GUIDELINES ON DESIGNING ELECTROMECHANICAL ACTUATORS TO IMPLEMENT AN ACTIVE SURFACE ON LARGE REFLECTOR ANTENNAS

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Technical Report IRA 410/07

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INDEX

1. INTRODUCTION

In this report we summarize the experiences acquired the design and production of two sets of actuators to implement active surfaces on Italian radiotelescopes.

The aim is to present general suggestions on key choices for the realization of proper electromechanical actuators, considerations about the performance of this class of mechanical device and evaluation on its limits of application.

In this last respect, in order to reach a deeper knowledge of the product, some consideration will be added about the possibility to push at the extreme performance this kind of device. It will be suggested that, although this actuator was conceived for application up to a wavelength of 3mm, its performances could be adequate also at shorter wavelengths.

2. GENERAL CONSIDERATIONS

The first consideration to be pointed out in implementing a lot of actuators on the back-up structure of a large antenna is the reliability. A maintenance free, high lifetime electrical/mechanical device should be a correct guideline. In order to achieve this, a device as simple as possible should be conceived, consistently with the requested positioning accuracy and loading specifications. The cost impact must be also taken into account if the actuator is too much complicated. The actuator accuracy has to be compared with the total rms surface error coming from all other sources, so it is sufficient to make it negligible and to select the cheaper class of mechanics fitting the specification. Because the total rms surface error is the root sum squared of all the rms error sources, an rms accuracy due to the actuator less than three or four times the surface accuracy specification is fully adequate. This rough evaluation of the actuator class could be improved only if this doesn't affect cost, simplicity and reliability. This is how we proceeded in the realization of the Noto 32m dish upgrade and in the new 64m dish Sardinia Radio Telescope.

As an example we report the relevant contributions on the total surface accuracy in the 64m Sardinia Radio Telescope,

SRT- SURFACE ERROR SOURCES (precision condition)	**RMS (µm)**
Panels manufacturing accuracy	65
Panels measurement error	25
Panel thermal deformation	11
Panel gravity deformation	29
Panel wind deformation	4
Panels field alignment	50÷150
Primary mirror BUS error (wind + thermal)	40
Primary mirror BUS corrected gravity deformation	0
Active Surface Actuator positioning accuracy	15
Subreflector panels manufacturing error	50
Subreflector measurement error	15
Subreflector thermal deformation	9
Subreflector gravity deformation	4
Subreflector wind deformation	4
Subreflector alignment error	40
Subreflector BUS error (wind + thermal)	22
TOTAL ACCURACY, RSS	**120÷186**

Tab. 2.1 Surface accuracy contributions for SRT

As it can be seen a total error ranging from 120 to 186 micron makes negligible the contribution of the actuator positioning accuracy of 15 micron rms. This would also be true if the required total surface accuracy were down to 70-80 micron, which is consistent with a minimum working wavelength around 1.5mm (200GHz) at $\lambda_{min}/20$ or 1.2mm (250GHz) at $\lambda_{min}/16$.
We will show at the end of this report that the actuator accuracy is probably adequate also at lower wavelengths.
On the other hand, looking for an “absolute” accuracy actuator, let’s say some micron accurate, can lead to a great increase of cost and complexity.
General consideration about reliability, modularity and maintenance could be the following:

a) it should be better to avoid brush motor. Sooner or later the brushes have to be replaced and to do that on hundreds of actuators distributed on a large back-up structure could be a nightmare. Today other more effective type of motors exist.
b) take care of the type of electrolitic capacitors used in the electronic board. The ones used in conventional boards or in power supplies do not have a lifetime of 20 years or more.
c) it is a good choice to make electronics board immersed in a protective coating
d) select the external connectors that guarantee a true airtight seal. The best way to do this is a previous experience.
e) the concept of distributed intelligence makes easier the architecture and modularity of the system. Designing an actuator with capability to manage and drive its positioning simplifies the cabling of the network of actuators (only a power supply wire and a communication wire are needed) and the control of the network (only addressing and sending the position to each actuator). This concept makes possible the modularity of the system allowing the same architecture for some tens of actuators as well as some thousands.

Whatever the adopted solution, a reliable network of hundreds or more of actuators need a deep testing of the prototypes, and of the complete network setup as well. A brief summary suggested is the following,

1) Load tests

The actuator must be tested with operating, maximum and survival loads. This must also be repeated at different temperatures in the temperature operating range. A good point could also be to stress one actuator at its breaking limit.

