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SPACE QUALIFICATION OF AN ULTRA LOW-SHOCK NON-EXPLOSIVE ACTUATOR FOR HOLD-DOWN AND RELEASE MECHANISMS: INITIAL TESTS

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ABSTRACT

This work addresses the space qualification test campaign of an innovative ultra-low shock non-explosive actuator (NEXA) suitable to space applications of hold-down and release mechanisms (HDRMs). The overall aim of the test campaign is to demonstrate that the NEXA design implementation and manufacturing methods have resulted in an engineering model conforming to the set of functional, performance and environmental requirements specified by the European Space Agency (ESA) and that it fulfills the relevant European standards for space application. Before the qualification test campaign, a fully functional engineering model underwent a series of characterization tests: preload monitoring system calibration, release time estimation and self-generated shock evaluation. The main results and conclusions are presented and discussed in this paper.

Keywords: non-explosive actuator, hold-down and release mechanism, qualification testing, ultra-low shock.

INTRODUCTION

Hold-down and release mechanisms (HDRMs) are standard components widely used in spacecraft in order to achieve mission related critical functions. Their main functions are to secure movable payload items, deployable appendages and separable mission elements during launch and to release them once in orbit. They can also be used in order to achieve timely synchronization for the deployment of specific appendages.

In general, HDRMs are composed of three fundamental elements: a *hold-down preloading assembly* (HDPA), e.g., bolt, nut, threaded rod, cable or rope, that provides the required preload, a *hold-down release actuator* (HDRA) which undertakes the release of the preload upon the command of an electronic device and is mounted on the fixed part of the separable interface and a *hold-down load carrying structure* (HDLCS) which ensures that the launch loads are transmitted between the fixed part and the part to be released. This is the only element that should be adapted to each appendage and spacecraft interface. Multiple technologies have been developed, specifically concerning to the HDRA which is the most critical component of the HDRM, and a wide range of devices are available today such as pyrotechnic devices, split spool devices (fusible or shape memory alloy wires), solenoid actuated nuts, electromagnets/magnetic clamps, thermal cutters/knife, piezoelectric actuators and electromagnetic/solenoid actuators.[1]

Pyrotechnic-based release actuators, a well-established solution in this overall domain, despite having a good mass/preload ratio they generate high shocks and are a source of contamination, a good example being the pyrotechnic device referred by Peffer et al. (2000a) that generates a shock acceleration peak of about 7200 *g*, having a mass of just 120 g. In addition, they require heavy and costly safety and handling procedures, and are not reusable (Peffer *et al.*, 2000b). All these aspects generate significant constraints at both platform and equipment levels in all phases of the development and implementation into a spacecraft. This is even more critical for small satellites because of the close proximity of the equipment to the shock source.

HDRMs can generally be classified within five categories with respect to their *shock response spectrum* (SRS) peak: high (> 3000 *g*), medium (between 1000 *g* and 2000 *g*), low (between 300 *g* and 1000 *g*), ultra-low shock (< 200 *g*) and no-shock (barely measurable) devices. Of these, it comes as no surprise that low to ultra-low shock devices were expected to cover 80-90% of the needs both for commercial and science/observation satellites before the end of the last decade (Peffer *et al.*, 2000a). Therefore, HDRMs are a critical technology of strategic importance on which ESA has promoted a research and development effort targeting its self-dependency in terms of commercial of-the-shelf equipment. Some relevant European suppliers already provide interesting solutions which main characteristics are presented in Table 1.

Table 1: State of the art non-explosive HDRMs from some relevant European suppliers.

Provider	**Device**	**Envelope /mm**	**Mass /g**	**Preload /kN**	**Release Time /ms**	**Shock Peak (SRS) /*g***	**Temperature Range /ºC (Non-Op.)**
Astrium / RUAG[2]	LSRU	85 × 60 × 54	900	30	< 100	~ 500	-95 to +120
Starsys[3]	Qwknut	76 × 51 × 41	200	13	< 35	< 150	-80 to +75
Sener[4]	NEHRA	Ø70 × 38	400	20	~ 10	N/A	-50 to +85
Arquimea[5]	S01.024S.FM	Ø116 × 79	450	20	~ 1.4	N/A	-90 to +75

Notes: N/A (not available); SRS (Shock Response Spectrum); Non-op. (non-operating).

