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Combined environmental testing device for picosatellites

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Abstract

As access to space conditions becomes more available, both technically and economically, scientists' interest in launching finer and more sophisticated experiments grows. To be qualified for launch, such experiments need to be carefully tested prior to the event. The tests should represent actual launch conditions as closely and in a detailed manner. Typical tests for payload include: vibration tests, thermal and vacuum tests, and sometimes shock tests. Acceleration tests with a centrifuge are rarely performed. In traditional static tests the load application tools are usually jacks or weights, in conjunction with a proper levers system to introduce forces on attachment points or pressure on surface pads. Alternative systems as air-bags are sometimes used. Such approaches are also notorious for their tendency to both over and under-test at the same time.

These are scolded as inadequate and in some cases causing damage to otherwise suitable for spacecraft structures. Furthermore, all these tests are performed separately, which disables study on any cross-correlation effects, for example changing of stiffness of some elements in changing temperature. A prototype of a solution is suggested in combined environment testing device for picosatellites. A prototype has been successfully tested in the Large Diameter Facility in ESTEC. The aim of the device is to recreate as accurately as possible: dynamic, thermal and vacuum environment of a space rocket. The prototype hosted a 1U CubeSat dummy with sensors to measure various environments.

Keywords: environmental testing, spacecraft testing, rams, systems engineering

Acronyms/Abbreviations
European Consortium for Space Standarisation ECSS

1. Introduction

According to ECSS-E-ST-10-03C [1], test planning, test requirements, and test criteria shall be derived from the design requirements. While each experiment/satellite/scientific payload has its own specific requirements, they all include "compliance to the vehicle" requirements. These ensure that the payload survives harsh conditions of rocket launch.

The tests should represent actual launch conditions as closely and in as detailed manner as possible. Typical tests for payload include:

- vibration tests (ECSS-E-HB-32-26A [2]),
- thermal and vacuum tests (ECSS-Q-ST-70-04C [3]),
- and sometimes shock tests (ECSS-E-HB-32-25A [4]).

Acceleration tests with a centrifuge are very rarely mentioned in ECSS. The Spacecraft Mechanical Loads Analysis Handbook [2] specifies, that sometimes the load application is a very simple matter, as for example for internal pressure in pressurized structure. In other cases it is very difficult to have a testing load condition representative of the flight situation. For example, in pressurized modules carrying payloads supported by secondary structures, the inertia launch loads are due to an acceleration field highly non-uniform, due to transient dynamic responses of the secondary structures.

The complexity of testing loads could influence the choice between possible test methods:

- traditional static test (with application of static loads),
- centrifuge test (with application of unidirectional linearly varying acceleration field),
- sine test on dynamic shaker (with application of quasi-static loads),

The centrifuge and sine tests sometimes are preferred because cheaper and shorter in schedule, but they have some limitations:

- for centrifuge test: the centrifuge implies acceleration fields varying linearly with the radius, not always compatible with the required test loading, and then imposing a first limitation to test article size the test facility capability could impose an additional limitation to the size of the test article

- for sine test: it cannot be used if the control of the loading duration time is mandatory the shaker powers allow only a certain mass/acceleration range of applications additional instrumentation (e.g. accelerometers) is required
- for both centrifuge and sine tests: they are unidirectional and require that the linear combination of the results can be applied (which could be difficult, due to e.g. common contact problems in the joints) the combination with other load types (e.g. pressure and temperature) could be difficult.

In traditional static tests the load application tools are usually jacks or weights, in conjunction with a proper levers system to introduce forces on attachment points or pressure on surface pads. Alternative systems as air-bags can be used to represent localized pressure loads. The most important point to design such loading fixture is however the decision of using dummies to represent payloads and reduce the number of testing forces. The drawback in this case is, again, to assess the dummy stiffness relevancy, and to evaluate if dummies with correct stiffness can be replaced by "rigid" dummies. It is important to emphasize that everytime concentrated forces in the tests represent forces which are more "distributed" in real life conditions (e.g. body forces produced by launcher accelerations), different local load paths should be accounted carefully, with proper predictions, measurements and evaluations

Such approaches are also notorious for their tendency to both over- and under-test at the same time. Researchers have expressed their concerns [5] or even open criticism [6] to sine swept testing. These are lambasted scolded as inadequate and in some cases causing damage to otherwise suitable for spacecraft structures.

This is clearly visible in the procedure of notching, i.e. decreasing the amplitude of sine swept testing for some specific eigenfrequencies, as the very nature of sine swept test might cause the element to fall into resonant vibrations, even if actual rocket launch will not cause such effects.

