilever beams was designed to amplify vibrations of a specific frequency (see Fig 3.1.2.). This system allowed for increasing the accuracy of the accelerometer measurement by means of mechanical amplification of the signal. The goal of this part of the experiment was to verify whether the signal amplification on each beam (at each frequency) corresponds to the level of acceleration measured on the rocket. Each cantilever beam was tuned to a specific eigenfrequency. This was achieved by moving an aluminium weight cube along the length of the beam. The position of the cube was determined by means of modal analysis, after which it was confirmed by modal testing with an impact hammer. The system's selectivity and its filtering capabilities was proved as a result of the flight [13].

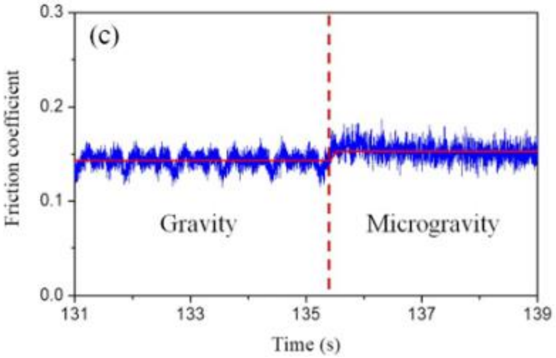

Fig. 3.

Recent studies performed at Beijing Drop Tower provide solid justification for a need for microgravity tests of the lubricant. Duan et al. [14] conclude that microgravity can not only change the value of friction, but also affect its dynamic characteristics. Therefore, we propose to study mechanical damping properties of MoS_2 lubricant in space-like conditions.

2.2. Inspiration for the project

The research stems from one of the authors PhD thesis - it is a natural extension of the topic to an interesting new environment - microgravity. Previous experiments such as HEDGEHOG, GDArms and STARDUST have all contributed to the teams' interest in gravity related research and reading various journal papers in the field. Presence at conferences, such as ESA Final Presentation Days and Workshops, International Astronautical Congresses and Courses led to meeting inspiring scientists including, but not limited to: Nigel Savage (ESA), Jack van Loon (ESA), Simon Lewis and Michael Buttery (ESTL), Artur Chmielewski (NASA JPL), Marek Moszyński (POLSA). Extended discussions with them and reading of their work along with exploration of our interests and capabilities in constructing space and microgravity experiments gave us the idea for the experiment. Friendly discussions with ZARM experts, especially Alois Gierse and Dieter Bischoff provided us with greater understanding of the fabulous possibilities the Drop Tower enables.

2.3. Previous studies of the problem in weightlessness conditions

The proposed subject was never studied in weightlessness conditions. Various properties of MoS_2 have been studied on ground [8], including work by ESTL that proves that space-like conditions could heavily affect its properties [10], but damping has not been investigated. This project's Science Coordinator characterised its damping properties on ground [11]. Seminal paper by [14] provides substantial evidence that microgravity affects dynamic behaviour of lubricants. So this research would be combining already obtained interesting results on ground with a strong argument that microgravity influences the phenomenon greatly.

2.4. Preferable platform for recreating the microgravity conditions

The phenomenon of damping is based on mechanical dynamics, so it can be studied in short durations. Additionally, the proposed test rig is small and contained. Since precise measurements of the vibrations are required, highest possible quality of vacuum and microgravity are required - this effectively disqualifies parabolic flights or sounding rockets as this experiment's platform. Considering above, we perceive drop tower as most suitable platform for conducting the proposed research.

The tunable beam mechanical vibration amplifier/filter (patent pending) can be designed to have various natural frequencies and vibration times [13]. Current test [11] and simulations were performed for a beam with 2.3 s of vibrations, but this could be adjusted ±2 s. Only highest quality of microgravity is for interest in our experiment, which, in case of utilising the ZARM Drop Tower, lasts about 3 s, what is enough for the experiment.

3. Proposed experiment procedure

Minimum of 2 launches are required - 1 without lubrication and 1 with lubrication. However, doubling the execution of each of the experiment's variants allows to exclude the uncertainty of erratic hardware behaviour. Additional 5th drop could be a spare one, that in case of successful drops 1, 2, 3, 4 and coherent results could be used for additional variants, with some changes of the experiment and/or environment variables. Drop mode of the drop tower is sufficient, catapult mode would allow multiplying the collected data, bat simultaneously would increase the experiment hardware complexity.

