SHAPE MEMORY ALLOY : REVERSIBLE HINGE FOR DEPLOYMENT APPLICATIONS.

Ph MOIGNIER – Matra Marconi Space-France

31 Avenue des Cosmonautes - 31402 Toulouse Cedex 4 – France

Tel : 33 (0)5 62 19 76 31 Fax : 33 (0)5 62 19 50 40

e-mail : philippe.moignier≅tls.mms.fr

ABSTRACT

In 1995 MMS initiated a R&D program to validate the design of a SMA (Shape Memory Alloy) torsion bar with 'one way' memory effect. The system delivers the actuation torque necessary for the deployment of space structures such as deployable radiators, reflectors, boom, shutters, covers, mast, solar array, etc.

The association of high torque with low-speed rotation achieves reliable and well-controlled in-orbit operations. Such characteristics are particularly suitable for one-shot deployment applications with stringent low shock requirements. The SMA motor cell can be rearmed and is able to work again for several one shot deployments.

In the meantime, emerging applications required more than the '*one shot*' deployment, such as : deployable radiator, protective cap for Space Instruments, etc. Self-restowage capability became necessary. In that respect, the existing one way SMA motor is adapted by adding a counter spring, providing self-rearming capability.

Nevertheless such motor shall demonstrate its ability to actuate an appendages not only during heating phase but still during the cooling phase despite external torque exhibited during each operation :

- during heating, the SMA acts on against the external resistive torque and the counter spring
- during cooling, the Counter spring works against the external torque and provides the minimum torque necessary for the SMA rearming.

Both behaviour shall consider space mechanism margin philosophy on different resistive torques and motorization.

1 - ONE-WAY SMA MOTOR CELL DESIGN.

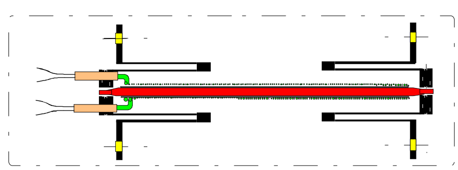
SMA structures have two stable solid phases : the 'cold' one and the 'hot' one. Transformation between the two solid phases can occur, exhibiting several thermo-mechanical properties under thermal or mechanical specific conditions. Among various SMA properties, the 'one way' memory effect associates two different shapes, one per solid phase ; this effect requires an initial education phase. When heated, the SMA provides a mechanical work - torque and rotation in our application - to evolve from the 'cold' to the 'hot' shape.

Since 1995 MMS has developed, patented and pre-qualified a motor cell design composed of the following three parts :

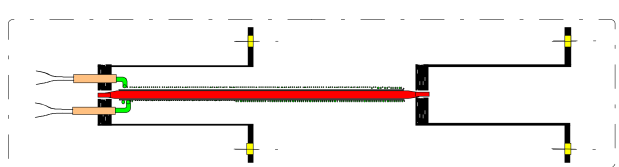
- SMA torsion bar for the motorization
- Heating and temperature sensing. The SMA bar is surrounded by a nominal/redundant heater used both for heating and for temperature control. The average SMA temperature feedback is given by the ohmic variation of such specific heater.
- Thermo-mechanical interface. The SMA extremities are fixed to two titanium thermo-mechanical interfaces. The single-piece thermo-mechanical interface is composed of one or several superposed Titanium thin cylinder . One end is connected to the SMA and the other end to the external structure.

Titanium was selected for the thin cylinder material, providing :

- thermal insulation (low section, low conductivity material) which limits the necessary heating power to a few Watt and guaranties a SMA homogeneous heating
- proper mechanical interfaces
  . loads withstanding in the thin cylinder wall : Titanium features efficient mechanical properties.
  . adjustable interface : angular adjustment by 4 screws in semi circular slots and length adjustment by shimming.



Nominal design



Alternative Design

Depending on the SMA bar length required (angular range) and the interface constraints, either the 'nominal' or the 'alternative' design is preferred and selected.

Functional description.

The SMA bar is heated up to 140°C. During the heating phase, the alloy transformation starts progressively at 60°C (depending of the resistive torque applied) and the bar provides a smooth and slow angular motion against the external resistive torque. During this deployment, the temperature can be monitored by checking the heater impedance (U/I). When the ohmic value corresponding to 140°C is reached, the heating power is switched-off.

Basic performances and adaptability.

This concept can be easily adapted to a wide range of appendage motorization requirements.

