NELS HDRS QUALIFICATION RESULTS AND LESSONS LEARNT

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ABSTRACT

The new generation of solar arrays requires high stiffness/strength performances to survive the severe conditions experienced during the launch, in combination with low mass and low emitted shock and the capability to function under a wide range of operational conditions. This changing scenario has pushed Airbus DS Netherlands B.V. to develop a novel Non Explosive Low Shock (NELS) Hold Down and Release System (HDRS) with the objective to enhance the capabilities offered by the previous HDRS.

In this paper, the main test results and lessons learnt during the NELS HDRS qualification test campaign are highlighted. The test results demonstrated the compliancy of the NELS HDRS to the requirements defined during the development phase and, therefore, it is possible to conclude that the qualification was succesfully achieved. Based on the test results, some minor design changes were made to improve the robustness of the NELS HDRS. The design changes are thoroughly discussed in the paper.

INTRODUCTION

The design of NELS HDRS has evolved through the execution of breadboard and engineering tests that have been already discussed in previous works [1-2]. In particular, the test results obtained in the frame of the engineering test campaign were used to implement some additional design changes in the hardware prior to the starting of the qualification test campaign.

The hardware submitted to qualification tests differed from the hardware tested during the previous engineering tests mainly for the use of a new heater plate design. This became necessary due to the difficulty of the supplier to tune the resistance of the heater plate, which eventually leaded to the impossibility to control the cutting performance. In fact the cutting performance varies depending on the resistance of the heater plate at a constant supplied voltage. The implementation of an alternative heater plate design also came with unpredicted thermal/mechanical interface problems, which were addressed and fixed during the course of the qualification test campaign.

Figure 1. NELS HDRS SA configuration.

Figure 2. NELS HDRS ADS configuration.

NELS HDRS has two application variants named respectively Solar Array (SA) configuration (see Fig. 1) and Antenna Deployment System (ADS) configuration (see Fig. 2). Although intended for different applications, the core design and the functioning of the two variants is identical. The only significant difference is the structural design of the conical bracket, which in the ADS configuration has some eccentric disks to allow more integration flexibility during the installation of the conical bracket on the spacecraft sidewall.

NELS HDRS consists of a central restraint cable made with Vectran fibers. The restraint cable is under mechanical tension during the launch phase to keep either the panels of the solar array wing or a deployable boom in a stowed configuration. At the end of the launch phase, the restraint cable is cut by the main thermal knife, which consists of a rotating arm and a heater plate mounted on the end part of the rotating arm. A second thermal knife is added for redundancy opposite to the main thermal knife.

A cross-sectional view of the NELS HDRS showing the main components is given in Fig 3. The main and redundant thermal knives and their mounting inside the NELS HDRS bracket are highlighted in Fig. 4. The thermal knives are actuated by a spring. The thermal knives rotate during the cutting of the restraint cable and stop against a stop-bolt after the restraint cable is completely cut. The stop-bolt can be replaced by a micro-switch sensor for release detection.

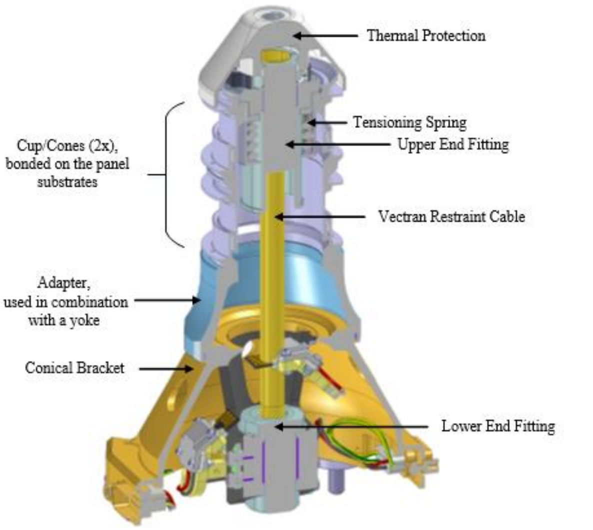


Figure 3. NELS HDRS cross-sectional view.