In this context, the developed NEXA model aims to be an ultra-low shock, fully reusable, HDRM solution with a high preload to mass and volume ratio which, in the course of an ongoing contract with ESA, was developed by Spin.Works and is now being tested by INEGI. The NEXA solution consists in an initiator and force-reduction mechanism that provide the needed grip to sustain a qualification preload up to 25 kN. It is also expected to present a low power consumption, not to generate any debris and the low release time (less than a half-second) is expected to enable synchronized releases.

As required by ESA, a complete qualification program was defined for a completely functional engineering model (EM) in order to verify by testing its functional performance, measure the self-generated shock and confirm the ability of the mechanism to withstand the mission

[1] http://www.esa.int/TEC/mechanisms/SEM9T0DR5GG_0.html, accessed on 25/02/2013.
[2] Muller and Andreau (2009)
[3] http://www.starsys.com/, accessed on 25/02/2013
[4] Vazquez and Bueno (2001)
[5] http://www.arquimea.com/actuators.html, accessed on 25/02/2013

constraints from launch to in-orbit stages, facing severe mechanical and thermal environments. Following the European Cooperation for Space Standardization (ECSS) recommendations (ECSS, 2002) the EM test campaign includes functional, sine and random vibration, shock and thermal vacuum testing. During and after all the tests of the test campaign the EM must remain functional and keep the required performance level demonstrating that it fits the design expectations and proving its ability to operate in the overall phases of a space mission.

Such a severe test campaign has to be preceded of a set of procedures to ensure that the engineering model and the electrical and mechanical ground support equipment (GSE) are entirely functional and accomplish the design purposes. Furthermore, it should be verified that both the model and the GSE are free from manufacturing and operating errors increasing the confidence level in the results to be achieved across the test campaign. This is an important step of the verification by test development stage, assumed to be the forerunner of the qualification test campaign, and to which the present paper reports. At this stage, focus is kept on the functioning, preload capacity, release time and self-generated shock of the developed HDRM, as these are the main features necessary to characterize the performance of the mechanism. Thus, in this work the mechanism requirements and adopted solutions are presented and the results of the preload monitoring system development, release time evaluation and self-generated shock characterization are presented and discussed.

DESIGN REQUIREMENTS AND ENGINEERING MODEL

There are two levels of requirements aiming to guide the development and the testing phases. The first one, concerning to functional and performance requirements, worked as a guideline across the development stages establishing general boundary constrains at the design level. The other group could be identified as a set of requirements demonstrable by testing that aims to rule the qualification program ensuring that all of the critical properties of the EM that directly result from the development activity and adopted design solutions are assessed by test.

Functional and performance design requirements

- Ultra-low shock;
- High reliability;
- High robustness and repeatability of performances;
- Low cost;
- Reusability, accessibility for reloading and, if any, minimizing refurbishment at spacecraft system level maintaining flight readiness at low spacecraft system cost;
- High preload to mass and volume ratio;
- Reduced number of parts and active elements;
- Minimal internal friction;
- Scalability (preload range) of the design;
- Standardization of interfaces.

Requirements demonstrable by testing

- Functioning (at ambient and worst case conditions including mechanical misalignment and extreme temperatures);
- Self-generated shock;
- Sinusoidal and random vibrations vulnerability;
- Shock susceptibility;
- Behavior under thermal vacuum cycling;
- Functional life cycling.

The development of the mechanism was made under several refinement stages in which the concept was progressively reviewed and upgraded. The restrictions imposed by the design requirements, ECSS standards and international patents, limited the range of possibilities with respect to mechanical solutions and materials to use, but definitively contributed to foster innovative design concepts compatible with tight safety factors and tolerances, pushing to the edge the demand on materials strength, manufacturing accuracy and handling care procedures.