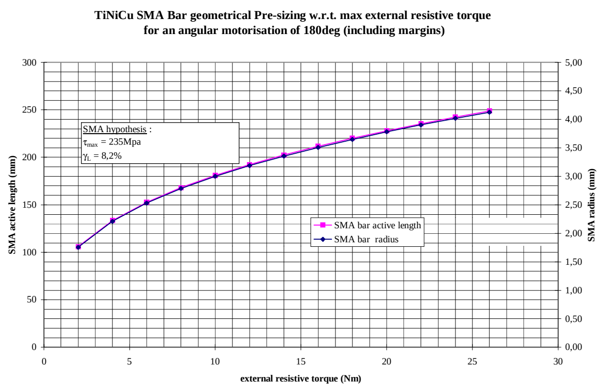


Figure 1 : SMA actuator design template.

The deployment angular range and the maximum torque can be reached by tuning the SMA diameter and length as shown on the figure 1. Computer-aided tools are available to translate the application requirements into the SMA torsion bar geometrical parameters.

The cell reference design has been extensively tested at ambient and under vacuum and has been vibrated.

The reference cell design has been validated with a 3.5 mm diameter shaft and 105 mm active length.

The figure 2 illustrates the measured performances versus the requirements.

Main interest of the reference design.

* Slow motion inducing no shock at deployment end.

* Self-adjustment to external resistive torque variations.

* Simple electrical redunded command : heater type.

* Temperature control through heater : no additional wire.

* High mechanical and electrical reliability.

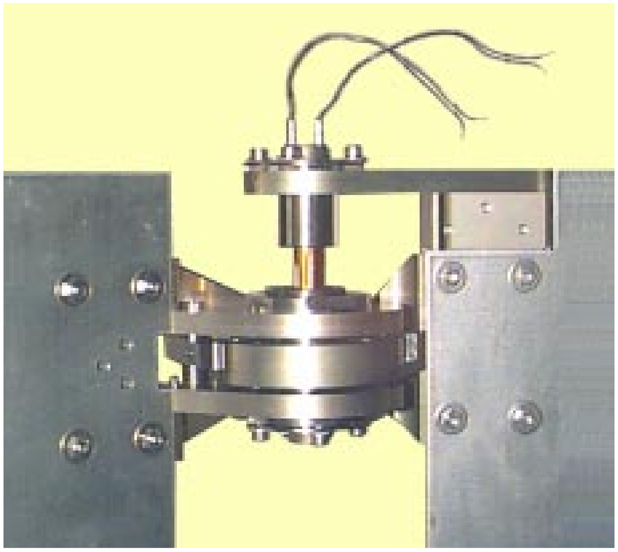
* High torque to mass efficiency

* Easy accommodation

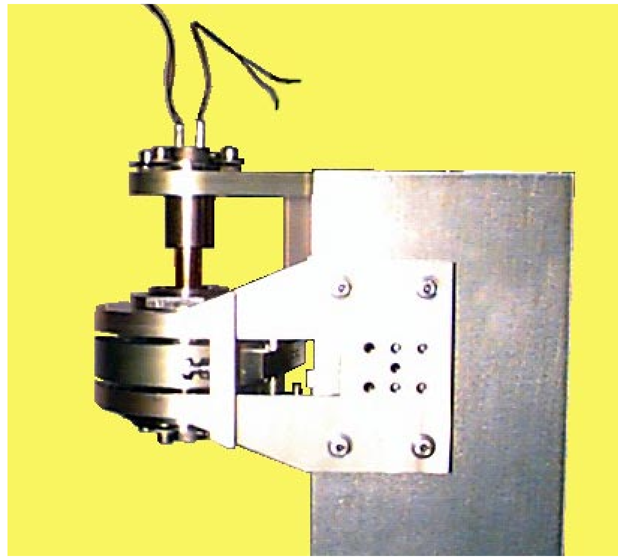
* Simple adjustable interface adaptable to existing hinge.