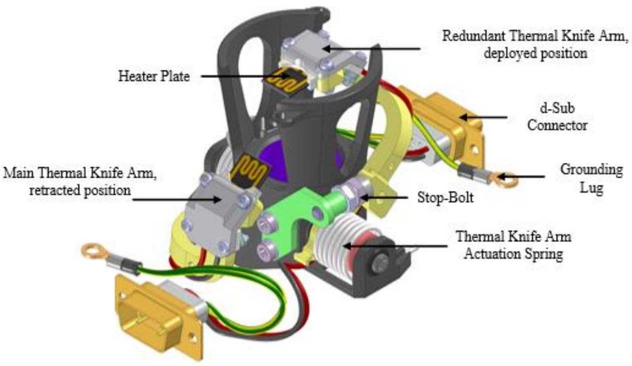


Figure 4. NELS HDRS cross-sectional view.

TEST PROGRAMME

The approach followed for the qualification test campaign was the so called "test as you fly" approach. This is an approach whose main objective was to reproduce all the on-ground and in-flight operations and environments the NELS HDRS hardware will experience during its entire life cycle and to eventually demonstrate thermal knives capability to cut the restraint cable with the required margins of safety.

The qualification tests were carried out according to the following test flow, which corresponds to the actual sequence of events the NELS HDRS will be submitted to during on-ground and in-flight activities:

- 36x cuttings at ambient conditions;
- Humidity, random vibration, shock susceptibility and thermal vacuum cycling test;
- 10x cuttings in vacuum and at different temperature conditions.

In addition to the tests above, the qualification test campaign also included the measurement of the shock emitted during the restraint cable cutting.

The qualification test campaign was performed on the following Qualification Models (QMs):

- QM-1: SA configuration (Fig .1), employing a 303mm long restraint cable;
- QM-2: SA configuration (Fig .1), employing a 52mm long restraint cable;
- QM-3: ADS configuration (Fig. 2), employing a 85.5mm long restraint cable.

QUALIFICATION TEST RESULTS AND LESSONS LEARNT

In this chapter, the most relevant qualification test results will be addressed including, whenever applicable, an overview of the challenges encountered and the way forward selected to address them.

Thermal Knife Cutting Performance Test

The performance of the thermal knife was characterized cutting the restraint cable in different operational conditions to demonstrate the thermal knife capability to succesfully meet its intended functionality. The performance of the thermal knife was succesfully demonstrated during on-ground and in-flight representative restraint cable cuts.

Before to start the qualification test campaign, a new heater plate was submitted to glowing cycles in ambient conditions as well as in vacuum conditions to demonstrate that its electrical resistance did not deteriorate beyond an acceptable threshold during the usage. The glowing cycles consist of power on/off cycles during which the heater plate gradually warms up and becomes white hot. The test results indicated a negligible reduction of the resistance of the heater plate. However, the upper ceramic plate that insulates the heater plate from the thermal knife arm structure was found broken during the visual inspection that followed the execution of the glowing cycles.

Fig. 5 shows the evolution of the thermal knife configuration throughout the additional glowing cycles performed during the ceramic plate breakage investigation. The grooves in the design of the upper ceramic plate were removed at first (see Fig. 5b) but the implementation of this design change did not solve the issue. Then crinkle washers were added below the screws' head (see Fig. 5c).

a)
b)
c)

Figure 5. NELS HDRS thermal knife a) initial configuration, b) intermediate configuration with upper insulating plate without groves and c) final configuration with upper insulating plate without grooves and crinkle washers below the screws' head.

The use of crinkle washers allows to compensate for the different out-of-plane thermal expansion of the components of the thermal knife, thus avoiding the upper ceramic plate (most fragile) to break. The updated upper ceramic plate design without grooves did not avoid the breakage of the upper ceramic plate. Nevertheless, it was decided to introduce it to the NELS HDRS baseline design because of the high stress concentration resulting from the grooves.