From conceptual to detailed design development, the target was to obtain a complete innovative HDRM assembly, encompassing developing both the HDRA and HDPA. The initiator system was duplicated to provide mechanical and electrical redundancy increasing the reliability of the mechanism. The force reduction mechanism was designed in a way that low initiation energy is required presenting a short release time scatter. The engineering model is presented in Figure 1. While in operation, the mechanism does not need any power supply until the release moment and due to its standard interfaces (mechanical and electrical) it is able to be used in most part of the current space systems.

The HDPA consists in an assembly of one M8 bolt (M10 is also available) of 12.9 grade steel and a set of washers/springs that promotes the bold extraction. The HDRM was designed in a way that it could accommodate a preload misalignment of 2° (half-cone). The most relevant HDRM design characteristics are presented in Table 2.

Table 2: NEXA reference design features and expected performance.

Device	**Envelope /mm**	**Mass /g**	**Voltage /V**	**Preload /kN**	**Release Time /ms**	**Shock Peak (SRS) /*g***	**Temp. Range /ºC (Non-Op.)**
NEXA	Ø60 × 60	320	40	25	< 250	< 200	-100 to +85

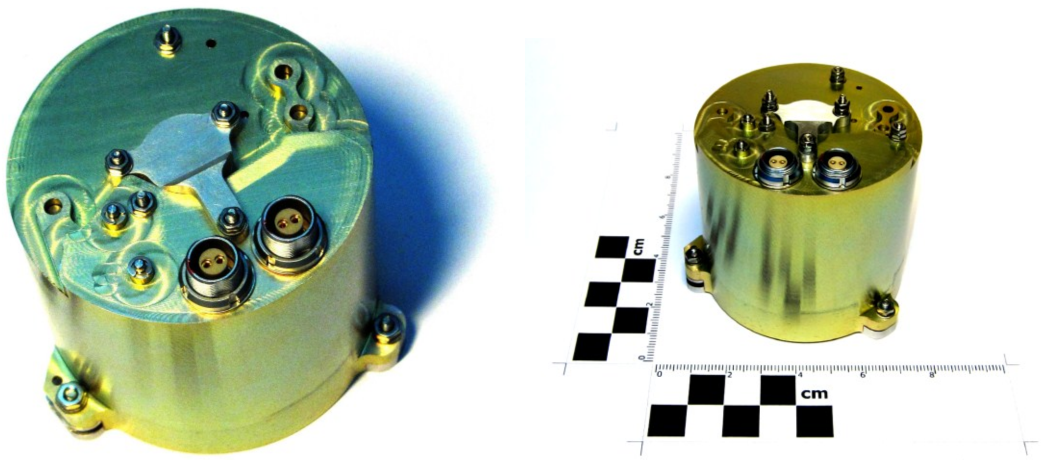

Figure 1: NEXA engineering model for HDRA.

TEST CAMPAIGN APPROACH

The target maturity level target of the developed HDRM is TRL 6. Therefore, a full qualification test campaign is required in order to demonstrate the model performance in a relevant environment (ground or space)[6]. Regarding the project requirements and specifications the test campaign was divided into two phases: preliminary testing and qualification testing.

Initial Testing

Initial testing is a crucial stage before carrying out the defined qualification test campaign. Its main objective is to ensure that both the electrical (e.g., power supply unit, data acquisition systems) and mechanical GSEs (e.g., physical support, reset tools, preload tools) are ready and working properly and that the engineering model is fully operational and ready for the test campaign. Emphasis should be given to the *load cell* calibration procedure, since this is the element that will acquire and monitor the preload levels across the entire test campaign. In addition, at this stage, the first measurements of the release time at room ambient conditions will be taken and the self-generated shock will be assessed. The results of these procedures will be presented and discussed in the next section.