Characteristics.	Requirement	Performance
Deployment angle	180 deg	Larger than 185 deg : . 295 deg under 0 Nm constant resistive torque . 254 deg under 2Nm constant resistive torque . 195 deg under worst case resistive torque profile (start at 0 Nm - end at 2 Nm).
Motor torque	2 Nm	. 5.5 Nm available at the beginning of the deployment. . 2 Nm available at the end of the deployment
Heating power [end of deployment under vacuum with 25°C environment]	< 10W	Power between 2 and 10 W. The deployment duration can be adapted with the heating power profile. Starting from 20°C : 4W under vacuum gives a deployment duration of 4 minutes
Redundancy	Redundant Heating and redundant temperature measurement	Two independent heating elements which allow to heat & control the SMA temperature with the same device (using temperature/ohmic relation)
Deployment start :	> 60°C	> 60°C for TiNiCu Alloy (> 100°C for Cu Al Ni Alloy)
Number of cycle [motorization + rearming]	> 50	> 200
Motor cell mass (including thermal and mechanical IF)	< 300g	120g (including 7g for the SMA bar)

Figure 2 – tested SMA actuator : characteristics versus requirements.



Open



Stowed

2. REVERSIBLE SMA MOTOR CELL CHARACTERISATION.

In order to evaluate the ability of a one-shot SMA motor cell to be used in a reversible space application with enough margins, it has been first necessary to measure its reversible performances and to define a general formulation of such performances.

Two sets of test have been performed.

The first set aimed at characterising the SMA motor performances with different rearming torques applied during the cooling.

The second set aimed at assessing the impact of consecutive cycling without dismounting the SMA Cell.

Test and modelling refinement.

The objective of the first campaign is to identify the SMA cell angular range with respect to the rearming torque applied during 'cooling'. A 2 Nm constant resistive torque is applied during the deployment.

Five rearming torques have been investigated :

2 Nm, 1 Nm, 0.5 Nm, 0.2 Nm and 0.04 Nm.

Reproducibility is checked by performing at least 2 cycles for each rearming torque selected.

Each cycle is composed of a 'motor' phase (heating up to 140°C under 2 Nm) and a 'rearming' phase (cooling down to 24°C) under the rearming torque considered.

The test results show that the relationship between the angle and the torque can be accurately approximated by a logarithmic law.

Among the different parameters, the maximum SMA motor strain under a null resistive stress is named the 'recovery strain limit'. This parameter reflects the motorization capability of the SMA for a dedicated rearming process.

The 'recovery strain limit' (γ_L) versus the 'rearming stress' (τ_{rear}) is illustrated in figure 3.

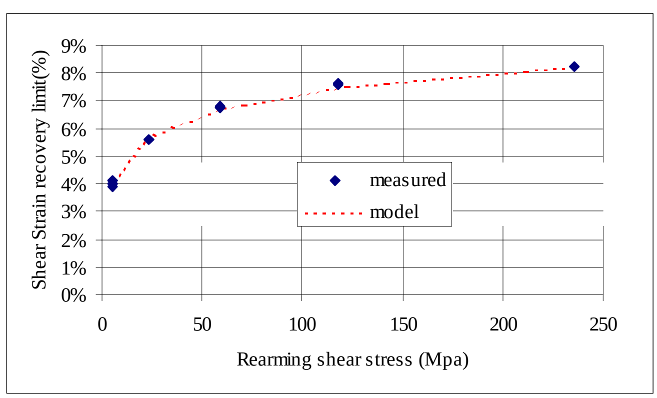


Figure 3 : experimental results and mathematical model matching the experiment data.

The associated mathematical model is built considering the following test conditions :

- during the 'motor' phase, the SMA is heated from 24°C to 140°C
- during the 'rearming' phase, the SMA is cooled down from 140°C to 24°C.

The following notation is used : let assume an initial rearming from 140°C to 24°C under a stress τ_r . The strain $\gamma_{(\tau_r, T, \tau_m)}$ is the SMA motor strain measured during the motor phase at a considered temperature T under the resistive stress τ_m,

The 'recovery strain limit' $\gamma_{L\ (\tau rear)}$ is computed using the following definition :

$$\gamma_{L\ (\tau rear)} = [\ \gamma_{(\tau rear,\ 140°C\ ,\ 0)} - \gamma_{(\tau rear\ ,\ 24°C,\ 0)}\ ]$$

The curve figure 3 fits accurately with the following formulation : $\gamma_{L\ (\tau rear)}$ =

$$[\ \gamma_{(\tau high\ ,\ 140°C\ ,\ 0)} - \gamma_{(\tau high\ ,\ 24°C,\ 0)}\ ] + u_\gamma * \mathrm{Ln}\ (\tau rear/\tau high)$$

with :

- $u_\gamma = 0.01163$
- $\tau rear$ = maximum stress in the SMA bar during rearming phase (induce by the rearming torque).
- $\tau high$ = maximum stress considered for the SMA bar design in the motor phase (induced by resistive external torques)

