Development and Testing of a Bi-Stable Actuator based on a High Transition Temperature Shape Memory Alloy

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Abstract

Pyrovalves, i.e., valves actuated by a pyrotechnical device, are very often used in space propulsion systems for their fast response, high reliability, low mass and low cost. However, they are hazardous and single use items. Their operation induces shocks and can generate contaminants. If a slower actuation is required or possible, shape memory-based actuators avoid the generation of shocks and contaminants while being fully resettable and non-hazardous devices.

The goal of this project was to develop a bi-stable Shape Memory Alloy (SMA) actuator for a specific Slow Acting Latch Valve with long life capability. The benefits of this actuator makes it interesting not only for valve actuation but also for any device that has to be actuated in a smooth and reliable way.

This paper presents the development of a bi-stable actuator based on high temperature shape memory alloys.

Introduction

Shape Memory Alloys undergo a phase transformation upon cooling from high temperature austenitic phase to a low temperature martensitic phase. This phase transformation is the basis for the unique properties of these alloys. At room temperature, the SMA can be readily deformed (low yield strength). When heated above the reverse transformation temperature A_f, the alloy reverts to austenite and recovers its previous shape. This property is known as the shape memory effect. With proper selection of SMA materials and production processes, the transition temperatures can be tailored to the engineering needs.

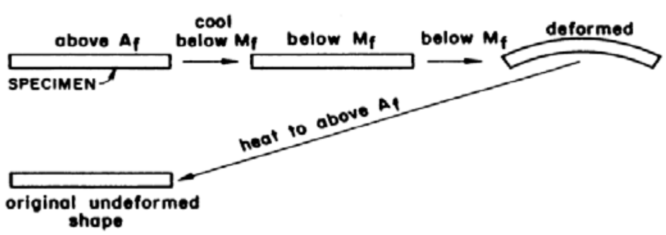

Figure 1. Shape memory effect principle

The team designed, manufactured and tested an actuator based on a high-temperature shape memory alloy. The SMA actuator main features are:

- High reliability
- Smooth-acting
- Resettable
- Light and compact
- High temperature SMA alloy (above 120°C)
- Withstands launch loads as high as 28.3 g_{RMS}
- Made of space-compliant materials

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The SMA actuator developed by Almatech is based on the following operating principle: electric current is used to heat up multiple SMA wires (in a parallel configuration) changing their crystalline structure in such a way as to shorten them and actuate the integrated latching/de-latching mechanism. Thanks to this bi-stable custom-designed latching device, no power is needed to maintain the actuator in one or the other stable positions.

The overall dimensions of the developed actuator are shown in Figure 2.

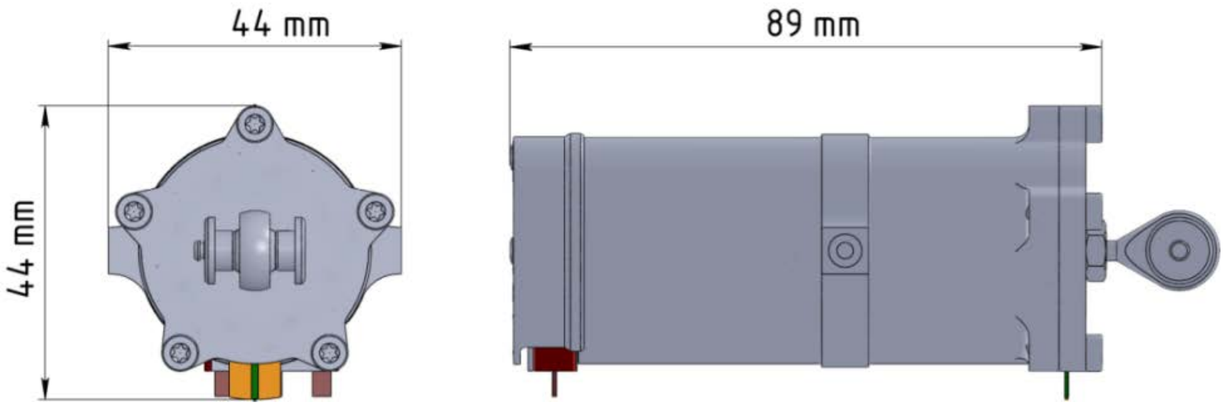

Figure 2. Overall dimensions of the Actuator

Main Requirements

Table 1 presents the main requirements that drove the design of the actuator.