The thermal knife cutting performance measured during the qualification test campaign are, as follows:

- **Nominal cutting:**
  - Pressure: vacuum
  - Voltage supply: 19 V- 21 V
  - Cutting time: 23s max. room temperature
    19s max. at +97˚C
    43s max. at -80 ˚C
- **Cutting with limited current:**
  - Pressure: vacuum
  - Voltage supply: 19 V
  - Current limit: 1.5 A
  - Cutting time: 40s at +97˚C
- **Cutting with interrupted power:**
  - Pressure: vacuum
  - Voltage supply: 21 V
  - Cutting time: 73 s at +97˚C including 45 s of power interruption

The same heater plate was used to perform 36 on ground cuttings and 10 cuttings in the environmental conditions the NELS HDRS will find in a flight mission, thus demonstrating the existence of the following Safety Factors (SFs):

- SF = 4 for on-ground cuttings;
- SF = 10 for in-flight conditions cuttings.

The existence of high SFs is particularly important because it allows to quickly refurbish the NELS HDRS after the cutting of the restraint cable. It is only necessary to remove the old restraint cable and to install and tension a new one before the NELS HDRS is operational again, which takes about thirty minutes. The advantage of this approach is that the thermal knife components do not required any replacement or disassembly/reassembly.

Random Vibration Test

The NELS HDRS qualification hardware was submitted to random vibration test to verify its capability to succesfully withstand the mechanical loads associated with the launch environment. Fig. 6 shows the qualification test articles QM-1 and QM-2 installed on the shaker for the in-plane random vibration.

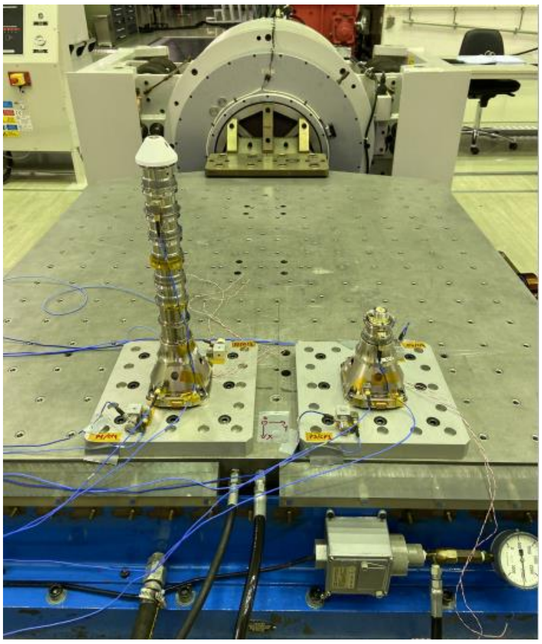


Figure 6. In-plane random vibration test setup showing QM-1 (left side) and QM-2 (right side).

During the visual inspection performed in between the random vibration runs along the first excitation direction and the second, some cut fibers of the restraint cable were observed. The cut fibers were in correspondence of the positions where the heater plates touched the restraint cable. The extent of the cut progressively increased during the subsequent random vibration runs along the second and third excitation direction up to cut the 25% of the cross section of the restraint cable, which means that 2 strands of the restraint cable over a total of 8 were cut.

The root-cause of the damge was the cutting edges of the heater plates rubbed against the restraint cable during the random vibration test causing the abrasion and the cut of the fibers. Even if the damage was acceptable and the overall functionality of the NELS HDRS was still guaranteed with 2 cut strands, the design of the heater plate was updated: the 0.5mm x 45˚ chamfers in the baseline design of the heater plate was replaced with a rounded cutting edge.

An additional random vibration test was then performed to demonstrate that the updated design of the heater plate was effective in preventing any damage on the restraint cable. QM-2 was submitted to a random vibration run at qualification level along the y-axis excitation direction. The y-axis is along the rotation axis of the thermal knives and it was selected because it corresponded to the excitation direction after that the highest amount of cut fibers was observed. A reworked heater plate with a rounded cutting edge instead of 0.5mm x 45˚ chamfers was installed on the redundant thermal knife while a heater plate with a baseline design was installed on the main thermal knife to provide comparison in interpreting the test results.

Fig. 7 shows the restraint cable before, in between and after the random vibration test. It can be clearly observed that while the baseline heater plate caused some damge, no cut fibers were detected in correspondence of the reworked heater plate. Based on the test results the baseline design of the heater plates was updated including a rounded cutting edge.

