LESSONS LEARNED FROM THE CRADLE HDRM DEVELOPMENT ON INSIGHT-SEIS

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ABSTRACT

In the frame of the SEIS instrument for the Insight mission, a separation mechanism was needed to release the SEIS instrument from the lander deck. This mechanism is part of the Cradle subsystem, which has been designed, assembled and tested by CNES. While going through the development and qualification process of the Cradle subsystem, this paper focuses on the lessons learned through the successive design iterations and issues general recommendations to the user of a Frangibolt system.

To protect the sensitive VBB and SP instruments on SEIS from the shocks, custom dampers from SMAC damping products have been implemented on the Cradle subsystem and have proven to reduce the shock level by more than 10 at high frequencies.

The SEIS Cradle has passed all qualification tests and has performed as expected on the Mars.

PROJECT CONTEXT

InSight (INterior exploration using Seismic Investigations, Geodesy and Heat Transport) is the twelfth mission of the NASA Discovery program to be launched. InSight aims to study Mars’ deep interior structure using a geophysical station deployed from a fixed lander to better understand the mechanisms that shaped the rocky planets in our solar system.

Figure 1: Selfie of Insight on Mars, before the deployment of the SEIS instrument, credit: NASA/JPL-Caltech

Using the SEIS [1] seismometer (Seismic Experiment for Interior Structures), it will measure Mars’ tectonic activity to learn more about its structure, for example the size of its core and the thickness of its mantle.

Figure 2: This cut-through view of the SEIS seismometer shows the dome-shaped wind and thermal shield (WTS), the remote warm box (RWEB), the levelling platform, and the inside of the evacuated sphere protecting the VBB pendulums, credit: IPGP/David Ducros

Meteorite impacts will also be analyzed by measuring seismic waves.

CNES is overseeing the development of the SEIS instrument in partnership with the Institut de Physique du Globe de Paris (IPGP), SODERN (EADS Group), the Swiss Federal Institute of Technology (ETH), the Max Planck Institute for Solar System Research (MPS), the Imperial College London and the Jet Propulsion Laboratory (JPL).

InSight has been launched on 5/5/2018 and it has landed on Mars on 26/11/2018. The SEIS-Cradle Frangibolts have been actuated on 19/12/2018 with the deployment of SEIS on Mars on the same sol.
SEIS-CRADLE DESCRIPTION

In Figure 5 the Cradle can be seen highlighted in the SEIS instrument. The Cradle consists in 3 nearly identical turrets at 120° apart that protrude in the SEIS instrument. This has been done in order to put the dampers (which constitute the top part of the Cradle) at the level of the centre of gravity of the SEIS instrument, in order to have a dynamical behaviour with low coupling between the axes, meaning that an excitation following the x-axis has a response on the suspended part that is also mainly along the x-axis. The separation plane is at the level of the thermal insulation (RWEB) of the SEIS sensor assembly. The HDRM is situated below that, staying on the Insight lander deck after deployment.

Figure 5: View of the 3 Cradle turrets in the SEIS instrument, with the Damper and HDRM functions highlighted

The SEIS Cradle HDRM has gone through 3 design iterations that will be described in this paper: the engineering model (EM) design, the FM1 design and finally the FM2 design as flown to Mars.

HDRV CHOICE: FRANGIBOLT

Frangibolts from TiNi Aerospace were chosen as the active component of the release mechanism, due to compatibility with available power supply lines and uniformity with other Insight payload HDRMs (12 Frangibolts are used on Insight).

The Frangibolt is a SMA (Shape Memory Alloy) based actuator, built around a notched Ti-6Al-4V STA (solution-treated and aged) fastener that is broken upon actuation. The SMA used is Nitinol: an alloy of Nickel and Titanium with a nearly 1:1 molecular share.

A driving constraint for this choice was that the only electrical interface available on spacecraft side to power the HDRM was unregulated bus voltage limited to 4A, so all pyro (or pyro interface-type) release devices were not an option. Moreover, the short development time meant a new HDRM component development could not started, with only 3 years from start of the subsystem development to launch.