The parameters measured are :

u_γ $\gamma_{(\tau high\ ,\ 140°C\ ,\ 0)}$ and $\gamma_{(\tau high,\ 24°C,\ 0)}$

This allows computing the motor strain capability γ_{mot}, at first cycle, under maximum resistive stress τ_{high} (during motor phase) and rearming stress τ_{rear} (during the rearming phase). The actuator strain capability is defined by : $\gamma_{mot(\tau rear,\ cycle\ 1)}$ =

$$\gamma_{L\ (\tau rear)}\ (1-k*\tau_{high}) - (\tau_{high} - \tau_{rear})*G_{140°C}$$

with :

- $G_{140°C}$ = SMA Shear modulus at 140°C of the TiNiCu alloy = 16.74 GPa
- k = corrective ratio to take into account non transformed martensite due to final resistive shear stress at 140°C.
- k # 460 ppm / MPa at 140°C

G and k are deduced from a full rearming/motorised cycle under τ_{high} with local loading/unloading measurements at 140°C and at 24°C.

The first campaign allowed to derive a mathematical model representative of a single deployment/rearming cycle with unloading phase at 24°C and at 140°C for rearming.

But successive cycling without unloading nor dismounting shows relative degradation of such capabilities. These aspects need to be considered in the model of a reversible hinge as the reversible characteristics will be function of the number of cycles.

In that purpose, a second test campaign was completed to evaluate and quantify the motorization evolution during n cycles with rearming under τ_{rear} and motorization under τ_{high}.

A set of 21 cycles has been performed with :

$$\tau_{rear} = 35\ \text{MPa} \quad \text{and} \quad \tau_{high} = 235\ \text{MPa}$$

Then 3 cycles have been completed with :

$$\tau_{rear} = 59\ \text{MPa and} \quad \tau_{high} = 235\ \text{MPa}$$

to verify the robustness of mathematical model.

Each cycle is composed of a 'motor' phase (heating up to 140°C under 2 Nm) and a 'rearming' phase (cooling down to 24°C) under rearming torque considered.

As previously, the results from this campaign show that the data can be accurately approximated by a logarithmic model.

This campaign shows a fatigue phenomena due to cycling, which has to be considered in the sizing of a reversible application. This fatigue is reflected by two main angular evolutions, as illustrated figure 4.

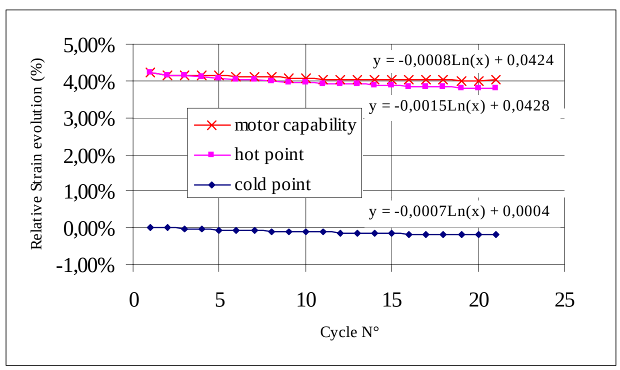


Figure 4 : Strain evolution w.r.t. cycling.

a) the first is a slow decrease of the angular range
b) the second is a shift of the initial angle at ambient temperature.

Both phenomena are linked to normal SMA fatigue mainly linked to martensite stabilisation. In hot condition the SMA is not unloaded so the martensitique transformation is not complete.

Angular range decrease.

The motor strain decreases after n cycles as illustrated figure 4. It can be approximated by the log curve :

$$\gamma_{mot(\tau rear,\ cycle\ n)} = \gamma_{mot(\tau rear,\ cycle\ 1)} - u_{cycle} * Ln(n)$$

$$\text{with } u_{cycle} = 0.0008$$

The strain shift γ_{shft}

In a one-shot deployment, this shift is not a problem. It can be compensated after each rearming through the mechanical interface adjustment capability implemented in the one-shot reference design.

In a reversible use, the motor cell is not dismounted after each cycle. As the final angle of deployment is fixed, this shift may decrease the angular capability of the cell during the rearming part of the cycle. For a reversible application, it is considered as a loss of angular capability. The shift can be approximate by :

$$\gamma_{shft} = u_{shift} * Ln(n)$$

$$\text{with } u_{shift} = -0.0007$$

For a reversible cell, all these tests lead to the general formulation synthesised in the figure 5 .