Qualification Test Campaign

The qualification test campaign was outlined in agreement with the project requirements and the relevant European space standards for testing (ECSS, 2002) and mechanisms (ECSS, 2009). The qualification engineering model will have to face a test sequence that begins with sine and random vibration testing, followed of a shock test and finally a thermal vacuum cycling test, covering all mechanical and thermal mission environments. The success criteria are based in performance assessment being expected that the engineering model preserves its functional performance. Thus, functional tests will be done regularly across the test campaign, monitoring the preload and measuring the release time. Life cycling is also a requirement demonstrable by testing since it was determined that the mechanism will face at least 52 actuations–functional life cycling according to ECSS (2009)–proving its reliability, reusability and repeatability.

RESULTS AND DISCUSSION

The main function of a HDRM is to hold a certain amount of load. In the verification by testing of these mechanisms the applied preload should be permanently monitored in order to determine the mechanism load capacity, its ability to retain the payload when facing severe environment constrains and to successfully release the payload at the actuation event. The release time, i.e., the time needed to completely release the payload from electrical signal application to the zeroing of the load level, hence an important device characteristic, is also determined in this preliminary testing stage.

Such a relevant parameter as the loading capability has to be accurately evaluated across all the qualification campaign, thus requiring the design and the use of a reliable and well characterized load cell. In this section the load cell calibration procedure and main conclusions are presented; the preload application monitoring is tested and the release time is calculated. Finally, the generated shock during the actuation is characterized for different preload levels and the different shock sources of the mechanism are identified.

Load Cell Calibration

The mechanical GSE, i.e., the mechanical interface between the EM and the ground (see Figure 2) was designed in order to allow the insertion of a cylindrical load cell. However, it is expected to find a non-uniform strain field because of the presence of non-symmetric support conditions inside the plate and an irregular preload transmission from the HDPA, provided by the

[6] http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=37710, accessed on 25/02/2013

extraction setup and misalignment accommodation elements. Then, it was chosen to place three strain gages 120° spaced as shown in Figure 2. In these initial tests, the specific constrains of the qualification test campaign were already taken into account since there are several environmental issues that may interfere in the load cell behavior: the chosen strain gages (HBM C Series) are able to operate at a temperature range from -269 °C to +250 °C when mounted using an hot-curing adhesive HBM EP310S. The electrical connectors (HBM Teflon-insulated flexible stranded wire, -200 °C to 260 °C) are also compatible with the temperature range of the thermal tests.

The calibration procedure was made in an Instron 4205 universal testing machine, with a crosshead speed of 0.1 mm/min, until a threshold load level of 26 kN is achieved. The signal acquisition and processing was made with a National Instruments CompactDAQ system (with the module 9237) using LabView SignalExpress 2012. Nine experiments were done rotating the mechanical GSE and the extraction elements with the purpose of mitigating the effect of the assembly misalignments in the final calibration curves. The experimental calibration setup, presented in Figure 2, shows the HDPA assembly and the mechanical GSE of NEXA used in this procedure consequently recreating exactly the real operation boundary conditions.

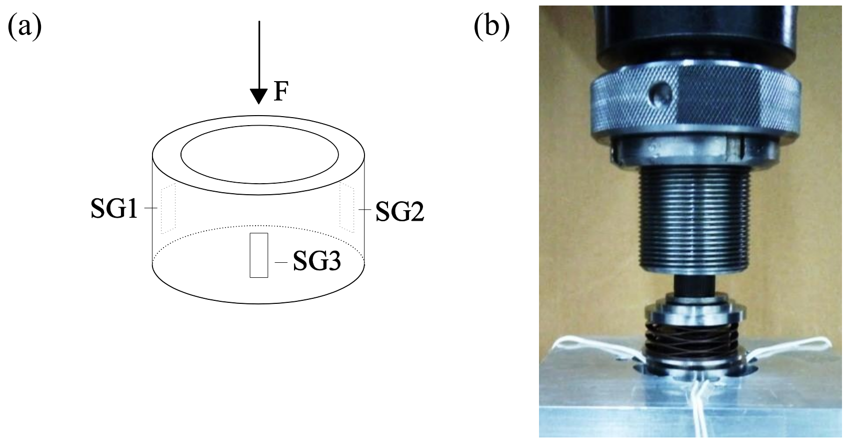

Figure 2: NEXA preload monitoring system calibration: (a) load cell scheme and (b) experimental calibration setup.