In order to have a more straightforward development with ample margins, a larger size Frangibolt would have had to be chosen, however due to power constraints this was not possible. A smaller Frangibolt has thus been
chosen, but needed to be used with a preload that was larger than its datasheet value. A preload of 2800lbf (12.5kN) was required, whereas the chosen FC4 Frangibolt was stated to be typically good for a preload of 1500lbf (6.5kN) at a maximum at 2500lbf (11kN).

ENGINEERING MODEL TESTING

Very fast an EM was made with the cross section in Figure 6 to get a hand-on experience with a Frangibolt system.

The preload was applied in this system by torquing the locknut to a defined value above the running torque, which is the nominal and most straightforward way of preloading a Frangibolt system.

While functional, the Frangibolt used in this design did not perform as good as during its acceptance testing at TiNi Aerospace, in the sense that the fastener broke after a longer time. The operating conditions (environmental conditions, firing voltage, preload) were chosen the same as the ones in the acceptance testing. This showed that the design of the joint assembly (being the only thing different) was not optimal. A close inspection indeed showed that the top thin washer was deformed as there was too much clearance between the fastener and the assembly part. The assembly part was modified which improved the performance as seen in Figure 7.

The complete assembly design was subsequently revised for the FM1 manufacturing.

PRELOAD CONTROL

Controlling the applied preload is essential in Frangibolt systems as for all HDRMs, but it contains some things that are specific and are worth mentioning.

In designs with ample margins, the most straightforward implementation to apply the preload is to torque the fastener or the nut with a torque wrench. This typically leads to a few tens of percent in dispersion on the applied preload. In the case of the SEIS-Cradle HDRM, this dispersion would have led to negative margins while still being compliant to the ECSS factors of safety. A tighter control on the preload was indeed needed in order to apply a preload that is as close as possible to maximum acceptable load.

TiNi Aerospace recommended to use strain gages integrated in the fastener to have a direct measurement of the preload. These strain gages are glued at the end of a axial hole in the fastener. Each instrumented fastener is then individually calibrated. If used correctly, this can give preload uncertainties of only a few %.

Additionally, in order to apply high preloads, the tightening torque should not be put on the notched portion of the fastener. The notch geometry increases the axial breaking strength due to triaxial stress, but not the shear strength seen because of the torque. This is why TiNi recommends to limit the preload to 1500lbf (6.5kN) on the ¼” fastener used here. Preload on the SEIS Cradle has been increased to a nominal value of 2800lbf (12.5kN) by counter-torquing the fastener.

The newly designed HDRM with the strain gage in the fastener can be seen in Figure 8.
FASTENER YIELDING ANOMALY

Anomaly description

With the new hardware procured, tests have been made to verify the functionality of the system in all combinations of starting temperature, firing circuit and firing power. Most tests were successful, but in one combination of cold environmental temperature (-75°C), low actuation power (60W) and secondary actuation circuit, the fastener would still fail to break.

In this failure case, the Frangibolt reached a more than sufficient temperature (220°C for actuation expected around 140°C), which indicates that the SMA did fully transition to austenite, but did so without breaking the fastener. At first it was though that this was due to a wrong integration, but we managed to reproduce this failure and only managed to do so with the said combination of starting temperature, firing power and firing circuit. An increase in length of the fasteners that failed to break has also been consistently observed in the failure cases.

A large effort was put into making a detailed thermal model of the whole system to get a better understanding of the heat exchange dynamics. The model includes conduction through solids, gaseous conduction, radiation and convection.

The main test-as-you-fly exception was the environment of 1atm of GN2 in test, whereas the hardware needs to actuate on Mars (7mbar CO2). The impact is that the gaseous conduction coefficient in the testing condition is 50% higher than on Mars. The convection was very small, as the natural convection was mostly blocked due to the test configuration and thermal chamber was turned off right before actuation thus blocking the forced convection.

Radiation and convection accounted for <5% heat exchanges.

Thermal modelling results

Once the model was in place and tuned with some unitary tests, the specific use case where the anomaly occurred was simulated, showing a large thermal gradient in the fastener (140°C). This gradient (which we will show later is responsible for the anomaly) was taken at the time when 80% of the Nitinol material reached its transition temperature.

At this time, the notch had heated up from -75°C to 20°C, while the strain gage hole region heated up from -75°C to 160°C.