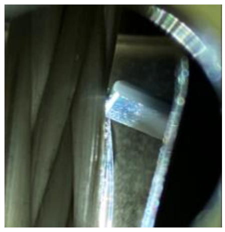
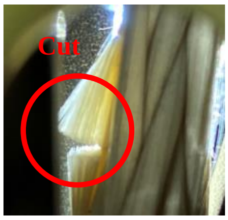
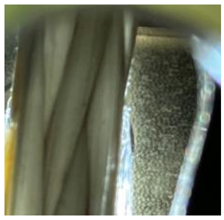
Step	*Main Thermal Knife with Baseline Heater Plate*	*Redundant Thermal Knife with Reworked Heater Plate*
a)		
b)		
c)		
d)		

Figure 7. Random vibration test results obtained respectively a) before test, b) after sine sweep, c) after random vibration at qualification level and d) after test, with thermal knife arm retracted. No cutting of the Vectran restraint cable is observed in correspondence of the reworked heater plate.

Emitted Shock Test

One of the main objectives of the NELS HDRS development was to achieve a low emitted shock upon the cut of the Vectran restraint cable. To verify this project requirement, an emitted shock test was performed at the end of the qualification test campaign. Fig. 8 shows the emitted shock test setup. The NELS HDRS was installed on a free hanging aluminium substrate (hanging rope not shown in Fig. 8) using flight representative interface washers and bolts. Accelerometers were installed on both the front and rear side of the substrate and at different distances from the axis of the test article, respectively 0, 100mm and 200m, to measure the out-of-plane emitted shock.

The Shock Response Spectra (SRS) of the shock emitted during the cutting of the restraint cable is shown in Fig. 9. The SRS correspond to measurements performed at 100 mm from the axis of the NELS HDRS and obtained during the cutting restraint cables tensioned at 15.5 kN and with a length of 85.5mm, 216mm and 303mm. Fig. 9 indicates that the acceleration response varies proportionally to the length of the restraint cable, with the lowest acceleration response (~200 g) measured for a length of 85.5 mm. The acceleration response was higher than expected and higher than measured during previous engineering tests [2]. The explanation is that the NELS HDRS configuration that was submitted to qualification tests significantly differed from the one submitted to engineering tests: the length of the restraint cable was increased, the thermal knife rotational arms were introduced and the tensioning spring was moved from the bottom side (spacecraft side) to the top side.

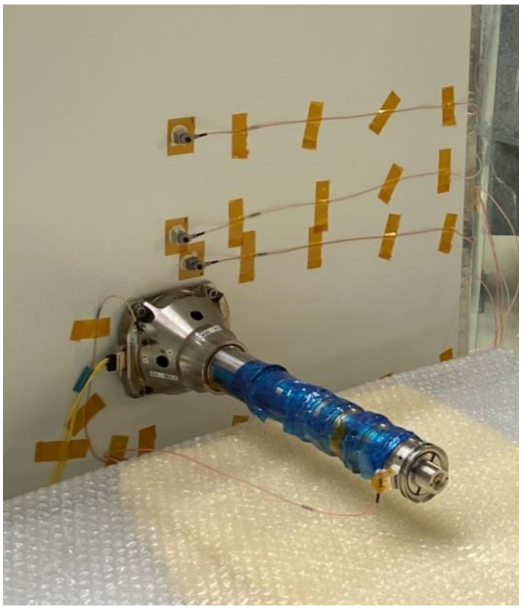


Figure 8. Emitted shock test setup.

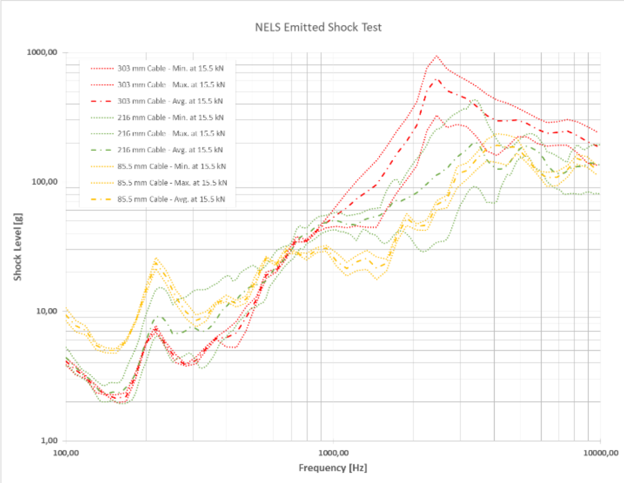


Figure 9. Emitted shock SRS measured 100mm from the axis of the NELS HDRS and relative to restraint cables with a length of 85.5 mm (yellow colour), 216 mm (green colour) and 303 mm (red colour).

