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ABSTRACT

The VST primary mirror is a 2.6-m meniscus made of Astro-Sitall. An active optics system is implemented to correct surface errors due to manufacturing or induced by gravity and temperature changes. The primary mirror is axially supported by 84 supports disposed in four concentric rings. Three of the supports, symmetrically placed and much stiffer than the other ones, define the axial plane of the primary mirror acting as fixed points. The remaining 81 supports are force controlled actuators, used to change the shape of the mirror according to wavefront measurements in closed loop operation, or to a look-up table in open loop. This paper describes the solutions adopted for the axial actuator, as well as the test campaign to assess their performance and degree of reliability.

Keywords: Actuator, Active Optics, Telescope

1. INTRODUCTION

This paper describes the design of the VST Axial Actuator and the safety solutions adopted to assure the integrity of M1 Mirror . The design itself, the material selection, the commercial components characteristics and the performance of each subsystem are then related to specific requirements, and, where applicable, calculations are included. A brief description of the test procedure is finally reported including some examples of the achieved results.

2. DESIGN DESCRIPTION

The VST Axial Actuator is a linear actuator that applies an axial force to the M1 mirror by a motor-screw mechanism that pushes springs acting on the mirror through a contact sphere.
A load cell is included to provide the feedback to the force control system. The figures that follow, fig. 1, 2, are section views of the assembly with the identification of the major components.
Here below follows a brief description of the force actuators cinematic system.
A d.c. motor (5) rotates a trapezoidal screw (15) coupled with a nut (17) that moves axially a piston (18).
The piston (18) acts on six helical springs (19) that transmits the load to the mirror through a load cell (29). Between the load cell and the helical springs (19) is located a preloaded spiral spring (25) to have the correct and pre determined system stiffness along the whole stroke of the piston (see fig. 17)
In fact as long as the load is less than the preload, then the spiral spring stay in contact with the preloading flange and the total system stiffness isn't influenced by the spring; conversely, when the load becomes greater than the preload the spiral spring moves away from the flange and its low stiffness modify the actuator behavior decreasing the total resulting stiffness (see fig. 17).

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The active stroke is long enough to get loads from close to 0 up to the maximum load of 400 N in all conditions, taking into account actuator both stiffness and manufacturing and mounting tolerances.
The load cell (29) can nothing but translate axially thanks to two flexible plates (30), that allow the load cell to translate with negligible axial load.
An M1ACB electronic board is mounted under the actuator, connected to the motor, to the load cell and to the limit switches. It receives through a CAN bus the signals required to move the motor and to control the force of the load cell.
Two electrical limit switches (14) give lower and upper end of stroke.