There are two experiment variants - dry (without lubricant) and wet (with lubricant). The 5 launch opportunities would be performed accordingly:

- 2 dry launches
- sputtering a layer of lubricant
- 2 wet launches
- 1 spare launch - to be used for an additional test, e.g. under conditions of 0,5 g recreated with utilisation of the ZARM centrifuge

The system would measure: vibrations of the beam and environmental parameters. The vibrations will be measured simultaneously by 3 sensors:

- beam accelerometer at the end of the beam (we expect values between 10 g to 0 g - this ignores values of the landing of the capsule);
- strain gauge at the start of the beam (we expect values between 200 MPa to 0 MPa);
- capacitive displacement sensor (we expect values ±2 mm).

Electromagnet must be operated in an automated way. The moment when we turn it off is crucial for experiment - we have to power it down when there is a sufficient level of microgravity and at least 2,3 s prior to the landing of the capsule. As the moment of triggering of the electromagnet is of utmost importance for the experiment, we would like it to be controlled by our hardware, so we can carefully test it prior to the campaign, therefore we would like to discuss with ZARM the possibility doing so instead of triggering it by CCS (according to ZARM Drop Tower Bremen User Manual - chapter 2.4.3.1).[16]

The electromagnet power could be controlled by two triggers connected in series (so if at least one of the triggers engages, the electromagnet is powered down) - primary trigger would power the electromagnet down after detection of sufficient microgravity by the experiment's electronics system, the secondary trigger would power down the electromagnet after given time after the launch (in case of malfunction of experiment's hardware) - this can be controlled by CCS.

We would like to use the ZARM's Photron Fastcam MC-2 in 2000fps mode to observe the behaviour of the experiment. The camera could be triggered together with the electromagnet.

4. Expected outcomes of the experiment

The expected outcomes of the experiment are the temporal profiles of vibrations of the beam including displacement (from strain gauge and distance sensor) and acceleration for both dry and wet cases. Afterwards, an optimization of finite element analysis will enable to identify damping coefficients in both cases. The difference of these values will be the damping coefficient of the lubricant.

Due to the high data rate of sensors, the values will be statistically valid. To exclude the uncertainty of erratic hardware behaviour, 2 launches per case will be performed.

5. Preliminary design of the experiment hardware

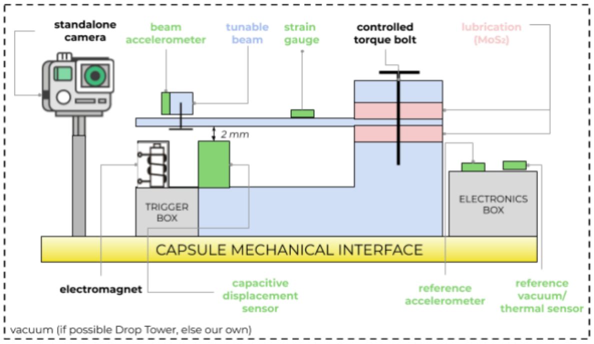

Fig. 4. System setup

The system is displayed in Fig 4. The experiment focuses on vibrations on a tunable cantilever beam. As described in 3.1, the cantilever beam is held by the electromagnet which both displaces in by 2 mm and holds it so that no external force causes the beam to vibrate. The cantilever beam is mounted to the structure (and thus, to the capsule) by a single loose, yet controlled torque bolt (described later). The bolt clamps the rear part of the beam between two support blocks.

The motion of the beam is monitored by multiple sensors: a 0.2 µm accuracy capacitive displacement sensor, a strain gauge in the place of maximum mechanical stress of the beam and an accelerometer on a tunable weight. The beam is tuned to be 300 Hz by means described in [ACTA]. There are additional reference sensors: accelerometer and pressure /temperature sensor placed in the electronics box, outside the beam. The whole experiment will be also monitored by ZARM camera.

As soon as the microgravity phase is detected (described later), the trigger box releases the electromagnet and the beam starts vibration (due to its initial deflection - a geometric initial condition). The vibration of the system will be measured by means of abovementioned sensors with great accuracy until the capsule lands safely on ground.