In other combinations of starting temperatures, heating power and actuation circuit, the gradient did not get this high.

It is worth noting that the main heat flow path to the fastener is the gaseous conduction, not the conduction through metallic parts.

Root cause

To get to the root cause, the spread in breaking strength of the fastener notch and in the yield strength of the fastener Ti-6Al-4V needs to be taken into account. For this, intervals have been computed based on
measurements from the same material and manufacturing lot, taken at 3σ at a confidence of 90%. The breaking strength of the notch at ambient temperature is in the range [19240 ; 23650] N and the yield strength is in the range [1093 ; 1268] MPa.

At the breaking strength of the notch, the stress in the fastener in its portion with the strain gage hole is [819 ; 1006] MPa, which is in all cases lower than the measured yield strength.

However, the material characteristics change with temperature as can be seen in Figure 10.

**Figure 10:** MMPDS temperature dependence of solution treated and aged Ti-6Al-4V alloy used for the Frangibolt fasteners, showing the reduction of 22% of the yield strength at +160°C (+320°F)

At the modeled temperature at the strain gage hole, the yield strength is 22% lower than at ambient temperature, so the yield strength is in the range [853 ; 989] MPa. The breaking strength does not need to be corrected as the notch temperature has been computed to be at room temperature (20°C) at the time of interest.

The yield strength range now overlaps with the stress range, so the fastener may start yielding in the strain gage region before it reaches the breaking strength at the notch.

The stroke produced by the Frangibolt is thus “lost” by yielding the fastener, explaining the observed increased length of the fastener in the test failures.

**Implemented fix**

The root cause of this anomaly was eliminated by using fasteners without the strain gage hole. The stress in the fastener decreased from [819 ; 1006] MPa to [613 ; 753] MPa, thus providing a worst case margin of 13% on the yield strength in the same conditions.

Other corrective actions were taken as well that further increased margins:

- An important gradient was also seen the Nitinol. Where this was in contact with the structural parts the temperature was lower by 150°C than at the hottest point. To reduce this gradient, the conductive isolation was improved by using a thick vented Ti-6Al-4V washer (see Figure 11).
- The issue being worse at cold temperatures, an increase in minimal environmental temperature was also requested. By then JPL decided to deploy SEIS in the afternoon on Mars, which allowed them to increase the cold operational environmental temperature for the Cradle from -75°C to -50°C.

Preload could not be measured by the strain gage anymore, but there was still a need for a tight preload control. An ultrasound based preload measurement was implemented that required gluing a crystal at the bottom end of the fastener. The ultrasound measurement effectively is a duration measurement between the time an ultrasonic impulse is sent in the fastener and the time it comes back after having been reflected at the top end of the fastener. This duration is function of the elongation of the fastener due to the preload and the wave velocity of the ultrasonic impulse in the fastener which is dependent of the stress in the fastener.

**Figure 11:** On the left the FM1 parts (instrumented fastener and regular washer), on the right FM2 parts (fastener with crystal for ultrasonic preload measurement and vented washer). The vented washer reduces the thermal leak while maintaining a good axial stiffness and a good spread of loads over a large contact area.
To have the required tight control on the installed preload (<5%), the ultrasound measurement was calibrated on each individual fastener right before installation in a separate set-up containing a load cell.

This design proved to be the final design, with a 100% success rate throughout the qualification campaign, and on all tests performed on the flight hardware. The performance in terms of time to actuate can be seen in Figure 14.

It can be noted that the Frangibolt actuates faster than during the reference acceptance tests at TiNi. The main reason for this is certainly the higher initial preload (2800lbf on the Cradle instead of 1500lbf used by TiNi).

**FRANGIBOLT RELEASE TESTING**

The cup-cone feature seen in Figure 12 is actually not in contact with each other when the SEIS instrument is held down by the Frangibolts in launch configuration. All shear loads are taken by friction. The purpose of the 57° cup-cone feature is to ensure that the SEIS instrument does not move by more than its 0.35mm radial gap when released. This has been verified by test on the maximum specified slope of 15°. For this test, a suspension system was put in place in order to compensate for the difference between the gravity on earth and on Mars. This release was filmed with a high-speed camera and the displacement was measured with a displacement sensor. The maximum measured displacement was 9.4mm, which is higher than the 4mm cone. The Frangibolts are however fired once at a time, so there are always 2 cup-cone features that stay engaged ensuring the position of the SEIS instrument after release.
along the +X axis. This test has been performed along the 3 axis in both directions.