The formulation applies for the current TiNiCu alloy. The parameters u_γ, , u_{cycle} and u_{shift} are assumed constant for a given material (equal respectively to 0.01163, -0.0008 and - 0.007). They reflect the material properties. The non-dependency with respect to the bar geometry would need more validation with other bar geometry.

Angular performances (deg) of an reversible SMA cell (single way assisted) =

$$\{ (180*R_{amf}) / (\pi*L_{amf}) \}*\{ \gamma_{L\ (\tau rear)} * (1-k*\tau_{high}) - (\tau_{high} - \tau_{rear})*G_{140°C} - 0.0008*\ln(n) - 0.0007*\ln(n) \}$$

Recovery strain limit (after a rearming phase under τrear)

Corrective ratio to consider untransformed martensite at 140°C

elastic strain

Strain motorisation capability decrease after n cycle without unloading in hot temperature

Cold referenced point strain shift after n cycles without unloading in hot temperature

$$\text{with } \gamma_{L\ (\tau rear)} = [\ \gamma_{(\tau high,\ 140°C,\ 0)} - \gamma_{(\tau high,\ 24°C,\ 0)}\ ] + 0.01163 * Ln(\tau rear/\tau high)$$

Figure 5 : synthesis of the reversible SMA cell model.

3. REVERSIBLE HINGE DESCRIPTION

The figure 6 illustrates the one-shot hinge design and its adaptation to get a reversible motion.

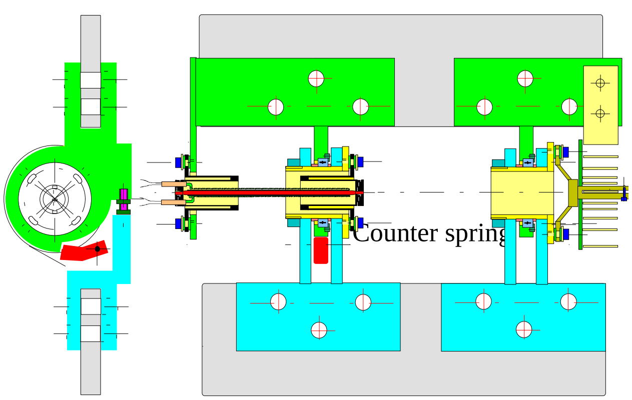


Figure 6 : one-shot hinge adapted to reversible motion.

It is composed of two main parts : one active hinge and one passive hinge.

The guidance is insured by two classical bearings lubricated with Fomblin.

Each hinge is assembled separately then mounted on the fixed and mobile panel without bearing preload.

A cam device mounted on the active hinge insures the locking in deployed configuration.

The SMA motor cell is fixed to both parts of the active hinge.

This one-shot hinge assembly has been manufactured and tested

To get a reversible angular motion, a counter-spring is implemented inside the reference design.

The two operational phases are :

- During heating the SMA acts on against the external resistive torques and the counter-spring
- During cooling, the spring provides the SMA rearming capacity and acts on against the external resistive torques .

The reversible hinge requires the adaptation of the locking function. A SMA helicoidal counter spring unlocks the hinge when heated. When cooled this SMA spring is rearmed by the cam internal torsion spring. This concept has been implemented and the feasibility was demonstrated .

4. MARGIN PHILOSOPHY

The design of space mechanism requires to apply dedicated margins on the different friction torques and motor torques. These margins, necessary to secure the design w.r.t. space environment and design uncertainties, induce a significant motorization over-sizing with respect to the strict needs.

By the way SMA reversible motorised hinge feasibility has to be demonstrated applying such design rules. This is the purpose of following paragraph.

The figure 7 summarises the different torques and margins considered in the MMS reversible hinge application.

Torque designation	values	origin	Applicable margin
Friction torque (bearings + locking device).	< 0.03Nm	Measured	1.5
Inertial torque	0.01	Computed with inertia I = 50 kg.m² Deployment acceleration $\theta°° = 2 * \theta / t^2 \# 2\ 10^{-4}$ rd/s² $C = I\ \theta°° = 0.01$Nm	1.1
Harness torque	Resistive during deployment Motor during restowing	Value to be measured (application dedicated). The safety factor is reduced in order not to be too pessimistic	1.5 for deployment 0 for stowing
Counter spring torque	Resistive during deployment Motor during restowing	Value to be measured (application dedicated). The safety factor is reduced in order not to be too pessimistic	2 for stowing (motor during stowing) 1.2 for deployment (applied on marged previous motor value)
Torque necessary for SMA rearming	Min value necessary to ensure angular range.	extrapolated from measurements	1.2 for stowing

Figure 7 : torque contributors and associated margins.