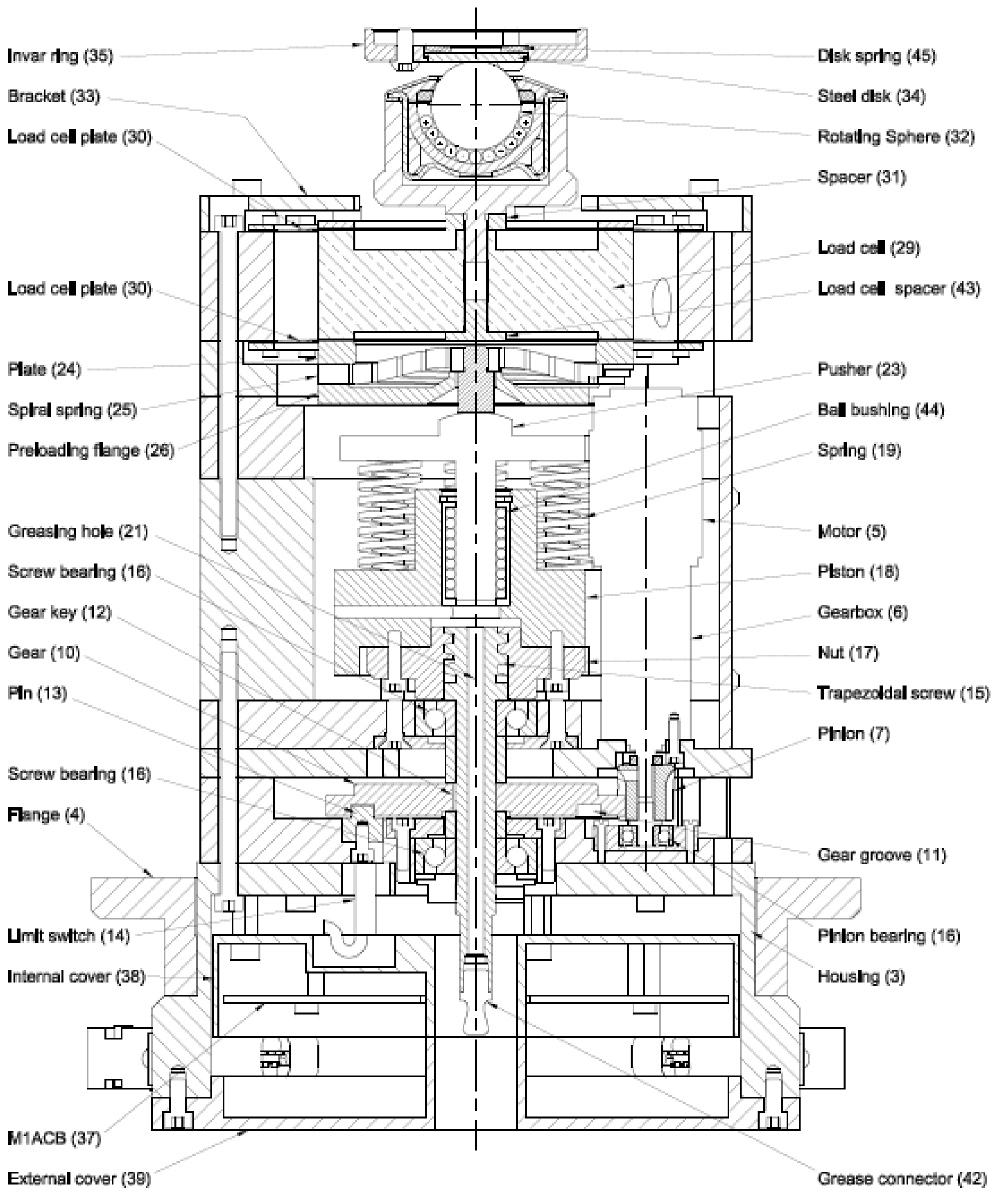

Fig. 1– Axial actuator section view 1/2

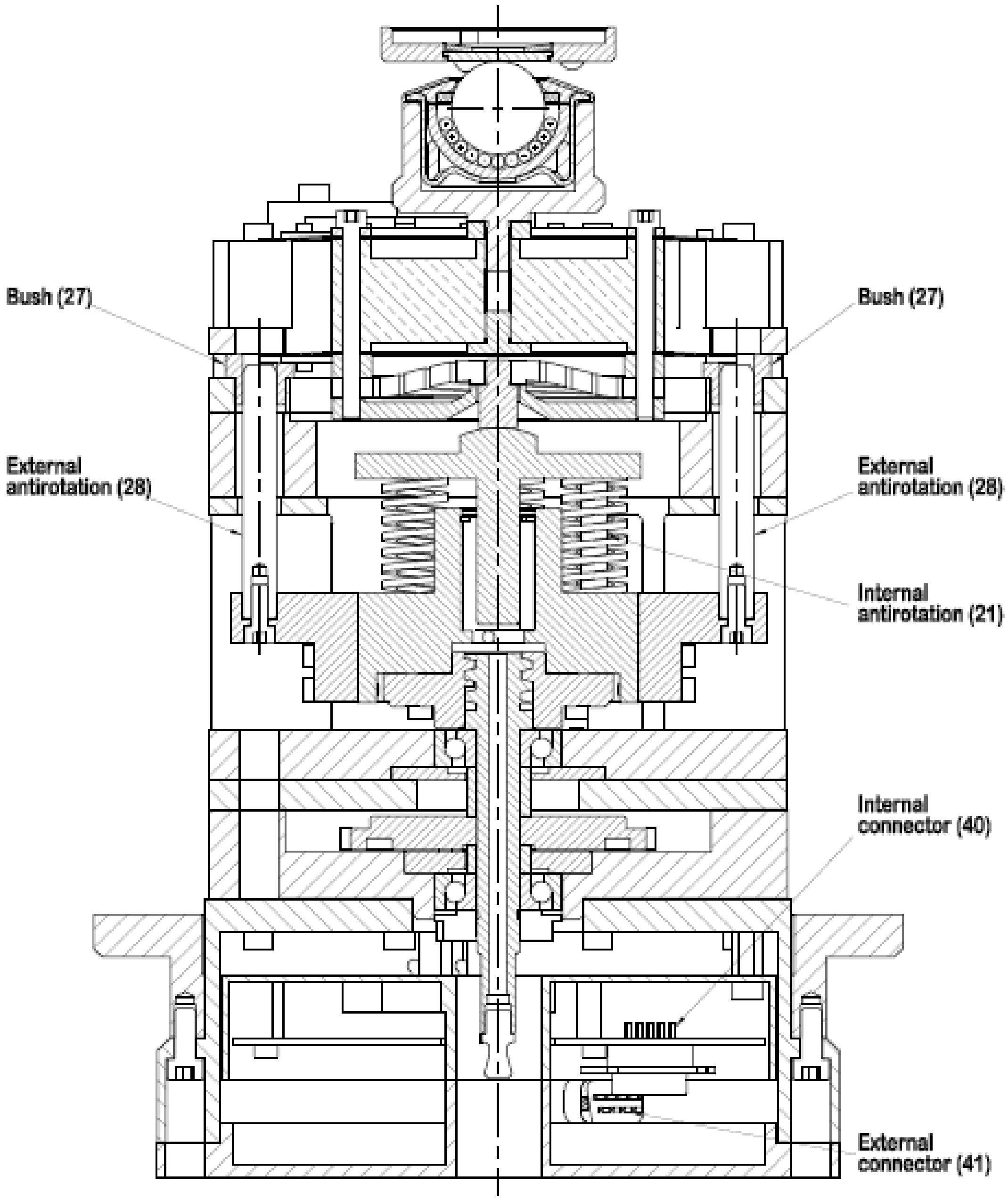

Fig. 2 – Axial actuator section view 2/2

2.1 Stroke-stiffness characteristics

The following Fig. 3 shows the force stroke diagram.

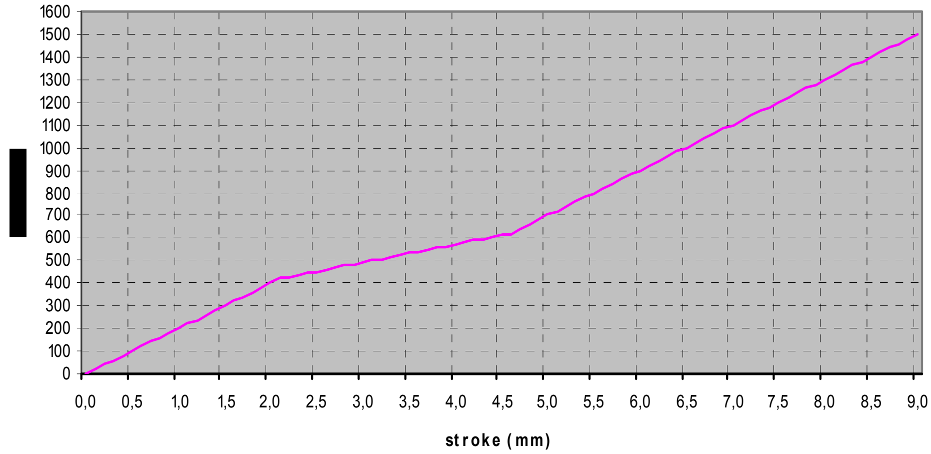

Fig. 3: Force/stroke diagram

As long as the force is less than 420 N , i.e. in operational conditions, the spiral spring stays preloaded holding its position and the stiffness is 200 N/mm.

When the force goes over this value the spiral spring, whose stiffness is around 140 N/mm, moves away from the previous position with an equivalent stiffness of about 80 N/mm, due to the series with the helical springs. The spiral spring has a maximum stroke equal to 2.5 mm; after this stroke it gets in touch to the internal ring of the load cell, and therefore (once completed this stroke, at about 625 N) the stiffness goes back to that of the helical springs, 200 N/mm.

The involved strokes are so:

2.2 mm

operational actuator active stroke

4.7 mm

max actuator active stroke in case of control failure

In case of control failure, the actuator can move to the upper limit switch position with a maximum internal stroke of 4.7 mm: the force on the mirror gets to about 620 N, but the load cell can still read such value.

2.2 mm 3.2 mm total = 5.4 mm

max actuator active stroke plus max earthquake passive stroke

In case of MLE earthquake when the actuator is at the maximum operational load of 400 N, the force reached on the mirror is about 780 N. The max axial movement of the mirror is limited by the presence of the axial safety devices.

4.7 mm 3.2 mm total = 7.9 mm

max actuator active stroke in case of failure plus max earthquake passive stroke

In case of MLE earthquake when the actuator is at the upper limit position (because of failure), the force reached on the mirror is about 1280 N.