The qualification to external shocks received from the lander pyrotechnic releases has also been used to characterize the shock transmissibility of the Dampers at the cold qualification temperature of -50°C (where the dampers are stiffer than at ambient temperature). This has been performed at the CNES pyrotechnics lab in Toulouse. For this, the whole SEIS-Cradle QM2 unit has been placed in a thermal chamber to be cooled down to -120°C. The unit has then been transferred to the pyro bench. The Damper temperature has been monitored by thermocouples and the shock has been measured with PCB 350D02 shock sensors. The CNES-ESA Pyroshock bench was fired once the Damper temperature has increased to -52°C.

Figure 17: SEIS-Cradle shock test on the CNES-ESA pyroshock bench. This test has been performed along the three axis at hot (+45°C) and cold (-52°C, pictured) qualification temperatures.

Figure 18: Shock level measured at cold at the basis of the instrument and behind the dampers, showing an attenuation larger than 20dB at high frequencies (>600Hz).

The SMAC dampers attenuate the external seen shock by more than 20db. The peaks seen at 3200Hz and after 6000Hz have been correlated to the free eigenmodes of the dummy mass and are not linked to the behaviour of the dampers.
FRANGIBOLT SHOCK GENERATION

Cradle release shock measurements were performed with shock sensors at the base of the SEIS instrument (one interface away from the separation) and on the Sphere subsystem containing the VBBs sensors (attenuated by the dampers). The set-up can be seen in Figure 19. Up to 2kHz the shock was <200g, but the shock rose to 5000g at 10kHz. SMAC dampers reduced this shock to under 140g over the whole spectrum effectively protecting the VBB sensors.

Figure 19: Test set-up for the Frangibolt release shock measurement on the SEIS flight hardware.

Figure 20: Shock Response Spectrum measured at the basis of the SEIS instrument and on the Sphere-VBB subsystem after attenuation by the SMAC dampers.

The shock created by the release of a Frangibolt system is much lower than that from pyrotechnical HDRMs, but is still significant in the high frequency range. The shock level here is linked to the amount of stored energy in the assembly and to how fast this energy is released. To actuate the Frangibolt needs to increase the installed preload in order to break the fastener, effectively increasing the stored energy in the system. The fastener also needs to be brittle to break at low elongations, so the energy is released suddenly explaining the high-frequency content.

CONCLUSION

The Cradle subsystem for SEIS on Insight has been successfully developed and tested, and has functioned nominally on Mars, ensuring the hold down and release functions while protecting mechanically the VBB and SP sensors from the random vibration and shock environment.

The TiNi Aerospace Frangibolt is a very efficient HDRM (in terms of mass/volume for a given preload need), and it can be easy to use and refurbish. Behind this apparent simplicity, having a good understanding of the driving physics of the a Frangibolt system is important for the user, as each implementation is specific. Testing the system in all combination of parameters with margins is very important to ensure the implementation of the Frangibolt system is robust. Moreover, each Nitinol lot and each notched fastener lot is somewhat unique, so the good practise is to fly hardware from the same manufacturing lots as those used for the qualification models.

Lots of care should be given to good integration procedures to ensure that the installation of the Frangibolt system is correct. Some operations remain somewhat operator dependant, so it is also good practise to keep the same operators throughout the life of the product from development testing to flight installation.

Both for designing the system and for anomaly investigations, a multi-physics model approach of a Frangibolt system is beneficial. The thermal model described in this paper helped understanding what the root cause was of the anomaly and what could be done to effectively improve the design.

Sensitive hardware as the VBB sensors on SEIS benefit from the protection from the SMAC dampers. Due to the highly non-linear structural behaviour of these sensors, no finite element model could predict what levels would be safe to test against (both for random vibrations and shocks). The development approach of SEIS has been to reduce the mechanical environments as much as possible by implementing the SMAC dampers, and test to this level only on VBB and SEIS level.

REFERENCES