Table 1. Main design requirements

Characteristic	Value
Mass :	< 200g
Overall max dimensions :	100 x 60 x 60 mm^3
Lifetime (with ECSS factors) :	≥1000 cycles
Power consumption (DC) :	<50 W (28V)
Output force:	165 N
Latching stroke:	< 1.7 mm
Total stroke	> 2.2 mm
Actuation time (slow actuation):	5s < t <60s
Max non-operating temperature (Qual):	-10°C / 120°C
Max operating temperature (Qual):	-5°C / 100°C
Launch vibration load :	28.3 g_{RMS}
Other feature	bi-stable (stable in both open and closed positions with no power supply)

Main Challenges

Nickel-Titanium (NiTi) alloys are the most commonly used materials for their shape memory effect. They are off-the-shelf products and relatively low cost due to their extensive use in the biomedical and general industrial fields. While their maximum transition temperatures (Ms, Mf, As and Af) are well adapted to these applications, they are all under 100°C, which limits considerably their use in space mechanisms design. In order to widen the application range of SMAs in space mechanisms, Almatech has initiated, in collaboration with the University of Applied Sciences of Sion, Switzerland, a new development based on another shape memory alloy, CuAlX. CuAl-based material can feature, with the adequate composition and treatments, transition temperatures higher than 120°C. In addition, shape-memory strains up to 8-10% can be observed with these SMA alloys representing a significant advantage over standard NiTi alloys limited to shape-memory strains up to 6-7%. On the other hand NiTi alloys are electrically resistive and can therefore be directly heated by Joule effect using through current as energizing source. Due to their high copper content, CuAl-based alloys have the main drawback of being electrically conductive such that CuAl-based actuators shall be equipped with a dedicated heating system that also needs to withstand deformations as large as 10% while keeping its full heating functionality. Higher transition temperatures and larger deformations make in general the CuAlX more suitable for space applications, however at the cost of a more complex SMA heating design.

Mechanically, the challenge was to establish a bi-stable design (no electrical current needed to maintain both end positions) that is highly reliable and able to sustain the launch loads without state change. Friction, wear, fretting and cold welding are issues that have been considered and worked around during the actuator development phase, but the true challenge turned out to be the mechanical stability of the bi-stable mechanism during launch, which required a particular effort.

SMA Wire Actuator Main Features

SMA wires work in traction in their straight configuration to provide their full capability while being accommodated in parallel in the actuator to allow redundancy.

The main challenge in the heating system design was to sustain the large actuation deformation (8-10%) produced by the CuAlXx alloy. Indeed to take full advantage of the capabilities of the selected SMA material, the wire was equipped with the following elements:

- Wire Ends, providing the mechanical interface
- An electrical crimp for electrical back loop through the SMA
- A heating system to provide the necessary thermal power to the SMA

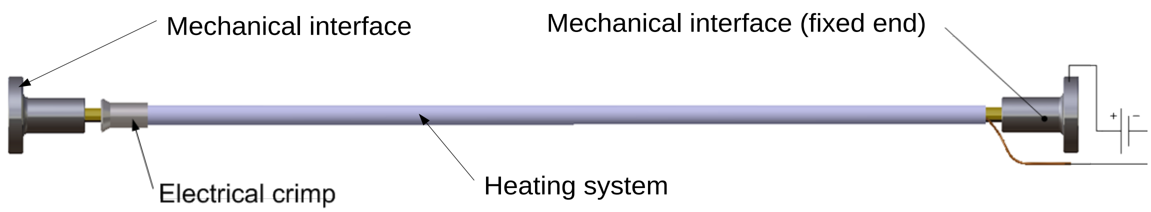

Figure 3. Equipped SMA Wire

A performance test highlighted the capacity of the naked wire (wire without heating system) to perform several thousands of cycles, making the required 1000 cycles life test easily achievable for the SMA itself.

The dimensional change leading to actuation is intrinsic to the microstructure of the material and therefore heavily dependent on the production processes. High reliability of the SMA wire can therefore be insured by a thorough control of the production processes and characterization of production batches. The heating system was identified as the main design challenge very early in the project and a particular effort was dedicated to improve its design and reliability. Therefore, each wire features a redundant heating system. In addition to this heating system redundancy, the device was designed to be fully operative and delivering the full nominal force with a single disabled SMA wire, providing a double redundancy in the system.

The SMA wire heating system is based on the use of a geometrically adaptive external heating element running along the full length of the actuating wires. The SMA wires being conductive, they are used as return lines to allow the electrical powering from a single side. This avoids the use of movable electrical connections following the extended and retracted states of the actuating wires on the opposite side.

On the moving end, an electrical crimp makes the electrical connection (see Figure 4) between the heating system lead and the SMA wire, while the opposite end (the fixed end) is directly connected to the electric power supply. The heating system lead located on the fixed end is connected to the other pole of the electrical supply.

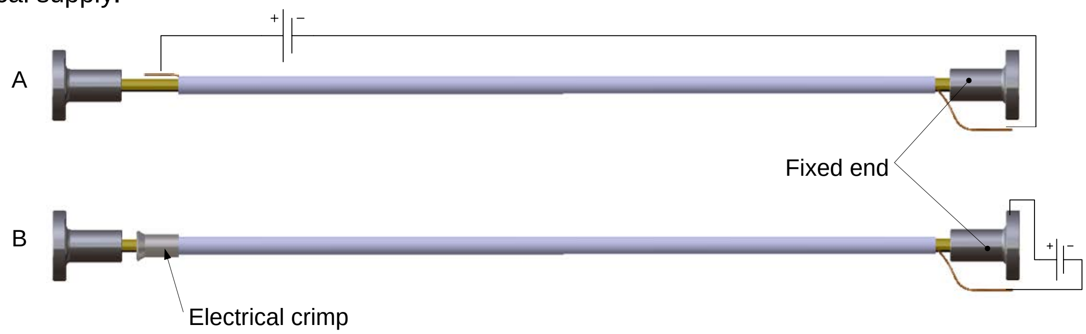

Figure 4. Electrical interface: (A) Flying leads after heating system installation (B) Connection from the fixed side

The thermal interfaces of the SMA wire system plays an important role in the performance of the full system. Although radiation is not negligible for space conditions, preliminary tests first focused on the conductive interface design. The initial SMA performance tests showed the strong impact of the conductive interfaces on the overall wire thermal behavior. It was observed that the conductive thermal flux significantly lowers the end of the wire temperature (see Figure 5). This gradient induced a significant loss of the net stroke of the sample by limiting the extent of the shape memory effect.