3. SAFETY SOLUTIONS

3.1 Rotation of Trapezoidal screw

The axial movement of the actuator is obtained by means of a trapezoidal screw (15) having an axial pitch of 5 mm and threaded shaft 8 mm long. The trapezoidal screw has a 16 mm diameter and a trapezoidal profile, assuring a large contact surface between the screw and the bronze nut; it further has a large thread section strength, in order to assure high reliability. It is possible to periodically grease the screw surface from the bottom to keep good lubrication conditions.

The rotation of the trapezoidal screw is limited in 340° by a fixed pin. The max axial stroke of the piston is so mechanically fixed in 4.7mm.

Two limit switches (14) give signals to stop the movement before the engagement of the pin.

3.2 Passive stroke

The passive stroke is defined as the stroke that the sphere can undergo when pushed by an external force.

The passive stroke is longer than the maximum axial mirror movement allowed by the safety devices. The actuator is designed to have at the same time the maximum active stroke (piston in the upper position) and the maximum passive stroke still keeping the force on the mirror below the max admitted value and without any damage to the actuator mechanics.

3.3 load cell protection by the spiral spring

When 625 N load is reached, the spiral spring completes its stroke and the pusher acts directly on the sphere by means of the inner metallic cylinder of the load cell itself, keeping at 625 N the max force acting on the load cell. The spiral spring design has been developed and fine tuned by means of FEA analysis to achieve exactly the predefined mechanical characteristics (see fig. 19)

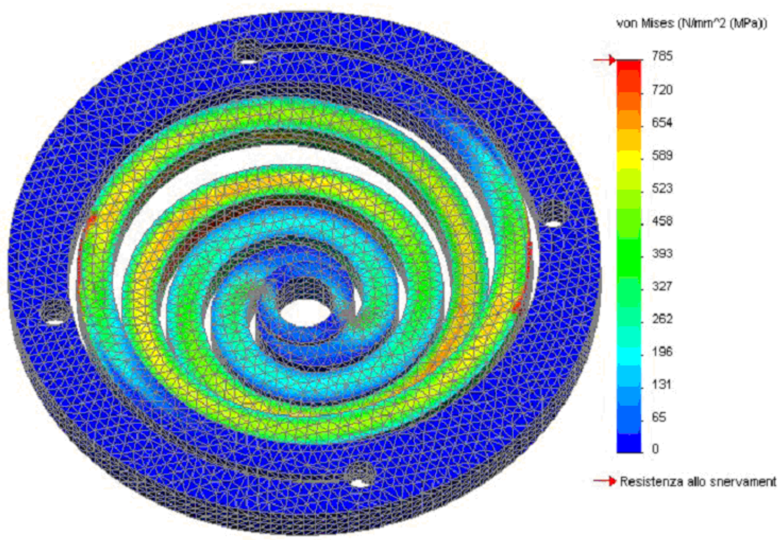

Fig. 4– FEA - Spiral spring loaded by 700N

3.4 Motor supply accessible from outside the cell

In case of failure of the electronics or of the load cell, the motor can be supplied from a power source placed outside the mirror cell, in order to move the piston down to the end of stroke.

3.5 Flexible plates

Two flexible plates (30) are designed to allow a good translation of the load cell, to accept the maximum stroke in all operational conditions and to accept the maximum deflection foreseen in case of earthquake. With the motor at the lower limit switch position, the flexible plates are axially centred to allow the maximum passive stroke foreseen in case of earthquake, equal to 3.2 mm. The maximum displacement admitted between external and internal ring has been verified by FEA, see fig. 5:

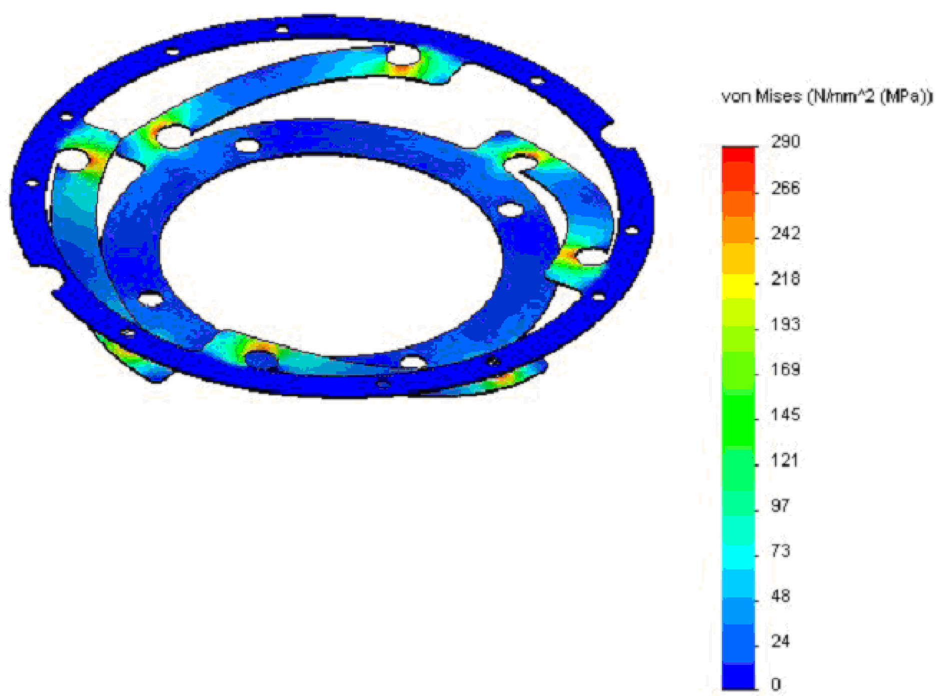

Fig. 5 – FEA, Flexible plates with 3.2mm displacement

3.6 Brackets

The upwards movement of the sphere, starting from the motor being at the lower limit switch position, is limited to 3 mm by the brackets (33), in order to avoid any damage to the flexible plates in case of failure.

3.7 Interface to the mirror

The interface to the mirror is made by a steel disk 34. The disk is held in position by a spring disk without preload (45) and an invar ring 35 having small radial and axial backlash. The elasticity of the disk spring reduces the force on the mirror below the allowed value in case of bump of the sphere due to earthquake occurrence.