The Spacecraft Mechanical Loads Analysis Handbook [2] states that: primary notching in sine testing of the spacecraft is mainly justified by the fact that the real environment in flight is of transient nature and is simulated on shaker by a sine sweep based on an envelope of LV/SC interface levels foreseen in the considered frequency band. This envelope doesn't account for the possible reactions of the spacecraft which can produce level reductions in some frequency bands.

Even sample requirements are provided that are very arbitrary and depend heavily on launcher authority's and customer's (!) experience in mechanical payload testing. These are [2]:

- "Notching criteria and implementation (for sine and random vibration tests) shall be approved by the customer and, if relevant by the launcher authority.
- Primary notching may be done.
- Secondary notching shall be approved by the customer. (NOTE: Secondary notching is generally not allowed)".

Furthermore, all these tests are performed separately, which disables study on any cross-correlation effects, for example changing of stiffness of some elements in changing temperature.

2. Scientific objectives

A prototype of a solution is suggested in GDArms experiment. The scientific objectives of GDArms experiment are to recreate as accurately as possible:

- dynamic,
- thermal
- and vacuum environment of a space rocket.

This element subject to all environments will be a small 100 mm x 100 mm x 100 mm, at max. 1 kg CubeSat (in gold in figure below) dummy with various sensors to measure all these environments.

Dynamic environment includes both high frequency but low amplitude vibrations as well as low frequency, quasi-static accelerations. This will be achieved by placing a custom designed shaker table (red/white in figure below) inside the Large Diameter Centrifuge, as shown below.

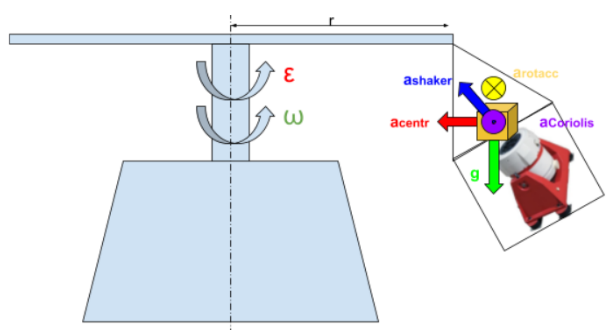

Fig. 1. Shaker table inside a centrifuge.

3. Theory and calculation

This is an interesting mechanics problem. The centrifuge is rotating with rotational velocity ω and rotational acceleration $\varepsilon = d\omega/dt$. The net acceleration on a test element is a (vector) sum of multiple vectors:

$$\overline{a_{tot}} = (\overline{a_{centrifugal}}) + (\overline{g}) + (\overline{a_{shaker}}) + (\overline{a_{Coriolis}}) + (\overline{a_{rotacc}}) = (\overline{\omega} \times \overline{\omega} \times \overline{r}) + (\overline{g}) + (\overline{a_{shaker}}) + (2\omega \times \overline{v_{shaker}}) + (\overline{\varepsilon} \times \overline{r}) \quad (1)$$

where:

- $a_{centrifugal}$ – variable (within LDC limits) centrifugal acceleration due to centrifuge rotating ω,
- g – constant earth gravitational accelerations,
- a_{shaker} – variable (within shaker limits) acceleration due to shaker table motion vshaker,
- $a_{Coriolis}$ – Coriolis acceleration due to motion of a rotating object
- a_{rotacc} – variable due to centrifuge rotational acceleration (or deceleration) ε

By controlling the centrifuge, high amplitude, quasi-stationary rocket acceleration due to thrust can be recreated, as mentioned in [7]. By controlling the shaker, high frequency (up to 2 kHz) vibrations can be recreated. On the shaker table, a small vacuum chamber will be mounted to allow for vacuum up to 0.01 bar 90%. Additionally, resistive heaters or lights will be mounted to allow for thermal testing. Typical values of up to 2 kW/m2 [8] are enough to recreate heat flux from Sun and Earth. This experiment aims also to recreate heat flux from aerothermodynamics of rocket launch. Such values can be up to 100 kW/m2 on small sounding rockets.

Many vehicles experience simultaneous acceleration and vibration loads during their missions and are therefore susceptible to nonlinear structural responses that can only be evaluated by combined environments testing. This novel approach to testing may allow payloads and vehicle subsystems to be tested in a more realistic setting prior to operations in the real world, and may lead to higher performance systems, as well as result in reduced cost [9].