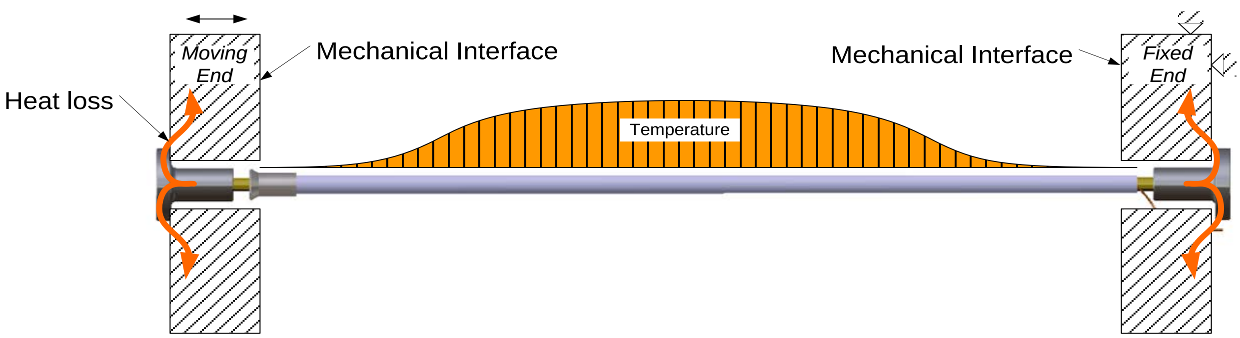

Figure 5. Temperature losses in the mechanical fixation

To enhance the thermal uniformity, the wire ends were thermally insulated from their supporting elements in a second setup. This led to the design shown in Figure 6 applied at each end of the SMA wire. While on one hand thermal insulation is desired to maximize the performance of the SMA wire by a uniform heating over its full length, heat rejection is required after SMA wire heating such that it can come back to its initial state and be actuated again with a new thermal cycle. Therefore, a compromise has to be found on the thermal insulation design that considers the trade-off between SMA wire heating efficiency and required actuation cycling times.

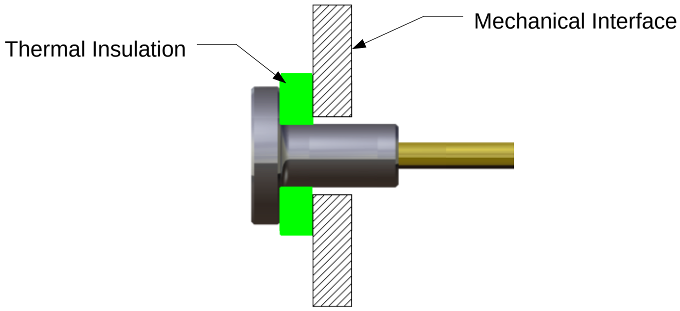

Figure 6. Thermal insulation at mechanical interface

Figure 7. Wire End crimped to the SMA wire sample

Stroke Control

The lifetime performance of a SMA being limited by its exposure to over stroke, overstress and overheating conditions, the powering of the SMA wires needed to be controlled to meet the required lifetime performance of 1000 cycles. In order to do so, an electrical switch has been integrated in the design to cut-off the powering of the SMA wires as soon as the system is latched and a mechanical end-stop has been integrated to guaranty a repeatable rest position after cooling down of all SMA wires.

The switch is integrated on the backside of the actuator. A switch lever is pushed down by a Spring Blade as illustrated in Figure 8. The switch is released once the Pusher rod is in latched position.

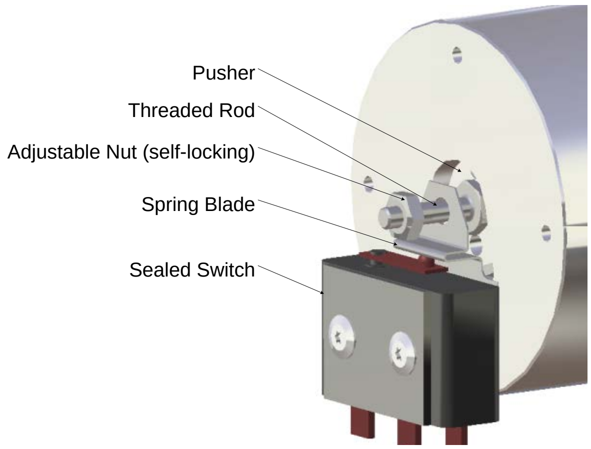

Figure 8. Switch actuating system

When the SMA Wires are activated, the Pusher rod travels forward. Once the adjustable nut supported by the threaded rod touches the Spring Blade, it shuts off the electrical supply and heating of the SMA wires.