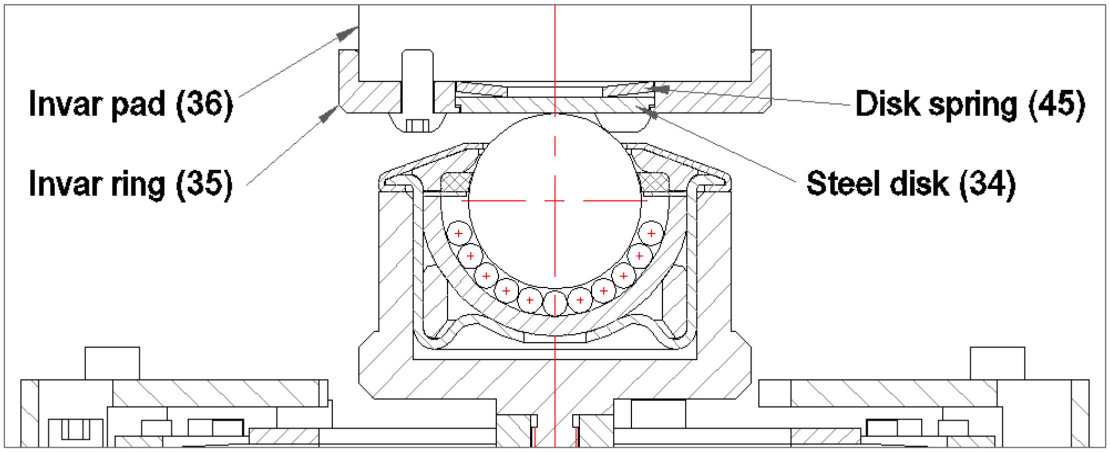

Fig. 6– Interface to the mirror

3.8 PCB protection

The M1ACB is protected by two covers that protect completely the board both internally (38) and externally (39). The connection to cables is external in order to avoid demounting the cover to connect the actuator.

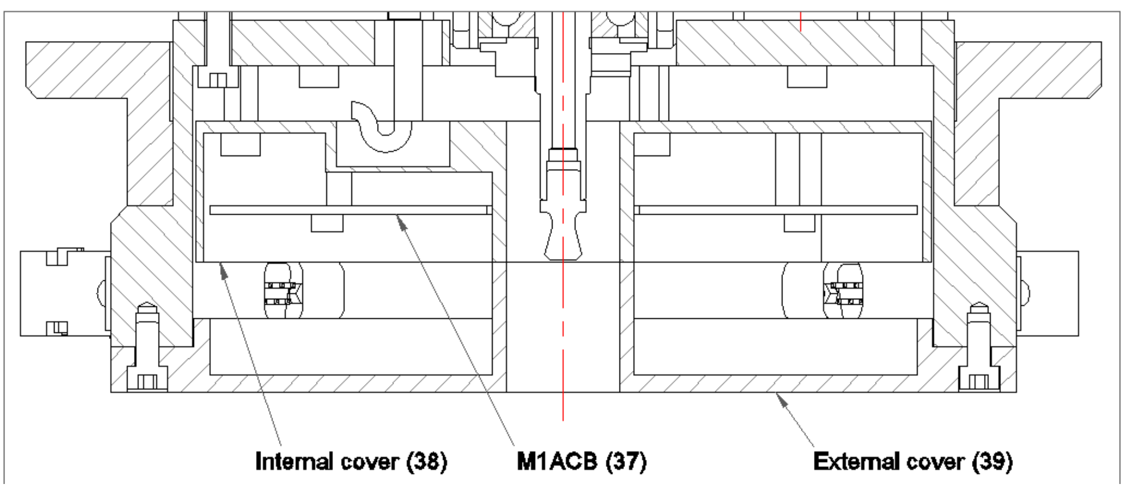

Fig. 7– View of the covers

4. TEST CAMPAIGN

4.1 Requirements & verification Matrix

To verify the correspondence between the Actuators performances and the related Tech. Spec. a series of test have been carried out as reported in the following Tab.1 , the VST actuators verification matrix.

Tab. 1 – Axial Actuator verification matrix

		Verification		
No.	**Description**	**Design**	**Analysis**	**Test**
R7	Environmental specifications	X		X
R14	Maximum force against the mirror	X		X
R21	Mechanical protection	X		X
R22	Axial actuator earthquake safety	X		X
R42	Axial actuators stroke	X		X
R43	Axial actuators stiffness			X
R44	Axial actuators force range	X		X
R45	Axial actuators setting accuracy	X		X
R46	Axial actuator differential setting accuracy			X
R47	Axial actuator force actuation rate	X		X
R48	Axial actuator force measurement resolution	X		
R49	Axial actuator EMC Requirements			X
R50	Axial actuator weight			X

4.2 Test description

8 different tests were developed, referred to the test procedure T0, T1, T2, T3, T4, T5, T6, T7 and T8.
The purpose and the conditions of each test procedure are summarised in the table below.
In the columns are reported, from left to right, the Test Procedure ref., the number of actuator tested, the environmental conditions and the parameter (or tech spec) object of the measurement.

Tab. 2 - Test Description

test	act.	temp.	Parameter/tech spec
T0	all	+20°C	**Ho**: height of the top of the sphere w.r.t. actuator mount flange on th M1 cell
T1	all	+20°C	**IM1**: maximum possible motor current **IM2**: current required at maximum load (400N) **Rfa**: maximum actuator force rate (R47) **Fm1cd**: maximum load with maximum cell deflection (1.2mm) **Ka1, Ka2, Ka3**: actuator stiffness (R43)
T2	all	+20°C	**Afa**: absolute force accuracy (R45), including the reading error of the internal load cells **Ffa**: force range (R44) **Msa**: minimum step accuracy (R46), i.e. whether or not the actuator reacts to a 1N force step **Ems**: maximum error on the minimum step (R46), i.e. force decay after 60s of M1ACB off **Rfa**: maximum actuator force rate (R47)
T3	all	+20°C	**Emlp**: whether the actuator can be moved to the lowest position by means of an external power supply (meant for the case of M1ACB failure) via external power supply, in case of M1ACB failure **Fupl**: maximum load in case of M1ACB failure (= motor at upper limit switch) **Spa**: minimum possible passive stroke (= worst case displacement in case of earthquake, combined with Feq400) **Feq400**: maximum load in case of earthquake (combined with Spa)
T4	1	-10 0 +10°C	**Afa**: absolute force accuracy (R45), including the reading error of the internal load cells **Ffa**: force range (R44) **Msa**: minimum step accuracy (R46), i.e. whether or not the actuator reacts to a 1N force step **Ems**: maximum error on the minimum step (R46), i.e. force decay after 60s of M1ACB off **Rfa**: maximum actuator force rate (R47) **IM2**: motor current at maximum load (400N)
T5	10	+20°C	Reliability, without loss of operational conditions
T6	1	+20°C	EMI compatibility
T7	1	+20°C	Pd: mean power dissipation
T8	all	+20°C	M1ACB functionality

4.3 Test bench description

The T1 and T3 tests have been performed on the actuators by means of dedicated test device with specific test set-up. See fig. 8. The top flange, sliding along the Z Axis, was used to load the actuators by a predefined weight. In case of necessity the movement of the top flange was blocked by the horizontal beam. The external load cell, characterized by a higher precision, was useful to control the correctness of the actuators loads readout while the micrometer gauge measured the axial movements.

