Shape memory alloy (SMA)-based launch lock

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ABSTRACT

Most NASA missions require the use of a launch lock for securing moving components during the launch or securing the payload before release. A launch lock is a device used to prevent unwanted motion and secure the controlled components. The current launch locks are based on pyrotechnic, electro mechanically or NiTi driven pin pullers and they are mostly one time use mechanisms that are usually bulky and involve a relatively high mass. Generally, the use of piezoelectric actuation provides high precession nanometer accuracy but it relies on friction to generate displacement. During launch, the generated vibrations can release the normal force between the actuator components allowing shaft's free motion which could result in damage to the actuated structures or instruments. This problem is common to other linear actuators that consist of a ball screw mechanism. The authors are exploring the development of a novel launch lock mechanism that is activated by a shape memory alloy (SMA) material ring, a rigid element and an SMA ring holding flexure. The proposed design and analytical model will be described and discussed in this paper.

Keywords: launch lock, shape memory alloy, flexure

INTRODUCTION

Satellites and spacecraft are launched in the orbit or outer space using powerful rockets that induce strong vibrations which add loads on the structural components or can cause mechanisms to move. Launch lock are necessary for securing moving components during the launch or securing the payload before deployment. The current launch locks are based on pyrotechnic, electro mechanically or NiTi driven pin pullers and they are mostly one time use mechanisms that are usually bulky and involve a relatively high mass. A special type of actuation, the piezoelectric actuation, is beneficial to NASA missions as it provides high precession nanometer accuracy. A drawback of this actuation in that it relies on friction to generate displacement. During launch, the generated vibrations can release the normal force between the actuator components allowing shaft's free motion which could result in damage to the actuated structures or instruments. This problem is also common to other linear actuators that include a ball screw mechanism.

We conceived a novel launch lock mechanism that locks an actuator to prevent movement of the mechanism during launch and releases the lock for mechanism deployment when receiving an activation signal. The objective of developing the reported mechanism is to simplify the current launch lock mechanisms using a configuration that has low mass and requires low power. The proposed concept takes advantage of the negative coefficient of thermal expansion of NiTi shape memory alloys and a combination of elements with different radial and axial stiffness. The developed mechanism would be made reusable for multiple activations and would not introduce additional shocks or vibrations when activated. The proposed design and analytical model will be described and discussed in this paper.

DESIGN CONFIGURATION

In the first iteration we designed a simplified model of the launch lock mechanism that includes a lock, an SMA ring, and a ring flexure. Figure 1 shows an isometric view of the design and a cross section. The SMA ring can be heated by an external source causing the ring to shrink. The ring is retained and located axially by a ring flexure. The ring flexure has a low stiffness in the radial direction and a high stiffness in the axial direction. The lock was designed as a tubular component with high radial and axial stiffness. Figure 2 shows a working sequence of the launch lock. In the locked configuration the SMA ring is not heated (the device is not powered) and the ring outer diameter is located in a groove on the inside of the lock. This way, the lock is constrained to move axially with respect to the SMA ring and flexure. In the next step, the SMA ring is heated and its outer diameter shrinks below the inner diameter of the lock freeing the lock to move axially. Once the two components are separated enough axially, the power to the SMA ring is shut off, the SMA ring cools and regains its original configuration. The lock and the ring flexure remain free to move axially relative to each other. This design iteration was tailored to fit available off the shelf SMA rings. SMA rings with 40.6mm (1.6") OD, 25.4 mm (1") ID, 7.62 mm (0.3") thick were purchased to be later used in the breadboard (Figure 3).

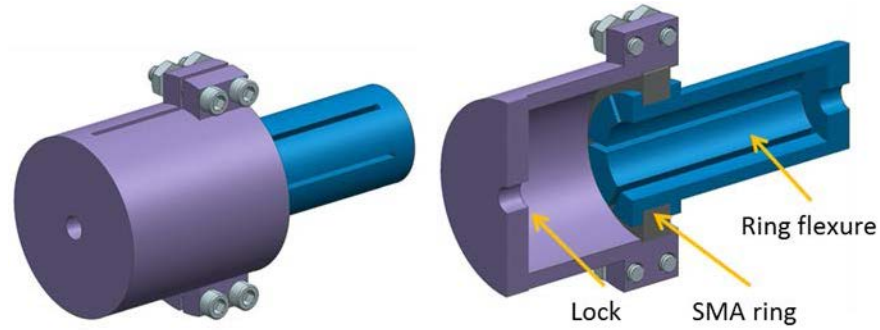

Figure 1: Isometric view (left) and cross section (right) of the first design iteration.