The results of the calibration are presented in Figure 3. A trend line was found for each strain gage considering the average of the nine experiments, being the guideline for future preload applications. The acceptable limit variation for each strain gage signal is assumed to be the envelope of the experimentally obtained calibration curves, expressed in percentage (see Figure 3). Being out of the interest region and because of the presence of significant non-linearity (as a result of the accommodation of the load cell in the support plate) the values below 2 kN were dismissed. Polynomial fitting curves (5^{th} order) were then calculated for monitoring the signal of the strain gages in terms of load force.

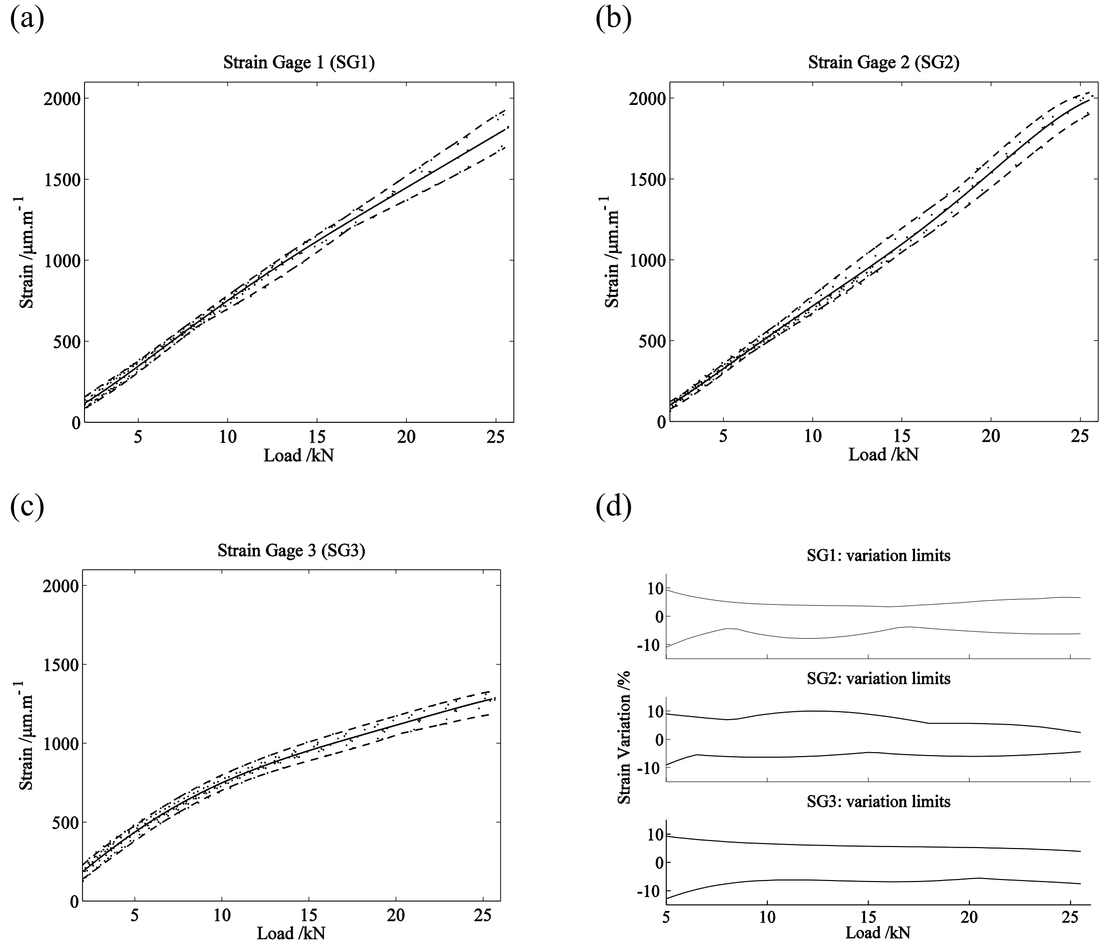

Figure 3: Load cell strain gages calibration results: (a-c) strain gages 1, 2 and 3 respectively; (d) measured strain maximum and minimum variation (%).