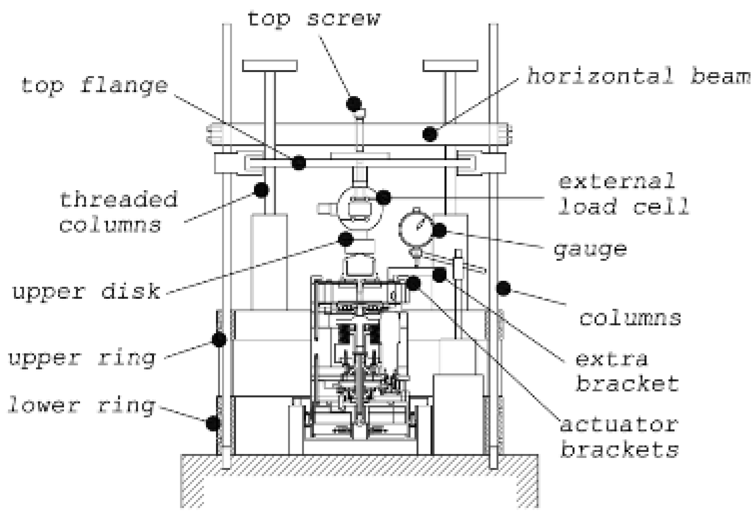

Fig. 8 - Test Bench set-up for tests T1 and T3

The tests T2, T4 and T5 have been carried out fixing a purposely designed "square bracket" on the top of the actuators to simulate the presence of the real mirror, see fig. 9

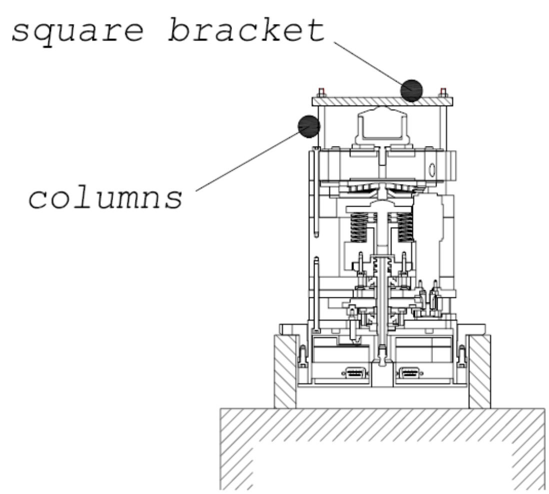

Fig. 9 - Test Bench set-up for tests T2, T4 and T5

5. TEST RESULTS

Here below a list of the test most representative test results

5.1 TEST T0

Test T0 needed a "flat granite bench", an external measuring system or "micrometer gauge" and a set of precision Johnson blocks. The following tab, shows the results compliance between the spec sand the measured values

Tab. 3 – Actuators height

Act. Nr.	Theoretical height [mm]	Δ[mm]	error [mm]
72	208,50	208,55	0,05
73	208,50	208,52	0,02
74	208,50	208,51	0,01
75	208,50	208,53	0,03
76	208,50	208,54	0,04
77	208,50	208,53	0,03
78	208,50	208,53	0,03
79	208,50	208,50	0,00
80	208,50	208,55	0,05
81	208,50	208,53	0,03
82	208,50	208,53	0,03
83	208,50	208,51	0,01

5.2 TEST T1

Here below an example of T1 test certificate

TEST CERTIFICATE OACN01.001/*13*

SUBJECT	VST M1 SUPPORT SYSTEM Axial Force Actuators Test T1	**ref. drawing** **OACN01.0104.000**	**TR** **GN & GM**
Verification	**IM1**: maximum possible motor current **IM2**: current required at maximum load (400N) **Fm1cd**: maximum force with maximum cell deflection **Ka1, Ka2, Ka3**: actuator stiffness (R43)	Cod ………..	………

a) actuator load offset (in cell counts), at the beginning of the test: ***9008*** [CC]

b) maximum possible motor current: **IM1** = ***0.200 A*** (expected < 0.4 A)

c) current required at maximum load (400N): **IM2** = ***0.187 A*** (expected < 0.4 A)

d) maximum axial force with 400N load and 1.2mm mirror cell deflection:

measured force from M1ACB, **Fm1cd** = ***400 N*** (expected 400 N)
measured force from ext. L.C., **Fm1cd** = ***395.3 N*** (expected 400 N)

f) stiffness

Given displac.	Reading from M1ACB [CC]	Reading from ext. L.C. [V]	Force from M1ACB [N]	Force from ext. L.C. [N]	Calculation	Stiffness [N/mm]	Expected [N/mm]
0.0 mm	***8991***	0.47	***67***	***52***	(starting position)	-	-
0.5 mm	***22181***	1.5	***166***	***153***	**Ka1**=Δforce/0.5mm	***202***	150-500
1.0 mm	***36156***	2.6	***271***	***261***	**Ka2**= Δforce /0.5mm	***216***	150-500
1.5 mm	***49982***	3.69	***374***	***368***	**Ka3**= Δforce /0.5mm	***214***	150-500
2.0 mm	***60765***	4.55	***455***	***452***	(safety spring)	-	-

g) actuator load offset (in cell counts), at the end of the test: ***8997*** [CC]

5.3 TEST T2

This test was performed to verify first the actuators load cell accuracy and then the global dynamic performances. A series of certified weights was placed on the test device flange and the load cells outputs (internal and external) were compared. Then predetermined loads commands was set by the control system and the actuators response was compared with the theoretical imposed values. Follow an example of test T2 certificate:

TEST CERTIFICATE OACN01.002/*13*

SUBJECT	VST M1 SUPPORT SYSTEM Axial Force Actuators Test T2	**Ref. drawing** **OACN01.0104.000**	**TR** **GN & GM**
Verification	**Afa**: absolute force accuracy (R45) **Ffa**: force range (R44) **Msa**: minimum step accuracy (R46) **Ems**: maximum error on the minimum step (R46) **Rfa**: maximum actuator force rate (R47)	Cod ………..	…………