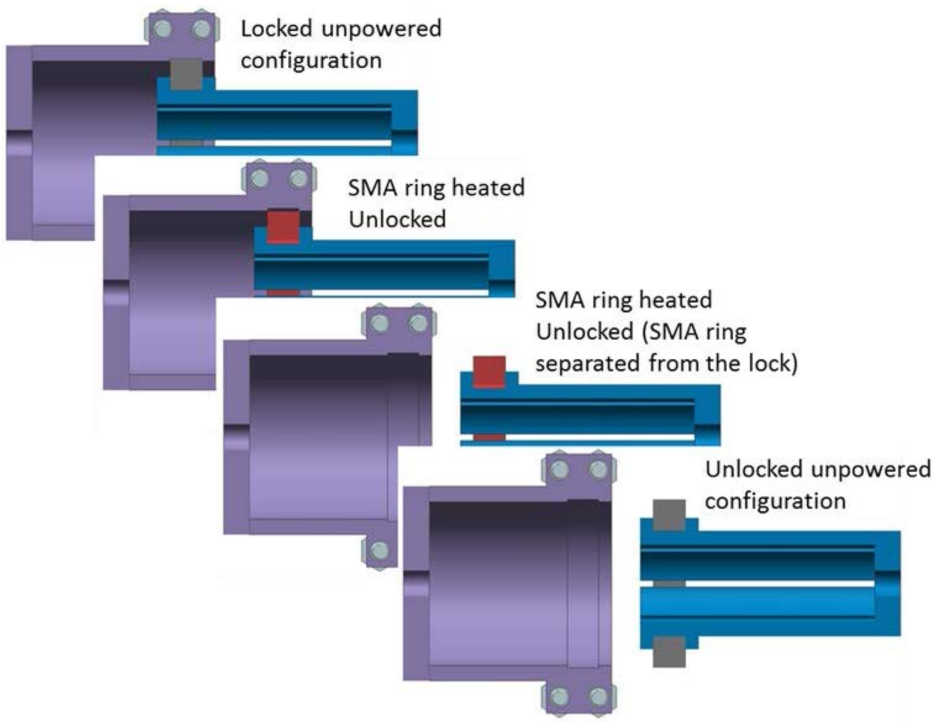

Figure 2: Launch lock working sequence – top left to bottom right

Figure 3: SMA rings (40.6 mm (1.6”) OD, 25.4 mm (1”) ID, 7.62 mm (0.3”) thick)

DESIGN FINITE ELEMENT ANALYSIS

The finite element (FE) analysis was performed in two steps: (a) Deriving the SMA ring material properties and (b) Analyzing the change in the SMA ring dimensions under different scenarios.

a. Deriving the SMA ring material properties for the FE analysis

Since the modeling properties of Nitinol type H (from Inctrinsic Device Inc.) were not available, the material property model was constructed based on the strain-stress curves of a low phase transition temperature Nitinol from the vendor's web site [http://www.nitinol.com/media/reference-library/013.pdf] (Figure 4). The phase transition temperatures from martensite to austenite were set as 65°C (As) and 72°C (Af). Using the constructed material model we obtained the strain-stress curves are similar to the reference curves except the temperature. Figures 5-7 show the stress – strain curves for various temperatures. At room temperature stress loading is necessary for the strain to decrease to initial state whereas heating above 72ºC allows full release of the stress (Figure 5).