Preload Application and Mechanism Actuation

Taking as example the application of a preload level of 10 kN, Figure 4 shows the response signal of the three strain gages (converted to load in kN). The increasing load steps correspond to the application of bolt torque, being achieved a convergence of the three signals around the 10 kN, with a measured deviation between the limits determined for a 10 kN preload for each strain gage (Table 3).

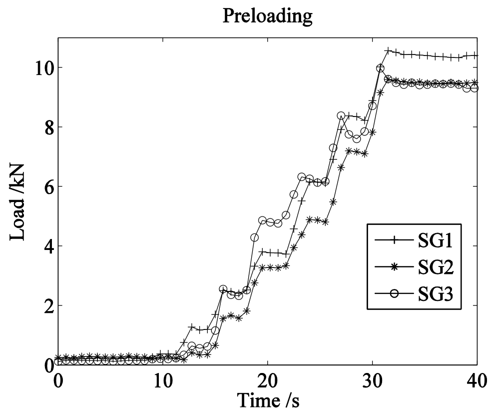

Figure 4: Load cell output signal for a 10 kN preload application.

Table 3: Strain gages measured signal variation for an applied preload of 10 kN.

Variation	SG1	SG2	SG3
Maximum	+4.17 %	+8.95 %	+6.59 %
Minimum	-6.85 %	-6.32 %	-6.34 %
Measured	+3.6 %	-5.4 %	-5.6 %

The mechanism does not require any power supply in operation until the actuation. At that time a 40 V electrical pulse should be applied (with a TTi CPX 400 DP power supply unit), during a period of time short enough to allow the initiation without damaging the initiator elements, theoretically estimated to be approximately 10 ms. The complete release of the preload was achieved in approximately 220 ms (Figure 5). The initiator and the force reduction mechanism are the main sources of the delay between the initiation and the preload release, still being fast enough to accomplish the specified design requirement of a nominal release time less than 5 s.

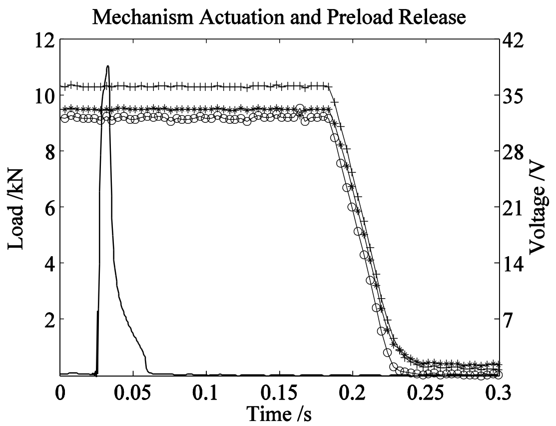

Figure 5: NEXA electrical actuation (40 V) and preload release.

Self-Generated Shock

Self-generated shock measurements were performed in order to characterize one of the most relevant features of the mechanism: the ability to progressively release the accumulated energy without generating a shock response that could damage the carrying structure and payload. Those measurements are closely dependent upon the adopted test method, but at least the response along the three main orthogonal directions has to be recorded. Taking advantage of the mechanical GSE plate design, it is possible to place three uniaxial accelerometers, therefore measuring the generated shock across the three orthogonal directions identified as axial, horizontal and vertical, as Figure 6 illustrates. Low mass accelerometers PCB 352C22 model were used and the acquisition was made with a NI CompactDAQ with the module 9234 at a sampling rate of 25.6 kHz.