Tab. 4 . Actuator load cell verification

T2/"load cell" axial force actuator nr.13									
Weight	**N**	**V (Ext)**	**N (Ext)**	**Ext vs W**	**CC (Int)**	**N (Int)**	**Int vs Ext**	**Lin. Err.**	**Displ.**
(flange) 0	0,0	0,470	46,1	0,0	9012	67,5	0,0	0,66	-0,66
5	49,1	0,970	95,2	0,0	15427	115,5	-1,0	-0,90	-0,13
10	98,1	1,470	144,2	0,0	21845	163,5	-2,1	-2,47	0,41
15	147,2	1,970	193,3	0,0	28221	211,2	-3,4	-4,03	0,65
20	196,2	2,480	243,3	1,0	34636	259,2	-5,4	-5,59	0,19
25	245,3	2,980	292,3	1,0	40956	306,5	-7,1	-7,15	0,01
30	294,3	3,480	341,4	1,0	47312	354,1	-8,6	-8,72	0,09
35	343,4	3,980	390,4	1,0	53565	400,9	-10,9	-10,28	-0,60

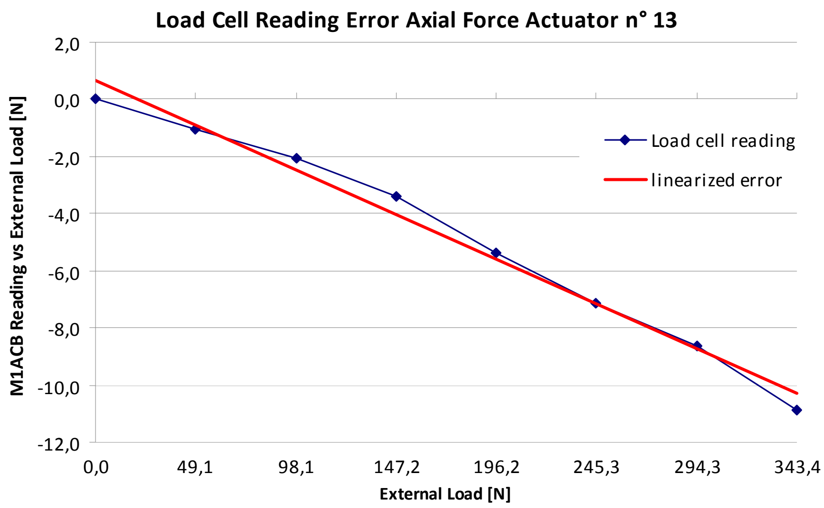

Fig. 10 – Actuator Load Cell error

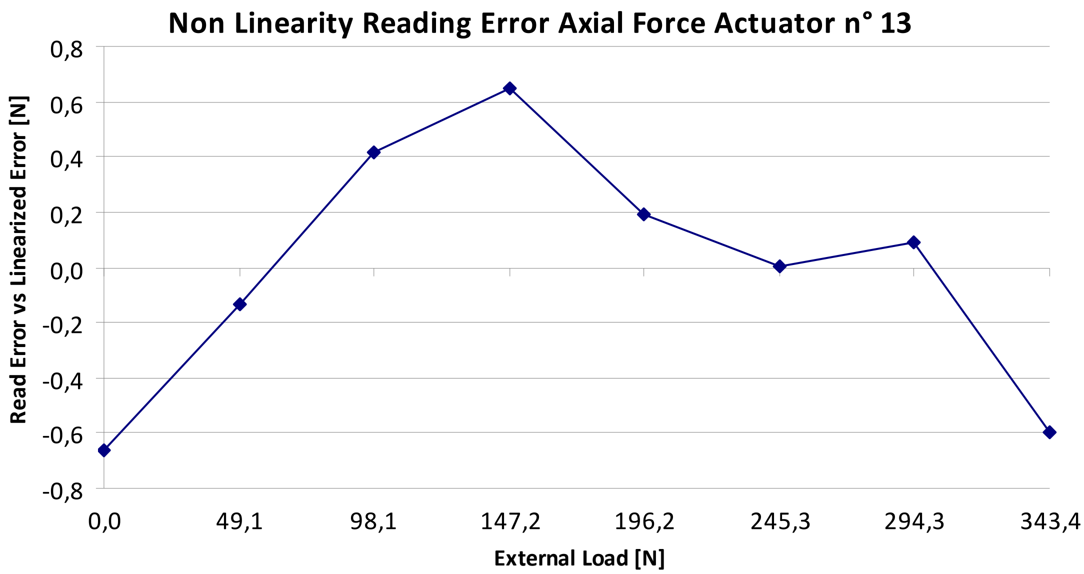

Fig. 11 - Actuator non linearity

b.1 - **Ffa**: minimum and maximum pre-set loads in the sequence can actually be reached: ***yes***

b.2 - **Afa** absolute force accuracy is within the tolerance ±5N: ***yes***

b.3 - **Msa**: the actuators react to force steps of 1N: ***yes***

b.4 - **Ems**: after any load step, observe the load of the actuator during the time that the M1ACB is switched off (in between 7s and 70s after the load step) and take the average value within 1min time interval: the load change is less than ±0.3N: ***yes***

b.5 - **Rfa**: after any load step, observe the load of the actuator during the time it takes to reach the set force value: the slope is ***25*** N/s (expected >20 N/s)

Plots of some test results are reported in the following Figures.