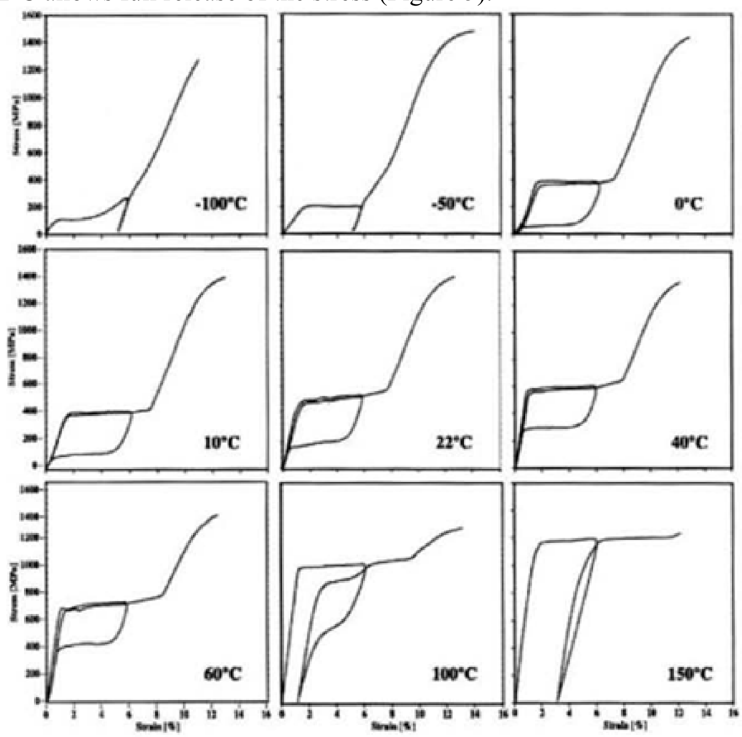

Figure 4: Tensile curves of a superelastic alloy at various temperatures

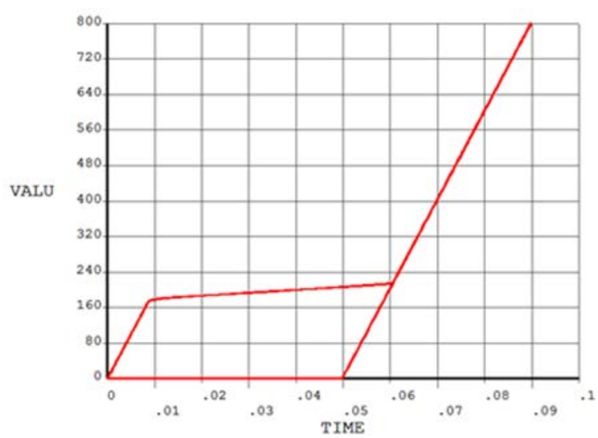

Figure 5: At 23ºC or below, applying 800MPa tensile stress, releasing the stress and rising temperature to above 72ºC.

b. SMA ring performance analysis

Two possible design configurations were investigated. In a first configuration the lock incudes an inner groove where the outer diameter of the SMA ring is located in the closed position. We simulated the SMA pre-deformation process by applying pressure (195 MPa) on the inner surface of the ring followed by pressure release to obtain a ring with expanded diameter (room temperature 23ºC, or below) with the dimensions as provided by the vendo4r. The dimensions of original ring were adjusted to obtain a pre-deformed ring that matches the specs of AHE1010-0303-0303. In this process, the outer radius increases 0.487 mm and the inner radius increases 0.689 mm. The recovery capability was verified by setting temperature above Af. By heating above the Af, the outer diameter shrank 0.974 mm. This displacement is large enough to allow using clamping with grove in the launch lock design. Figure 8 shows the FE model (left) and deformation (right).