Figure 9. Fully assembled SMA Actuator

SMA Actuator Test Sequence

The test campaign consisted of the following test sequence:

a. Cycling tests at SMA wire assembly level
b. Cycling tests at mechanism level
c. Mechanism vibration test

The first test aims to verify the correct actuation of a wire alone before integration into the actuator. It allows to ensure its capability to actuate under the required load and over the required number of cycles. Full performance test results of the developed Engineering Model were prioritized over the verification of its structural resistance to launch loads, such that these tests were performed at the end of the campaign and followed by final functional tests. The corresponding test results are presented hereafter.

SMA Wire Cycling Test Results

The goal of the life test was to demonstrate the maximum number of actuation cycles that can be performed by an equipped SMA wire. The pass/fail criteria considered was the successful achievement of more than 1000 actuation cycles with 2.7-mm stroke under 70-MPa load.

The schematic drawing of the test jig is shown in Figure 10. The equipped wire samples were mounted to the fixtures of the test jig and a weight was attached to the lower fixture. The test setup is such that the initial position of the weight can be either in contact with the platform (load relief) or hanging on the SMA wire (free load). The SMA wire is actuated using the developed heating system using a constant current. The wire shrinks when actuated and lifts the weight in a loaded configuration. The displacement is measured using an LVDT transducer. As soon as the required displacement is achieved, the current is switched off. The weight then gradually returns to its initial position as the wire cools down and a new cycle is initiated. The test finishes when the predefined number of cycles are performed. The SMA wire temperature is monitored continuously using a type K thermocouple.

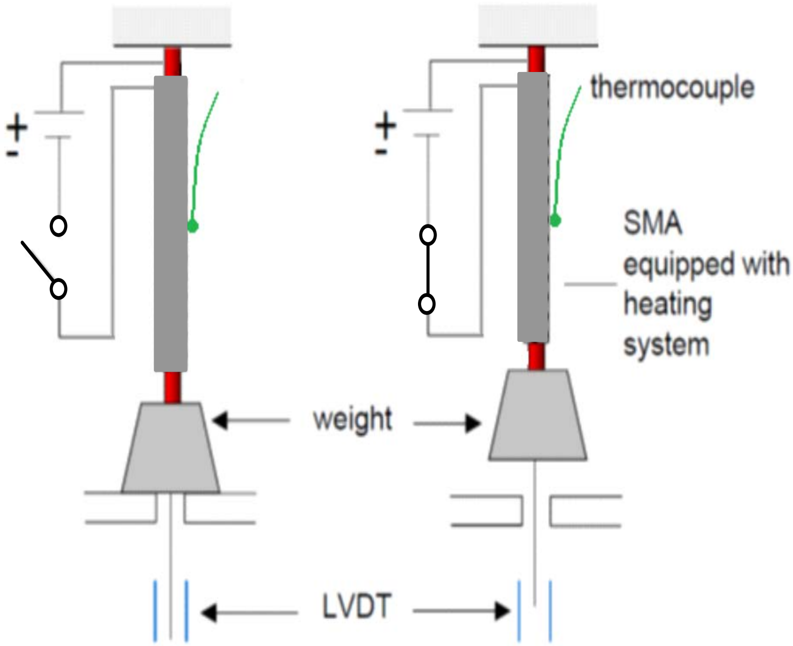

Figure 10. Schematic drawing of the equipped SMA wire test jig

The tests were performed starting from two initial positions: free load (weight hanging) and offloaded (weight in contact with the platform). The position of the upper fixture was adjusted using a micrometric screw.

Two tests were performed with the following load conditions:

- 40 MPa (30.62 N), to verify the ability of the SMA to reset (recover the original position)
- 70 MPa (51.12 N), the maximum determined stress for infinite cycling