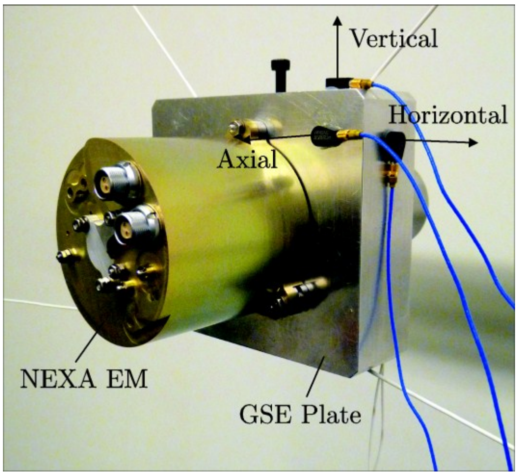

Figure 6: Self-generated shock measurement setup: NEXA EM, GSE and accelerometers.

The mechanism self-generated shock was registered for several preload levels (5, 10, 15, 20 and 25 kN) in order to verify the functional preload capacity and the ultra-low shock performance of NEXA. In Figure 7 the measured acceleration signals for an actuation with a preload level of 25 kN for each direction and the correspondent calculated Shock Response Spectrum (SRS) are presented (Tuma *et al.*, 2011). The SRS peaks are 72.7g, 166.7g and 71.9 g for axial, horizontal and vertical directions, respectively.

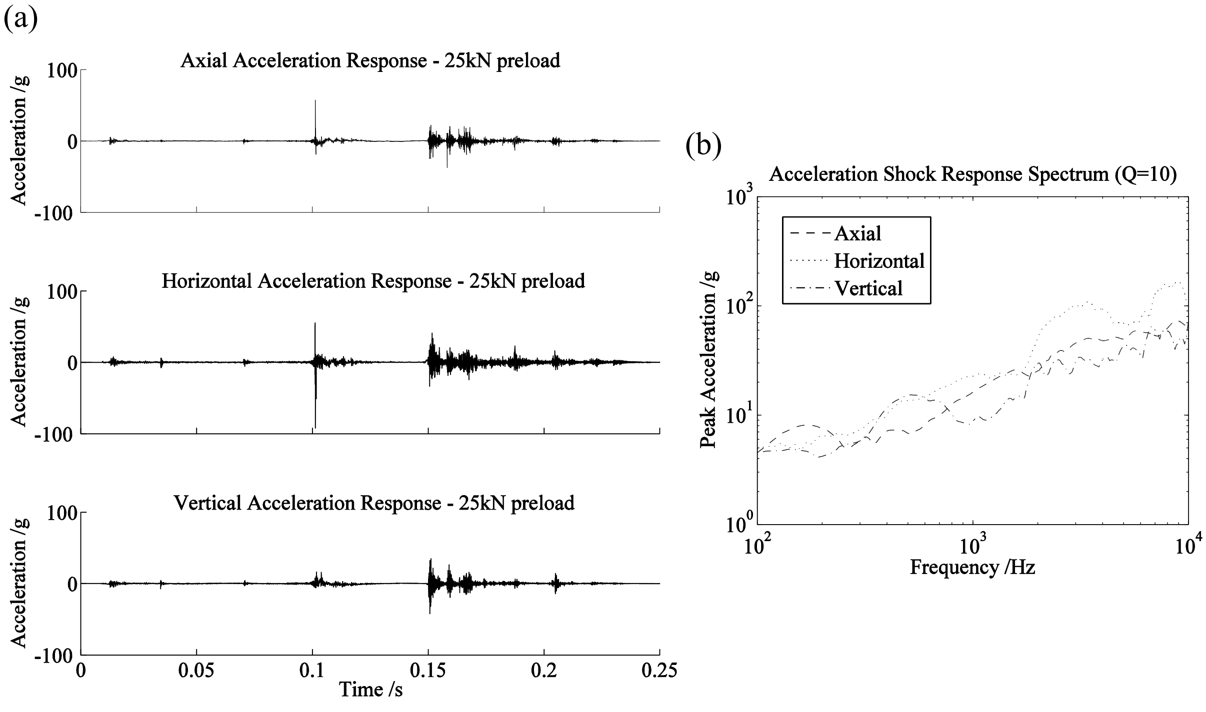

Figure 7: Self-generated shock for a preload of 25 kN: (a) acceleration time-history in three directions and (b) corresponding Shock Response Spectrum.