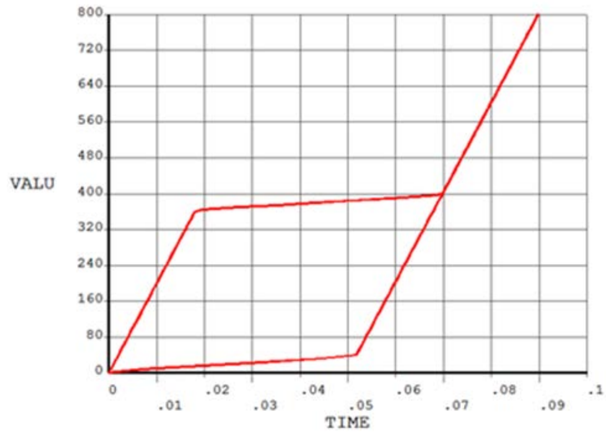

Figure 6: At 72ºC applying 800MPa tensile stress and releasing the stress

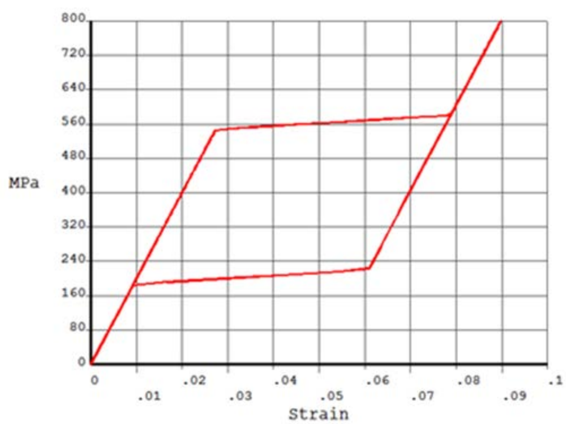

Figure 7: At 122ºC applying 800MPa tensile stress and releasing the stress

In a second design configuration the lock has a smooth inner surface and the SMA ring is held in place in the closed configuration by friction. In the friction based configuration the ring is clamped at the outer diameter by the lock. The SMA ring is predeformed as specified above and then loaded with pressure on the outer diameter. The analysis results of this behavior are shown in Figure 9. A sharp drop in the outer radius happens at the pressure ~80 MPa. In designing such a launch lock we should avoid applying a large clamping pressure close to that value. In fact, for these ring dimensions such a large pressure is not necessary for a large friction force. The axial friction force as function of clamping pressure on the outer diameter of the ring is listed in Table 1. The friction coefficient of 0.2 is assumed in the calculation. When a metal surface is perfectly clean in a vacuum, the friction is much higher than the normal accepted value. For examples, coefficients of 0.74 – 0.78 for static steel-steel friction and 0.36 for titanium- titanium (alloy Ti-6Al-4V) were reported [http://www.roymech.co.uk/Useful_Tables/Tribology/co_of_frict.htm]. In addition, an increase of the roughness of the surfaces should help to obtain large friction coefficient. From the table one could see that an axial friction holding force greater than 1000 lbs could be achieved by applying 25 MPa clamping pressure.

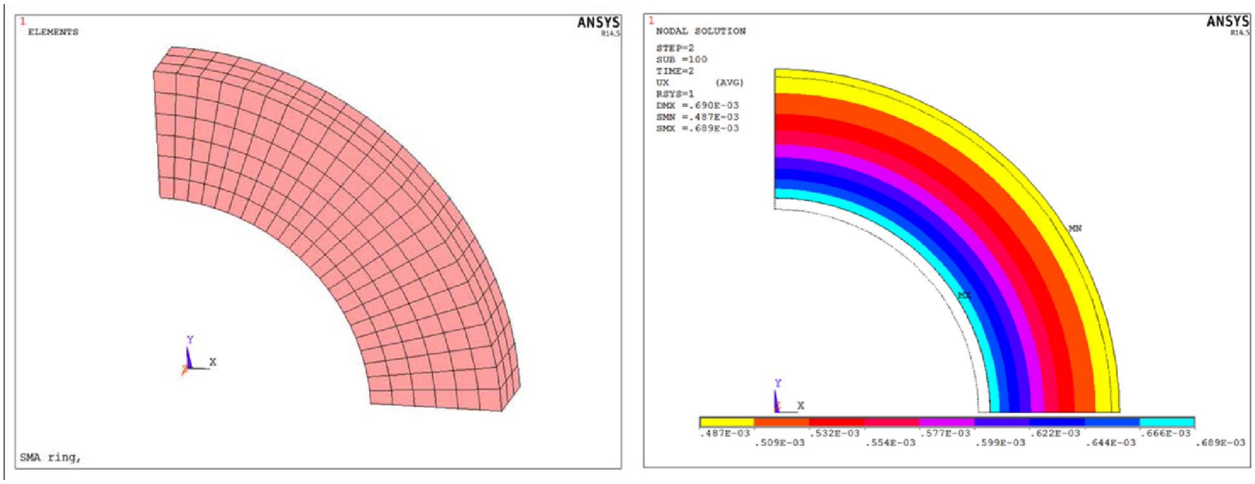

Figure 8: FE model (left) and deformation (right)

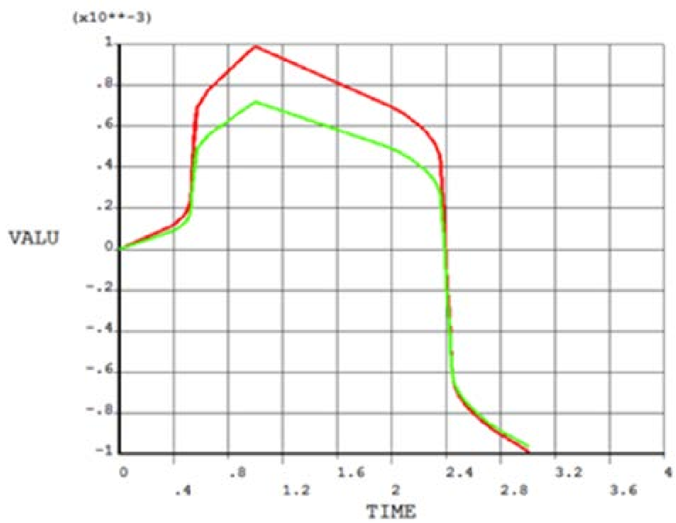

Figure 9: The changes of inner radius and outer radius under pressure. The unit of vertical axis is in meter. The pre-deformed ring is formed at time equals 2. A pressure applied at outer diameter increases linearly from 0 to 195 MPa. A sharp drop of inner radius and outer radius happen at the pressure ~80 MPa.