The input data are issued from the one-shot SMA motor cell performances, adapted to the reversible cell design.

The motorization capability is 2 Nm over 135°, with a rearming under 0.23 Nm.

Two parameters shall be determined :

- the counter-spring capability to be implemented.
- the acceptable harness resistive torque.

A two-step approach is followed :

First step : considering the previous margins during the rearming phase (stowing), the counter spring is designed to deliver finally a rearming torque of 0.23 Nm.

Second step : using as input the first step results and the SMA motor torque capability (2 Nm), derivation of the acceptable harness resistive torque.

In both steps, the uncertainty factor and margins are applied.

The results are detailed figure 8.

It is found that the reference one-shot cell is able to motorise a reversible hinge with a harness resistive torque of 0.1 Nm. This reversibility corresponds to a 114° deployment during 50 cycling.

It is possible to extrapolate the SMA characteristics adequate for other applications.

The figure 9 presents the SMA geometry required for :

- the same harness torque but over 180° during 50 cycles.
- different harness torque (between 0.1 and 2.12 Nm) over 180° during 50 cycles.

This show that the sizing of a reversible hinge requires the utilisation of a SMA torsion bar featuring large torque capability, about 9 times the resistive torques. Such design guarantees that the necessary safety margins and uncertainty factors are fulfilled.

Expected reversibility with a SMA torsion bar initially sized for a one shot deployment of **180 degrees under 2Nm**

Stowing torque budget					
(5) : Spring torque at beginning of stowing phase – With margin :	Spring sizing (sum of 1 to 4)	(4) : Bearings + Locking device	(3) : Harness resistive torque	(2) : Inertia	(1) : Min torque needed for SMA rearming
0.664 Nm	0.332 Nm	0.03 Nm	0	0.01 Nm	0.23 Nm
Applied margin ratio :	2.00	1.5	1.5	1.1	1.2

Deployment torque budget					
SMA motor torque at end of deployment – With margin.	Nominal SMA motor torque (sum of 5 to 8)	(8) : Bearings + locking device	(7) : Harness resistive torque	(6) : Inertia	(5) : Spring torque deployment end with margin
2.01 Nm	1.00 Nm	0.03 Nm	0.10 Nm	0.01 Nm	0.66 Nm
Applied margin ratio :	2.00	1.50	1.50	1.10	1.20

Performance synthesis:		
Spring torque at end of deployment	with margin	0.7 Nm
SMA motor torque at deployment end	with margin	2.0 Nm
Harness torque	w/o margin	0.1 Nm
Angular deployment	at 1st cycle 50 cycles 100 cycles	135° 114° 110°

Figure 8 : counter-spring sizing and assessment of the acceptable resistive torques.

Expected reversibility with Several SMA torsion bar geometry						
SMA bar diameter	mm	**3.52**	**3.52**	**4.8**	**6**	**7.6**
SMA bar length	mm	**106**	**164**	**223**	**280**	**353**
Rearming torque	Nm	0.23	0.23	0.57	1.15	2.3
Marged counter spring torque	Nm	0.66	0.66	1.48	2.87	5.63
SMA Motor torque capability	Nm	**2**	**2**	**5**	**10**	**20**
Harness torque (without margin)	Nm	**0.1**	**0.1**	**0.5**	**1**	**2.1**
Angular deployment at 1st cycle	deg	137	212	212	212	212
Angular deployment for 50 cycles	deg	117	180	180	180	180

Table 9 : SMA reversible hinge sizing.

5. CONCLUSION

This paper recalled the experience gained by MMS for the design and the validation of a one-way SMA torsion bar. A complete mathematical model was issued based on the TiNiCu alloy, taking into account disturbing effects such as the number of cycles.

A reversible hinge was extrapolated from the reference design, by implementing a counter-spring for the SMA self-rearming.

The mathematical model was used for sizing the SMA reversible hinge, demonstrating that the design can accommodate the usual safety factors.

In addition, computer aided tools are available for the sizing of a one-way SMA torsion bar, allowing to translate application requirements – angular range /torque – into SMA bar design and geometry definition – SMA length and diameter.

The theoretical background combined with the experimental capabilities and results constitute now an engineering maturity adequate to define and develop a safe design for both one-way and reversible in-orbit applications.

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