The measured acceleration response is the result of a series of mechanical shock events that occur after the initiation, as shown in Figure 7. It is an expected phenomenon since the actuation is composed itself of a sequence of events, each one having its own dynamic signature in the shock response. Thus, for the characterization of the self-generated shock of NEXA, the definition of the different shock sources present in the measured acceleration time-history is also presented. Other measurements were done in order to isolate the potential shock sources and the obtained axial acceleration time-histories are presented in Figure 8. In the first one, the initiator was armed and actuated resulting in a single transient response with a low acceleration amplitude; in the second test, the effect of the force reduction mechanism was added resulting in a response composed of two acceleration peaks; in the third experiment a preload of 10 kN was imposed, but the bolt-catcher was removed, being noticed a slight increase of the acceleration peak; finally, the completely assembled mechanism with a preload of 10 kN presents the shock signature of each component of the mechanism and also the effect of the bolt rebound on the bolt-catcher.

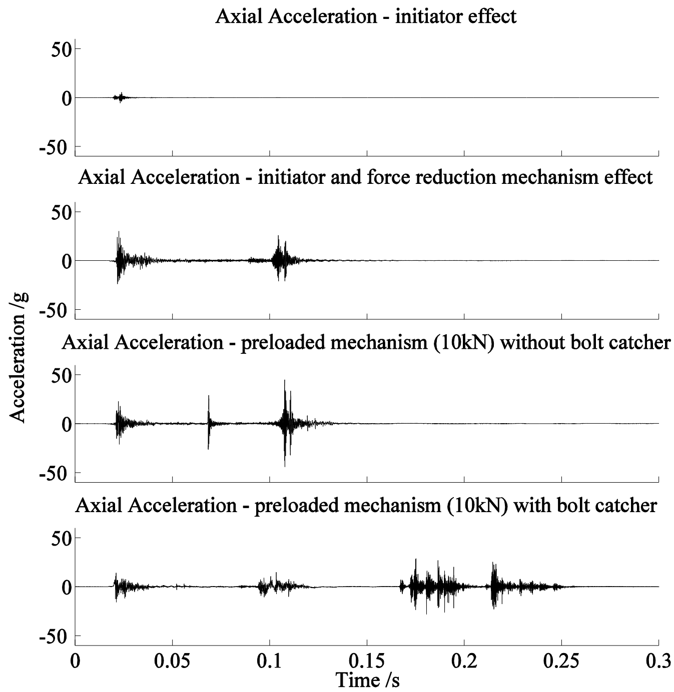

Figure 8: Axial acceleration response of the NEXA and components identification.

CONCLUSION

The first phase of the space qualification test campaign of the developed NEXA for HDRM consisted in manufacturing an engineering model and in the definition of a dedicated functional measurement setup to assess its functional performance and to characterize it in terms of preload capacity, release time and the self-generated shock.

In the series of initial characterization tests carried out, the mechanism functionality was verified, confirming the adequacy of the design to its purpose and the performance expectations at ambient conditions. Preload levels from 5 to 25 kN were applied, demonstrating the high preload capacity of the developed NEXA. Further, the release time was measured to be approximately 220 ms (actuation with a 40 V pulse); with the 52 actuations to be done in the qualification test campaign, the release time scatter will be determined to assess the mechanism ability to operate where high precision synchronization is critical. Lastly, the ultra-low shock capacity was demonstrated for the maximum preload of 25 kN, a SRS maximum peak of 166.7 *g* being obtained.

This set of initial tests also aim the detection of the eventual deterioration of critical components, highlighting the significance of this preliminary testing phase in order to enhance the success of the qualification test campaign that follows it. A stable and reliable behavior of the initiator provides good expectations for this element performance in the upcoming tests. Still, the reliability of the obtained results and the mechanism capacity to survive to the simulated operational environment could only be proved in the qualification test campaign that concludes the testing stage of the developed NEXA.

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