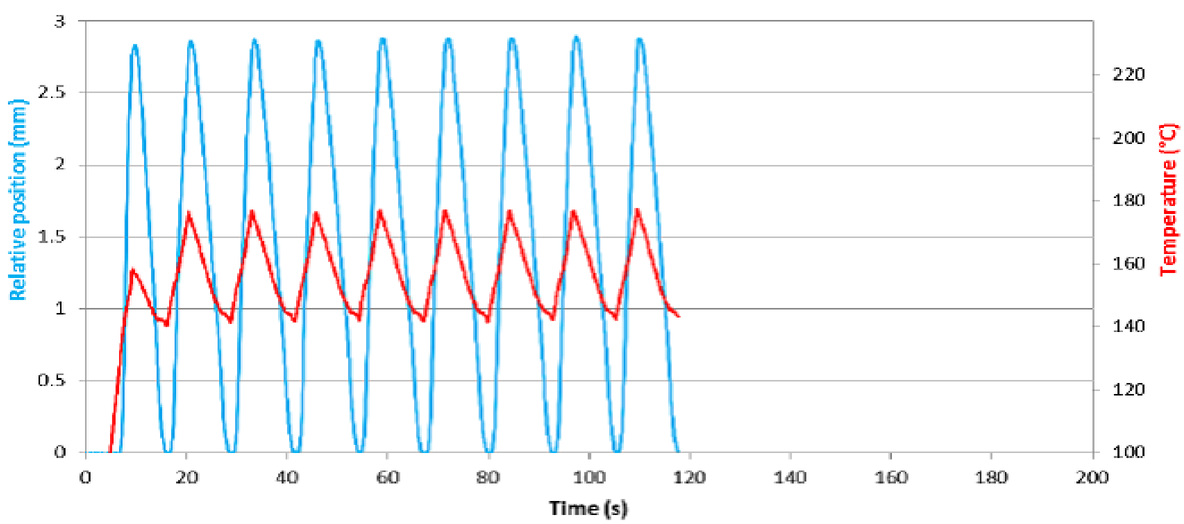

Figure 11. Cycling under the load of 70 MPa

Figure 11 shows a uniform cycling demonstrating the adequate behavior of the wire at 70 MPa. The same test was performed at 40 MPa demonstrating its ability to reset fully at this stress level.

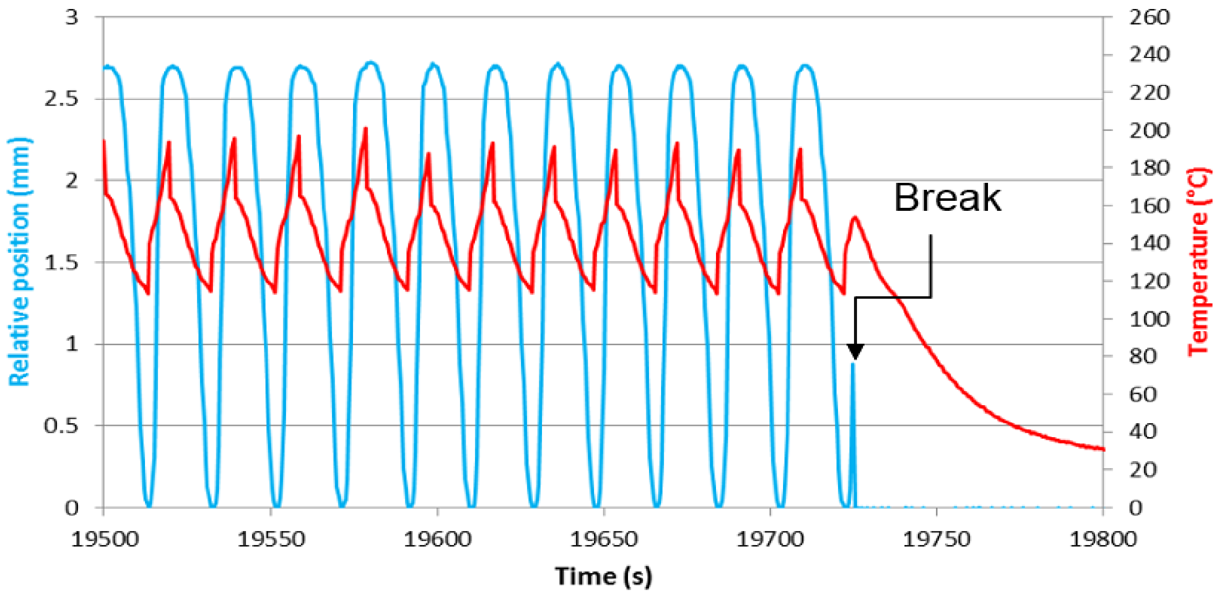

Figure 12. Cycles 7646-7657, load 70 MPa, stroke 2.7 mm, current 1.94 A

By the end of the test, 7657 cycles were successfully performed as illustrated Figure 12. During the cycle 7658, a fatigue failure occurred close to the middle of the wire as shown in Figure 13.

Figure 13. Equipped wire after wire failure

Actuator Cycling Test Results

In order to study the cycling and time-dependent properties of the actuator, the following test was performed:

- Loading force = 96 N (reduced from the theoretical 175 N to ensure SMA cycling survival and verify the heating system over the full lifetime requirement)
- Power supply : 1.79 A, 27.8 VDC, 49.8 watts
- Cooling time between cycles = 15 seconds (to ensure that the actuation time at the next cycle will not be affected by an incomplete cooling at the previous cycle)
- Heating time limit = 15 seconds (overheating risk)
- Standard ambient temperature and pressure conditions

The actuator survived the required 1000 cycles and switched its state (latched or released) automatically at each cycle. The cycling test of the actuator was fully successful as illustrated in Figures 14 and 15 showing the four initial cycles and the last four cycles.