Such a device altogether was able to perform not only tests, but also to recreate conditions of a given rocket launch to enable investigation of failures.

4. Experiment description

GDArms experiment hardware can be divided into different subsystems responsible for specific functions:

1. Shaker subsystem – responsible for generating and controlling the vibrations of the UUT.
2. Thermal vacuum chamber subsystem – responsible for recreating desired ambient pressure and thermal conditions affecting the UUT.
3. Electronic subsystem – responsible for controlling the experiment hardware.
4. Power subsystem – responsible for supplying the hardware elements with power according to their specific needs.
5. Control algorithms subsystem – software responsible for actuating the hardware elements recreating the rocket conditions, using the feedback from sensors.
6. Mechanical structure subsystem – responsible for supporting the whole hardware configuration inside LDC.
7. Unit under test (UUT) - system acting as payload tested by our device, it has sensors for acceleration, temperature and pressure measurements and is capable of having its mass alternated by adding dummy steel blocks.

The diagram below shows the subsystems or their significant elements with respect to their placement in LDC and signal interfaces. That diagram lacks the power connections and mechanical connections.

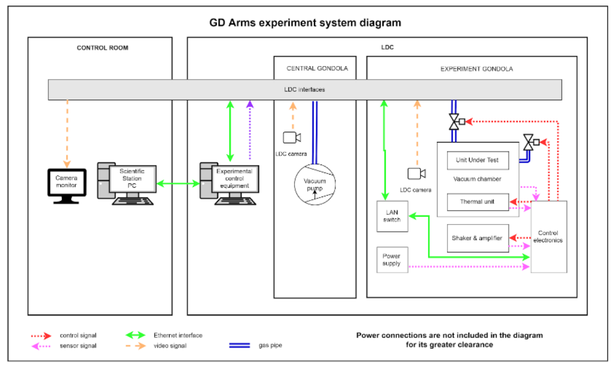

Fig. 2. GDArms experiment system diagram.

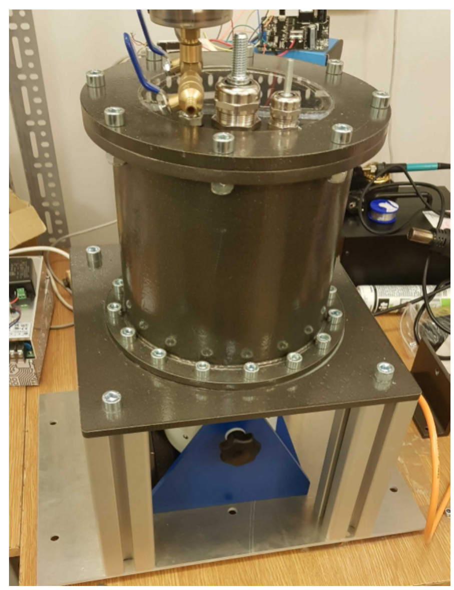

Fig. 3. Overview of the experimental platform.

4. Results

During the LDC tests, the waveforms of vibrations, heat flows and pressure recorded during the HEDGEHOG experiment during the flight of the

REXUS25 rocket in March 2019 from the Esrange spaceport in Kiruna were reproduced [10]. Due to the limitations of the centrifuge (accelerations during REXUS missile flights reach 25 g, the centrifuge can reproduce a maximum of 20 g), it was decided to use the Soyuz rocket acceleration profile [11], shown in Fig. 4.

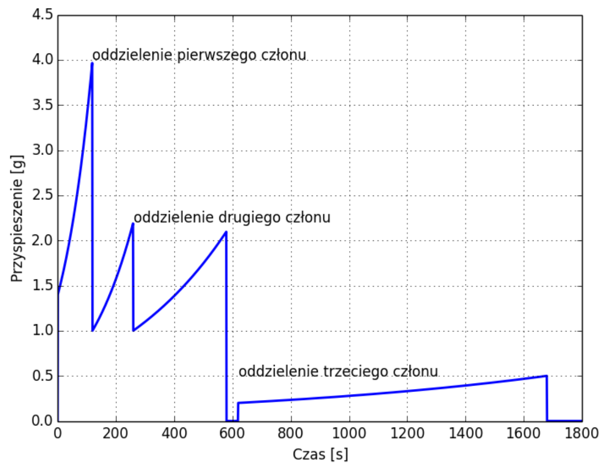

Fig. 4. Soyuz rocket acceleration profile [11].