Table 1 Friction forces for a friction coefficient of 0.2, the SMA ring size described above and various pressure values

Pressure (Mpa)	10	20	30	40	50	60	70	80
Force (N)	2025	4049	6074	8099	10123	12148	14173	16197
Force (lb)	455	910	1365	1820	2275	2730	3185	3640

Another design configuration can be obtained by applying preload on the ring inner surface by the mounting structure. This configuration can help the ring sustain a large clamping force on the outer surface. The Figure 10 shows the changes of inner and out radius when applying pressure equally on both inner and outer surfaces. The pressure is up to 195 MPa linearly increasing in time from the moment time equals 2 to the moment time equals 3. At a pressure of 100 MPa the outer radius is still more than 0.4 mm greater than the initial value.

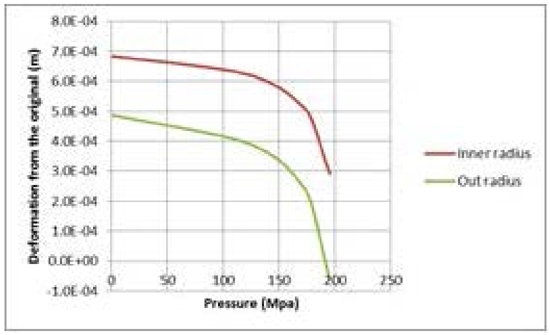

Figure 10: Radius deformation with applying pressure equally on both inner and out surfaces

The results shown in Figure 11 are for the case holding (locking) the ring by applying 78 MPa on both the inner and outer surfaces of the ring (time equals 3 on the horizontal scale), which provides more than 3000 lbs axial frictional locking force according to the previous estimation. The outer diameter of the ring is 0.87 mm (2x0.435 mm) greater than the original size. During time period form time equals 3 to time equals 4, the temperature is gradually increasing by 130ºC from 23ºC and the pressure on the outer surface is reduced to zero. The big diameter reduction in value corresponds to the SMA phase change that occurs at 90.6ºC. Against the 78 MPA on the inner surface the outer diameter of the ring is able to shrink to 0.182 mm more than the original. The temperature induced outer diameter deformation is 0.698 mm in this case.

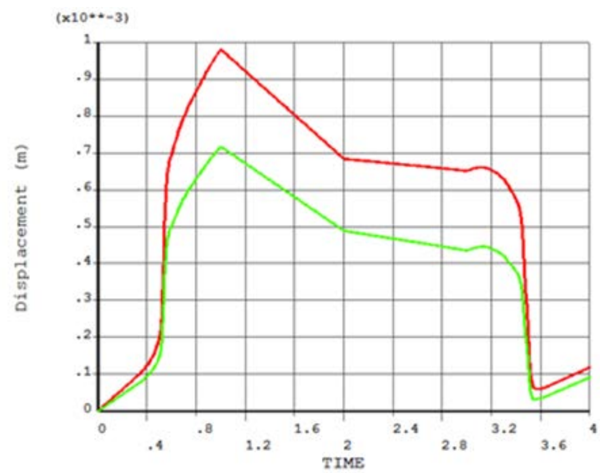

Figure 11: Inner and outer radii deformations. From time equals 2 to time equals 3 up to 78 MPa are applied on both inner and out surfaces of the ring. From time equals 3 to time equals 4 the outer surface pressure is released and the temperature is increased by 130ºC. Both changes are linear.

CONCLUSIONS AND FUTURE WORK

A launch lock mechanism based on an SMA ring was proposed and analyzed. The results of the reported analysis show that a launch lock can be designed in two possible configurations:

- A groove based configuration where the outer diameter of the SMA ring is located in a groove less than 0.4mm deep on the inner face of the lock. Upon heating the SMA ring shrinks more than the groove depth allowing the ring to be moved away from the proximity of the lock.
- A friction based configuration where the SMA ring is preloaded against the inner surface of the lock with a stress large enough to create the desired axial friction force. Upon heating the SMA ring the pressure is released and SMA ring is free to be moved away from the lock.

Pending experimental demonstration of the analysis results, this device can be used as a low mass high force alternative to the existing launch locks.

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