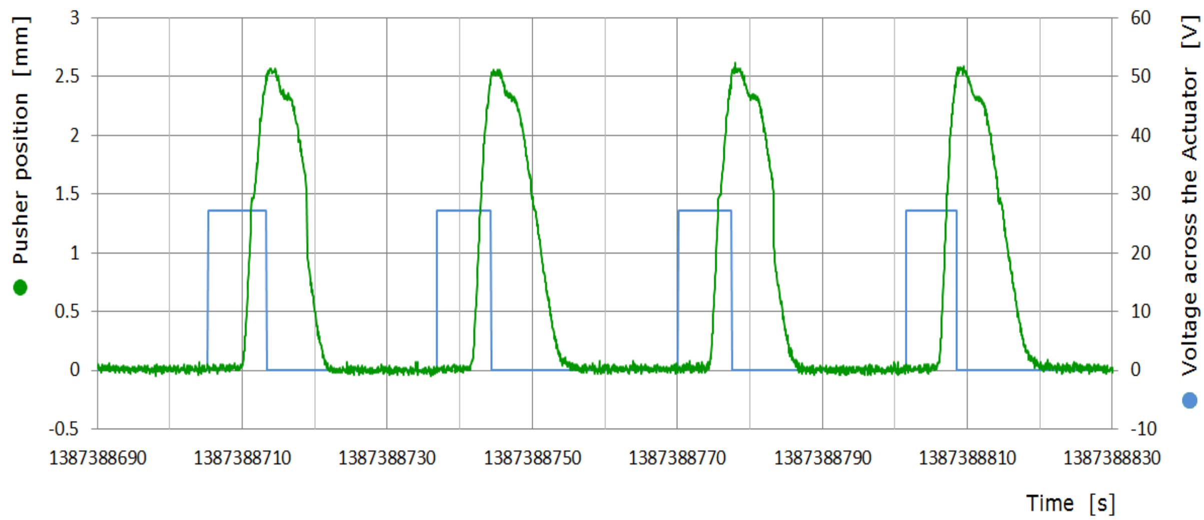

Figure 14. Cycles 1-4

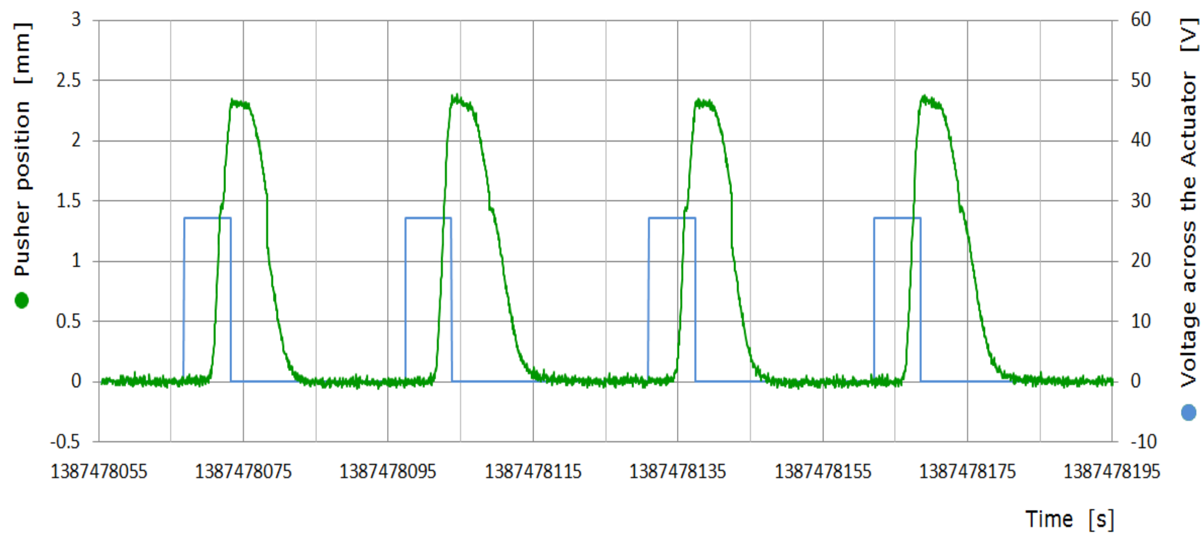

Figure 15. Cycles 1054-1057

Actuator Vibration Test Result

Resonance search and random vibration tests were performed in order to ensure adequacy of the actuator design to the required launch loads. The tests were performed in axial and radial directions.