Over 5 GB of data was recorded during the GDArms experiment. They describe the 16 hours of operation of the device. The challenge was also to recreate the course of the atmospheric pressure of the rocket flight. The dynamics of the pump allowed to obtain the appropriate speed of air suction. It was not possible to obtain a vacuum of better quality than 100 hPa. Additionally, rapid changes in pressure were recorded during the re-entry phase, which are not reproducible with a simple pump system. The comparison of the pressure courses between the HEDGEHOG and GDArms experiments is shown in Fig. 5.

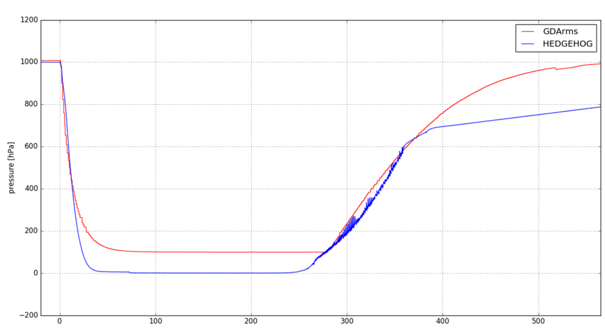

Fig. 5. Attempted recreation of air pressure profile of REXUS25.

During the experiment, the conditions of static acceleration (1 g, 2 g, 3 g, 4 g) and the course of the quasi-stationary acceleration of the Soyuz rocket (max. 4 g) were reproduced, both with active and inactive vibration exciter. The recorded acceleration data (Fig. 5) showed that the LDC centrifuge is able to stably maintain the level of static accelerations despite the operation of the vibration exciter on a scale of several hours. During the post-test inspection, it was found that the inductor was damaged.

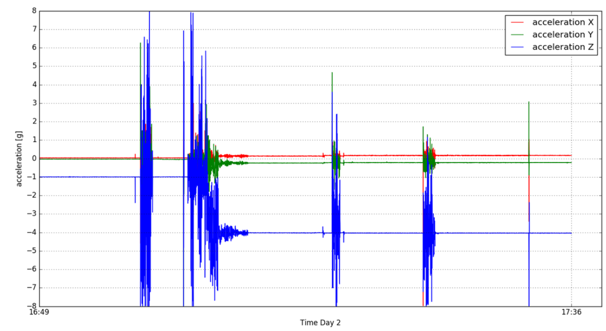

Fig. 6. Accelerations measured during GDArms experiment.

During the experiment, however, a certain limitation was noticed due to the dynamics of the centrifuge. Due to the high inertia, rapid changes in acceleration (jerks) are not possible, as occurs during rocket flight. To reduce the acceleration level from 3.5 g to 0 g, about 20 s are needed, while in the Soyuz rocket flight conditions it happens almost immediately (<1 s).

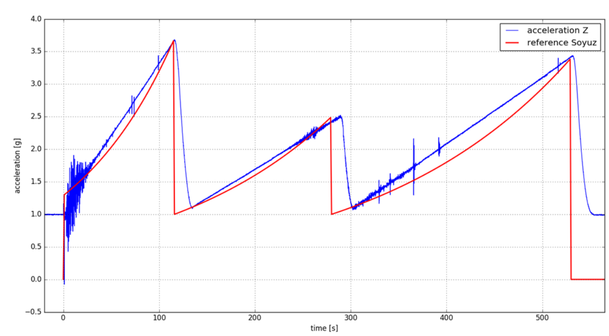

Fig. 8. Attempted recreation of Soyuz acceleration.

5. Discussion and conclusions

The research goal was partially achieved. The analysis of the collected data shows that while it is possible to reproduce the rocket accelerations in the LDC centrifuge, the high inertia of the device makes it impossible to reproduce the jerks (changes in acceleration) that occur when a given stage burns out. Likewise, the electrodynamic exciter is able to reproduce the vibrations of the rocket. Mechanical damage to the inductor after the tests suggests that the target device reproducing space conditions should have a different design so that the exciter rotor is not exposed to large overloads [12].

The pressure waveform was also reproduced, although a more powerful pump would have resulted in a better vacuum quality. Additionally, the use of chokes would improve the dynamics of the process. Reproducing the environmental conditions of rockets is therefore still an open question, and the presented research shows the direction to be followed.

6. Conclusions

This novel approach to testing may allow payloads and vehicle subsystems to be tested in a more realistic setting prior to operations in the real world, and may lead to higher performance systems, as well as result in reduced cost. Such a device altogether will be able to perform not only tests, but also to recreate conditions of a given rocket launch to enable investigation of failures.

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