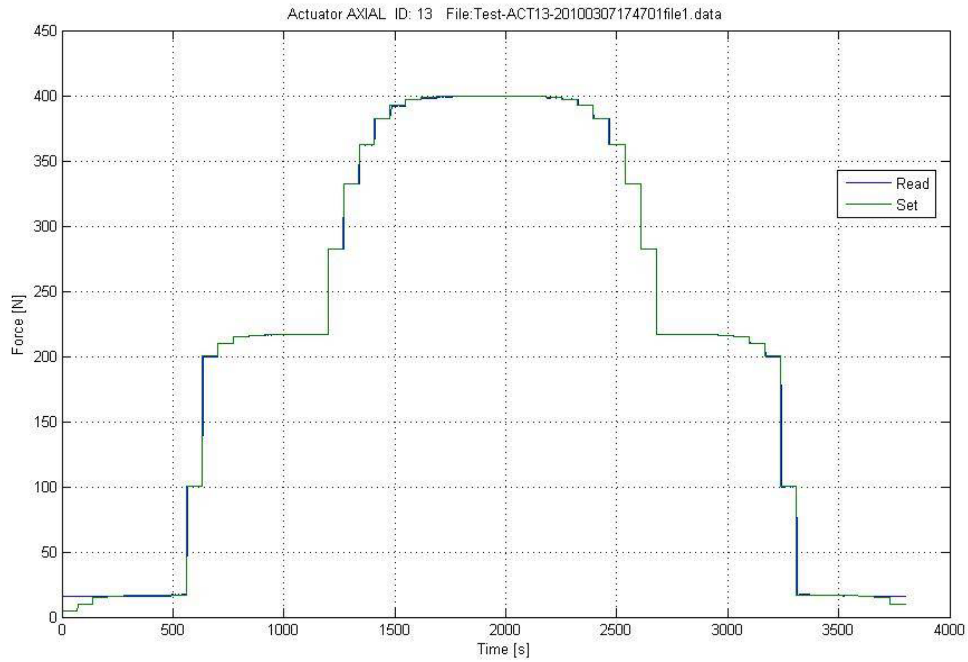

Fig. 12 – Plot of a test diagram

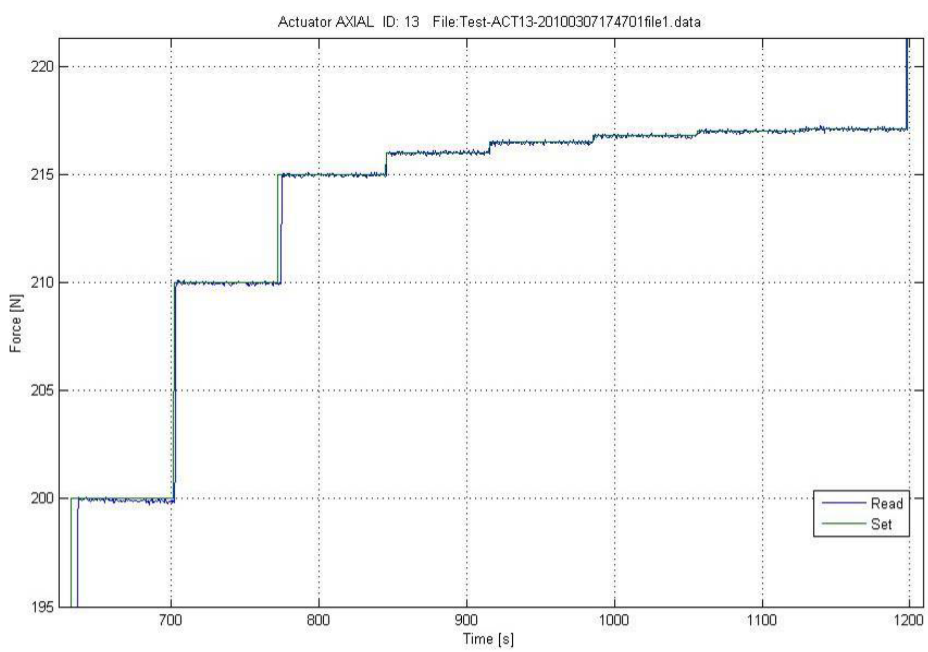

Fig. 13 - Plot of a test diagram, zoom

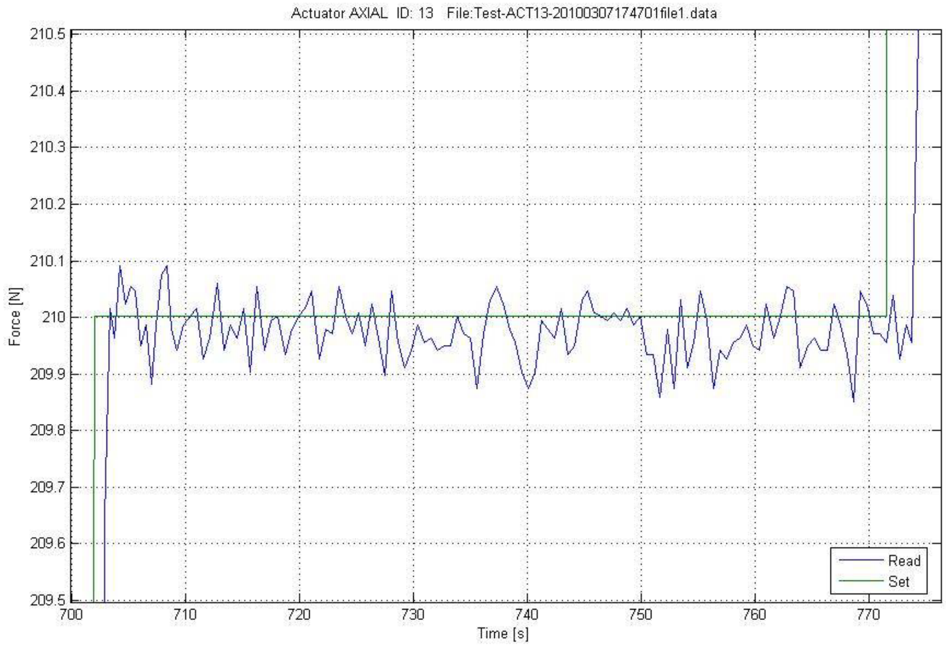

Fig. 14 - Plot of a test diagram during increasing load, zoom

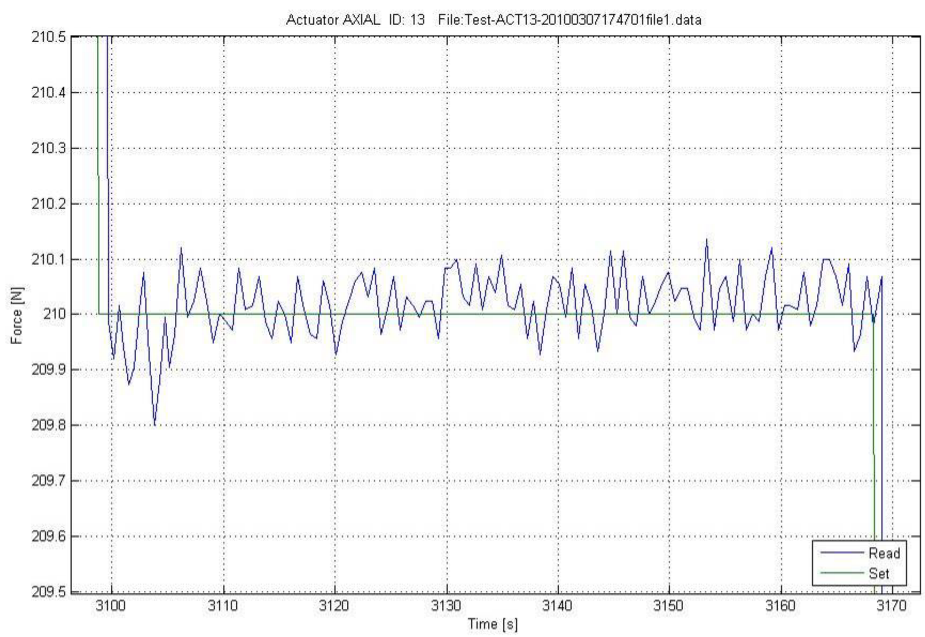

Fig. 15 - Plot of a test diagram during decreasing load, zoom

5.4 TEST T3

Here is a T3 test certificate example:

TEST CERTIFICATE OACN01.003/*13*

SUBJECT	VST M1 SUPPORT SYSTEM Axial Force Actuators Test T3	**Ref. drawing** **OACN01.0104.000**	**TR** **GN & GM**
Verification	**Emlp**: whether the actuator can be moved to the lowest position by means of an external power supply (meant for the case of M1ACB failure) **Fupl**: : maximum load in case of M1ACB failure (= when motor at upper limit switch) **Spa**: minimum possible passive stroke (= worst case displacement in case of earthquake, combined with Feq400) **Feq400**: load in case of earthquake (combined with Spa)	Cod ………..	……………

a) actuator load offset (in cell counts), at the beginning of the test: ***9731*** [CC]

b) the motor can be moved to the lower limit switch position via external power supply: **Emlp** = ***yes***

c) maximum axial force when motor at upper limit switch position:
reading from M1ACB (cell counts): .... [CC]
reading from external load cell: .... [mV]
measured force from ext. L.C., **Fupl** = ***679.8*** N (expected < 750 N)

d) maximum passive stroke in case of earthquake, **Spa** = 3.2mm reached: ***yes***

e) maximum axial force in case of earthquake:
reading from M1ACB (cell counts): .... [CC]
reading from external load cell: .... [mV]
measured force from ext. L.C., **Feq400** = ***874.1*** N (expected < 1500 N)

f) actuator load offset (in cell counts), at the end of the test: ***9729*** [CC]

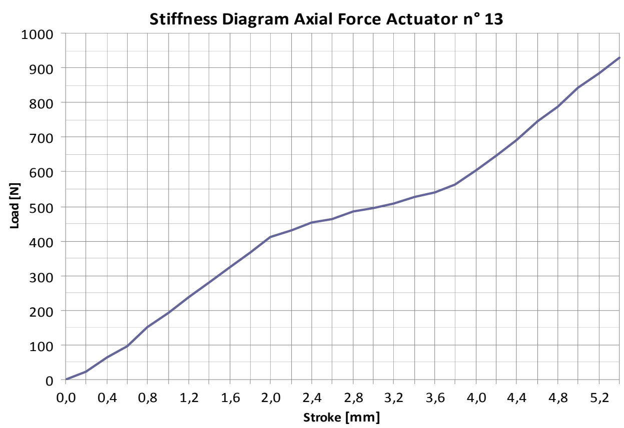

Fig. 16 – Axial Actuator Stiffness Diagram

5.5 TEST T5

A suitable load sequence is defined for the reliability test T5: this includes about 23 hour large force steps with short delay and a 1 hour-long "performance test T2 load sequence", with force steps of different size and longer delay. The test started in February 2010 and, every day, ten actuators at once have been tested. Some examples of loading sequence plots are reported in the following

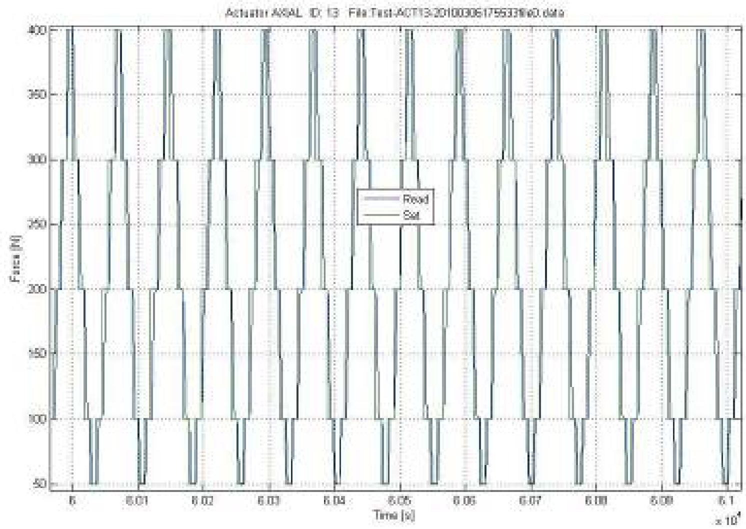

Fig. 17 – Part of Reliability Load Sequence applied for 23 hours

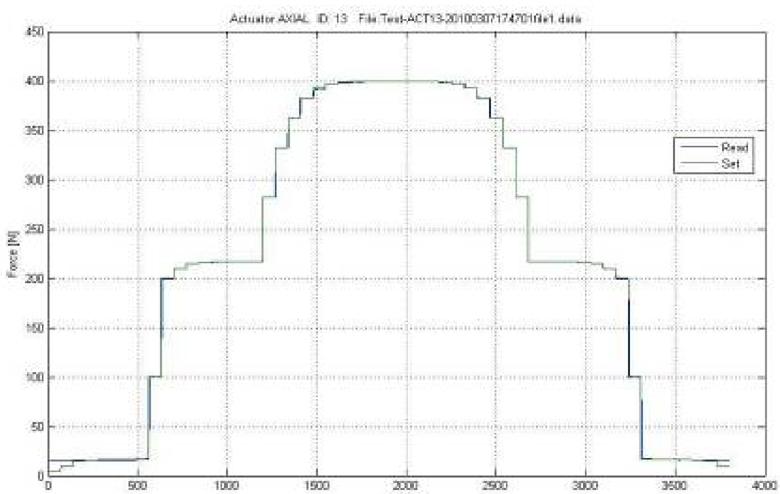

Fig. 18 – Performance Load Sequence applied after reliability sequence

5.6 Reliability

A reliability test has been performed to verify the life-time of the motor, for the load cell and for the mechanical parts of the actuators.
For these parts the life time is proportional to the wear that depends from the total stroke and to the fatigue or the number of cycles.
The "stressing" test has been applied on 10 actuators for about 2 months in order to perform a length of stroke and a number of cycles as for 20 years, in operational conditions, on each actuator.
Every day (24h) the test foresee about 23 hour of large force steps with short delay (1150 iterations of a force sequence with 100N steps, with 9s delay between two force step commands and with 7s M1ACB "time-out"), and a 1 hour-long performance test, with force steps of different size and longer delay.
In fact the daily force rate chosen for the test was 131 higher than the one applied in the operational conditions.
During the test no one failure occurred on the actuators; a good reliability is so guaranteed.

6. CONCLUSION

All the performed tests have demonstrated that all the 81 actuators satisfied all the requirements and particularly, in the normal operational field, the load sensitivity is of 0.1N and for each applied load and after the electronic board is switched off, the load is maintained without appreciable variations (less than 0.1N).

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