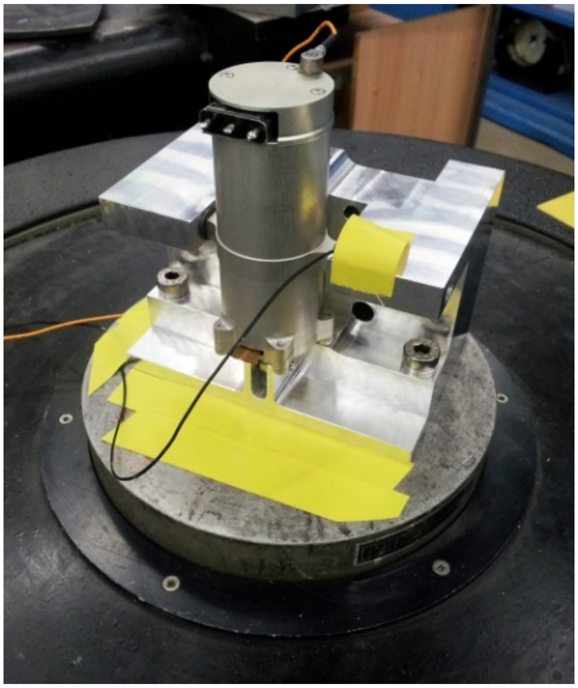

Figure 16. Axial vibration of the Actuator

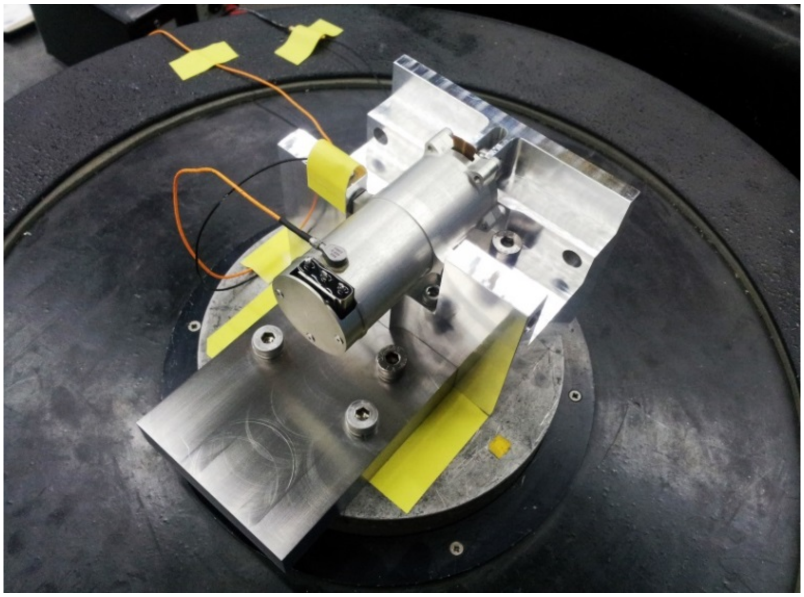

Figure 17. Transverse vibration of the Actuator

The overall acceleration of the applied random vibration profile was 28.3 g_{RMS} and the total test duration was 3 minutes. The vibration spectra acquired during the tests are shown in Figure 18 and Figure 19.