The analysis of the time domain data indicated that the highest emitted shock was measured well before the release of the NELS HDRS, i.e. before the cutting of the restraint cable was completed. This can be also concluded from Fig. 10, where two SRS are highlighted: one SRS is obtained including the emitted shock over the entire time domain data measured during the cutting of a 303 mm long restraint cable, the other SRS is obtained only including the emitted shock time domain portion corresponding to the final cut of the same restraint cable. This shows that the primary source of emitted shock is given by the cutting of the restraint cable fibers. In addition, the emitted shock results suggests that a higher amount of energy is stored in the long restraint cables than in the short ones, which is not gradually released while the cutting is proceeding resulting in a higher acceleration response.

The emitted shock requirement, i.e. 1000 g level over the frequency range 5E+1Hz-1E+4Hz, was reached at 100mm from the axis of the NELS HDRS regardless of the restraint cable length.

The ultra-low shock definition, i.e. 300g level over the frequency range 5E+1Hz-1E+4Hz, was achieved only for a short restraint cable. In addition, the acceleration response associated with the cutting of a short restraint cable is comparable to the acceleration response associated with the impact of the thermal knife arm against the stop-bolt. Thus reducing the travelling distance of the thermal knife arm with respect to the stop bolt or damping the impact of the thermal knife arm against the stop bolt could allow a further reduction of the acceleration response below 200g.

In the frame of the engineering tests, the heater plates were found broken as a result of the impact of the thermal knife against the stop-bolt after the cutting of the restraint cable. The brakeage of the heater plates was avoided adding an adhesive spot bond to damp the impact of the thermal knife arm. The adhesive spot bond is indicated by the red circle in Fig. 11. The implementation of this solution also helped in limiting the shock emitted by the impact of the thermal knife arm against the stop-bolt, which from Fig. 9 is smaller than 100 g over the range 5E+1Hz-1E+4Hz.

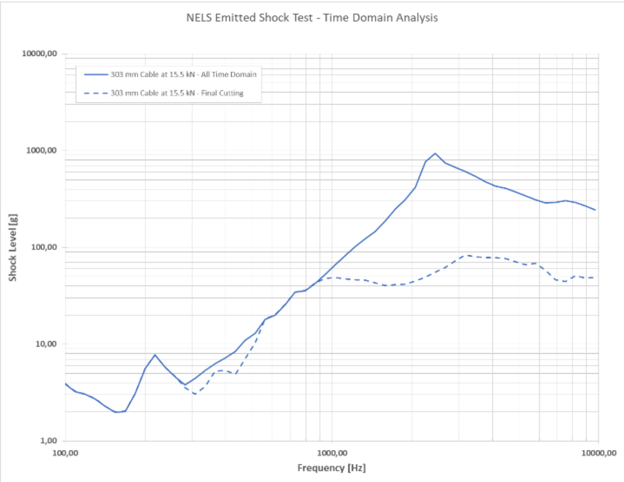


Figure 10. Emitted shock test results.

Figure 11. Stop-bolt damping.

CONCLUSION

The NELS HDRS qualification test campaign was succesfully completed. The NELS HDRS improved the capabilities already offered by the previous HDRS design by the Airbus DS Netherlands B.V.. The maximum mechanical tension of the restraint cable was increased up to 15kN, which augmented the stiffness/strength performances. The emitted shock was lowered to values below 1000 g level over the frequency range between 5E+1Hz-1E+4Hz. A nominal functioning was proved over a wide range of environmental conditions, which covers temperatures between - range between -143˚C and +151˚C.

The first set of NELS HDRS flight hardware has been already integrated and accepted for use on the solar array wings of the JUpiter Icy moon Explorer (JUICE) spacecraft and it is ready for its first mission.

ACKNOWLEDGMENTS

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