There are two variants of the experiment: one without lubrication and second, with MoS2 lubricant placed on both sides of the mounting part of the cantilever beam. Since the experiment will be in vacuum (Drop Tower level of vacuum is sufficient) and the setup will be subject to no gravity, only material damping and lubrication damping will be the factors that will eventually dampen the vibrations of the beam. By repeating the experiment with and without lubrication, it could be determined how much the lubrication contributes to damping, thus determining mechanical damping properties of the lubricant.

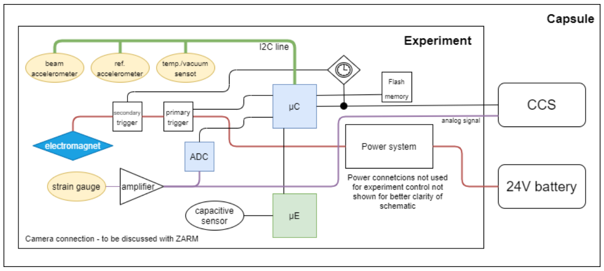

Fig. 5. Electronic system diagram

The system consists of 5 sensors and 1 actuator. The sensors are:

- capacitive displacement sensor - microepsilon capaNCDT with DT6222 system;
- beam accelerometer - STMicroelectronics LSM6DSLTR accelerometer;
- reference accelerometer - STMicroelectronics LSM6DSLTR accelerometer;
- strain gauge - Vishay N2A-13-S5155Q-350/E4;
- reference pressure & temperature sensor - Honeywell HSCDANN001BA2A3;

The microepsilon capaNCDT is designed for non-contact measurement of displacement, distance and position, as well as for thickness measurement. Due to its high signal stability and resolution, capacitive displacement sensors are applied in laboratories and industrial measurement tasks. In production control, for example, capacitive sensors measure film thickness and application of the adhesive. Installed in machines, they monitor displacement and tool positions.

The special sensor design, triaxial sensor cable and innovative controller technology result in a perfectly matched measurement system. Therefore, capaNCDT measurement systems stand for high precision and signal stability. Even in industrial applications, capacitive sensors achieve resolutions in the submicrometer range.

Capacitive displacement sensors from Micro-Epsilon are often used in vacuum and clean room applications where they achieve resolutions in the subnanometer range in particle-free surroundings. For vacuum applications, Micro-Epsilon offers special sensors, cables and feed-through accessories. These sensors and cables are particle-free to a high degree and used in clean rooms up to clean room class ISO1.

The modern capaNCDT controllers are equipped with different interfaces such as analog, Ethernet and EtherCAT. Capacitive measurement systems can be easily adjusted using a web interface displayed via a web browser. The controller is connected to a PC via an Ethernet interface.

As the system is fully autonomous, it will be recording for the whole course of the experiment.

All other sensors will be connected to the main microcontroller which will safely store the data on a flash memory and transmit the data (in lower frequency) to the control room. Both accelerometers and pressure & temperature sensors communicate with the microcontroller through an I2C (or alternatively SPI) interface. The HSCDANN001BA2A3 is a 0.25 % accuracy pressure sensor with 0 to 1 bar operating pressure.

Both beam and reference accelerometers are STMicroelectronics LSM6DSLTR high accuracy accelerometers with 6666 Hz output data rate, (adjustable ±2/±4/±8/±16g range) and 0.00061 g (sic!) accuracy.

Strain gauges measure mechanical stress in the place of maximum cantilever beam stress, which is lineary proportional to the beam deflection. Vishay N2A-13-S5155Q-350/E4 strain gauges were chosen as a result of a simulation to ensure their suitability. For 350 Ω strain gauges there is 400 mV difference between channels, enough for the built-in ADC to reliably read.

The Valley Forge & Bolt Maxbolt™ Load Indicating Fastener System continuously measures and displays the amount of tension in a bolt or stud. The system offers a simple method for accurate joint assembly and is the only product available, for most applications, which will continually monitor clamping force while the fastener is in service. This aids in maintaining the integrity of the bolted joint.

The dimensions of the system are around 300 x 200 x 100 mm with a mass of around 7 kg. Both the dimensions and the mass are within ZARM Drop Tower constraints.

Acknowledgements

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