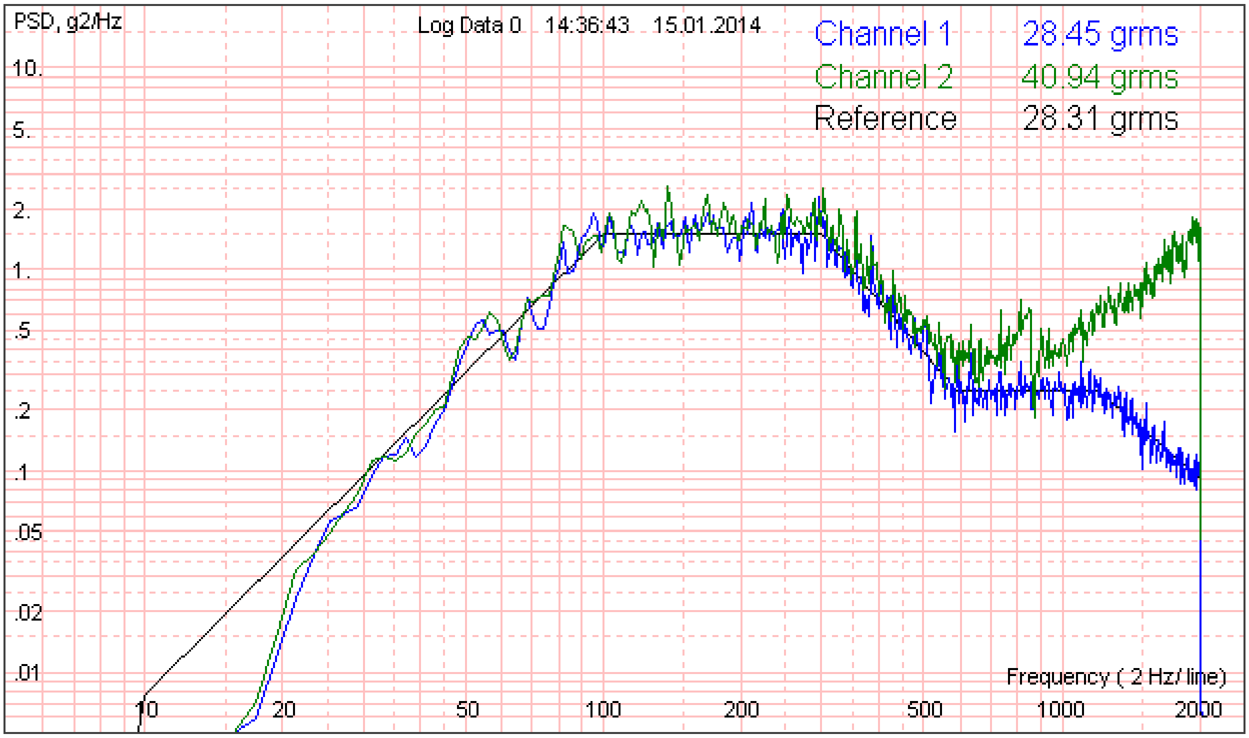

Figure 18. Random vibration spectrum in the axial direction

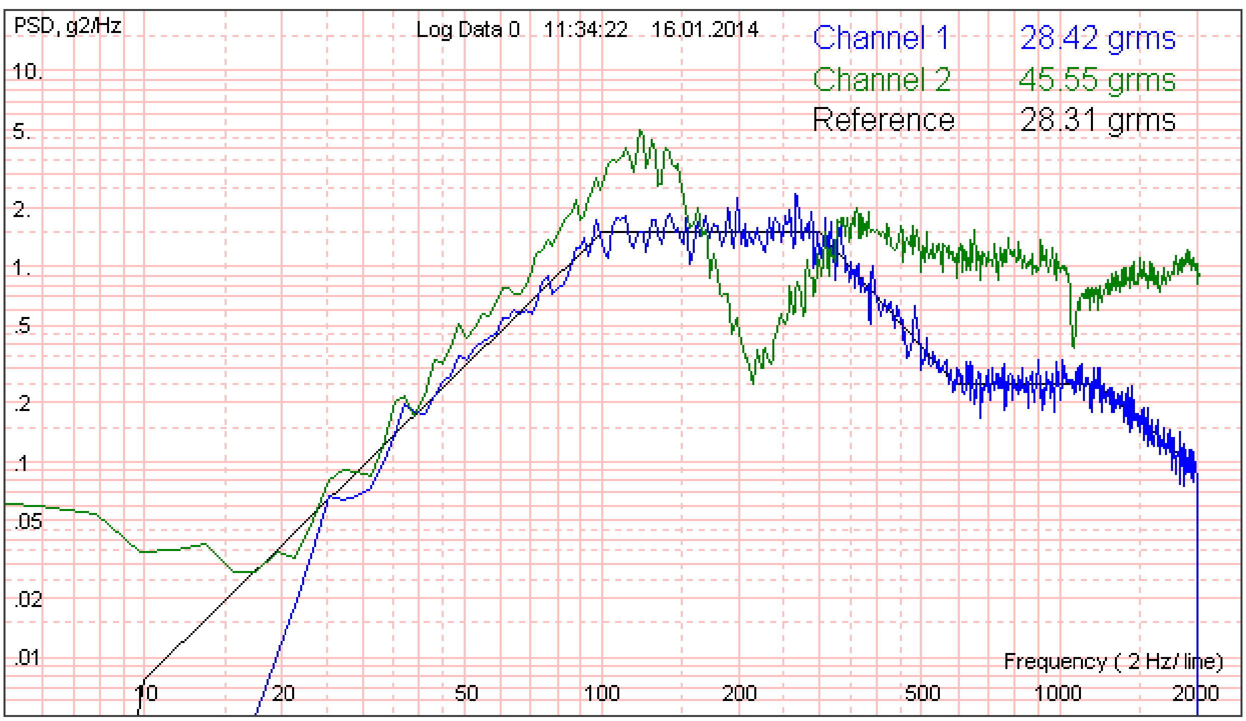

Figure 19. Random vibration spectrum in the radial direction

The SMA actuator successfully sustained both axial and transverse random vibrational loads with overall acceleration of 28.3 g RMS and duration of 3 minutes each. No changes in the resonance search results were observed before and after the random loads application showing that no structural failures have occurred. A post-test functional verification showed that the actuator remained fully operational after the test. It proves that the design is able to survive the required launch vibration loads.

Synthesis of Actuator Characteristics

Table 2. Actuator main characteristics

Characteristic	Value	Requirements
Mass :	118 g	< 200g
Overall dimensions :	89 x 44 x 44 mm3	100 x 60 x 60 mm^3
Lifetime:	1055 (stopped, no damage)	> 1000 cycles
SMA wire lifetime:	> 7657 cycles	--
	49.8 W (27.8V, 1.79A)	< 50W (28V)
Verified output force:	96N*	165N
Latching position:	1.5 mm	< 1.7mm
Maximal stroke:	2.5 mm	> 2.2mm
Push duration:	6.5± 0.4 s	5s < t < 60s
Pull duration:	11.9±5.4 s	5s < t < 60s
Max operating temperature:	120°C	> 70°C
Launch vibration load:	verified	28.3 g_{RMS}

**The quality of the produced CuAlX monocrystalline wire samples was not sufficient to reach the cycling stability under the required force. It was therefore decided to reduce the test load at 96 N (from 165 N) for the test campaign. Recently, industrial quality level CuAlX wires are commercially available and should meet the design load of 175 N.*

Conclusion

A bi-stable actuator based on a high transition temperatures Shape Memory Alloy has been successfully designed, manufactured and tested. This mechanism, able to provide slow-acting pushing and pulling forces, showed great repeatability over a high number of actuating cycles demonstrating high overall reliability of the selected design.

One major challenge was to design a SMA heating system compatible with the use of high transition temperature SMAs that are highly conductive and have shape-memory strains up to 10%. A novel heating system has been developed and successfully tested on single wire setups as well as on a fully integrated mechanism.

Through this project, the technology based on high transition temperatures SMA reached the readiness level TRL-4. Further material characterization tests on industrial quality CuAlX wire as well as additional environmental tests are to be performed to reach TRL-5.