2) Temperature tests

The specification of the actuator, particularly the positioning error, must be validated in the overall temperature operating range, demonstrating its repeatibility. A good point could also be to stress one actuator well beyond the temperature range.

3) Positioning error tests

They comprises the evaluation of backlash, linearity, stiffness and hysteresis. All of these should be done changing the load and in the temperature operating range. This experience will come useful at the production time to provide to the manufacturer suitable test benches. At that phase it could be a good choice to require the characterizazion of each actuator so that look-up tables can be ready to use.

4) Reliability and Lifetime tests

In order to demonstrate the specified lifetime the prototypes must be subjected to a realistic movement cycle under loading, repeated continuously. It would be better to carry out this test at the antenna site in order to experiment under real environmental conditions. The aim is to make an accelerated test of lifetime and at the same time to check if the actuator has unwanted stops and faults. After many equivalent years (more than the specified lifetime) are accumulated the device must be dismounted in all its parts in order to check the wear of its parts.

5) EMC tests

Tests of electromagnetic compatibility, executed at a certified laboratory have the purpose to verify that the actuator doesn’t emit significant interferences and it is immune to electrostatic discharge, bursts and surges. Of course each actuator box, once mounted on the antenna, must be properly connected to ground. The meaning of these tests is to characterize the device both “from the actuator to the output world” (you could have hundreds of interference generators on the antenna) and “from the output world to the actuator”, i.e. its immunity to external electrical impulses.

Only after positive results are obtained from these tests the mass production can be taken into consideration. This is a delicate phase and needs appropriate documentation to be delivered to the manufacturing company.

After the delivery of all actuators it should be a safe decision to connect all of them in the same fashion they will be on the antenna (cables, segments, subnodes, nodes,...) in order to test the actuators network as well as the control and monitoring software before the installation. In fig. 2.2 the network setup, 1116 actuators connected as they will be on the antenna, is shown for Sardinia Radio Telescope (SRT). This follows the experience we gained during the development of the active surface of the 32m dish Noto antenna.

Fig. 2.2 1116 actuators network for SRT

Following the delivery of all actuators produced by the manufacturer a test bench already in use at the time of the work for the active surface of the Noto 32m dish has been used in order to characterize a sample of the production in term of LINEARITY, STIFFNESS and HYSTERESIS.

At the time of the production the manufacturer was instructed to perform measures on BACKLASH on the majority of the actuators, giving us the possibility to check the manufacturing results with respect to the mounting tolerances requested.

In this technical report the overall positioning accuracy will be reported together with a detailed updated data sheet of the actuator characteristics. It will be shown that the actuators fit ~~with~~ the required total surface accuracy for SRT but, in order to have a deeper knowledge of the product, some considerations will be added about the possibility to push at the extreme performance this kind of device.

We recall here a brief summary of the actuator mechanics where the rotation of a step motor is converted to a linear motion using a backlash-free ballscrew mechanism and a low backlash worm gear.

This worm gear has a 35:1 reduction ratio, i.e. the actuator is self-locking. The wormshaft engages to the stepping motor shaft, backlash-free, by a high torsional stiffness coupling. The wormwheel is connected to the ball screw nut housing by bolts.

The ball screw nut housing is supported at both ends by ball bearings. In order to avoid ball bearings axial clearance, precision shims are added between bearing and gear housing in the mounting phase.

The ball screw spindle is connected to the actuating rod and is fixed by spline against rotation. In order to avoid radial loads on ball screw spindle plastic bushings are used.

The linear position of the actuator is directly calculated through the steps of the motor, no additional linear measuring system is provided.

In a very simple mechanical system like that one described above, the possibility to maintain backlash in the desired range is given only by the combination of experience trick together with opportune manufacturing tolerances.

3. TEST BENCH SETUP

The test bench uses a pneumatic cylinder driven by compressed air and is able to apply both compression and tensile stress on the actuator axis. A load cell is interposed between the pneumatic cylinder and the actuator in order to measure the applied force. The reading of the load cell is shown on a digital display while the actuator displacement is monitored by a digital dial indicator (Mitutoyo) mounted parallel to the axis of the ball screw. A precise parallelism of the dial indicator and screw axes is essential for the accuracy of the measure. In fig. 3.1 the setup can be seen, while in fig.3.2 the arrangement of the dial indicator as placed in the measurement setup is shown.

Fig. 3.1 Measurement test bench setup

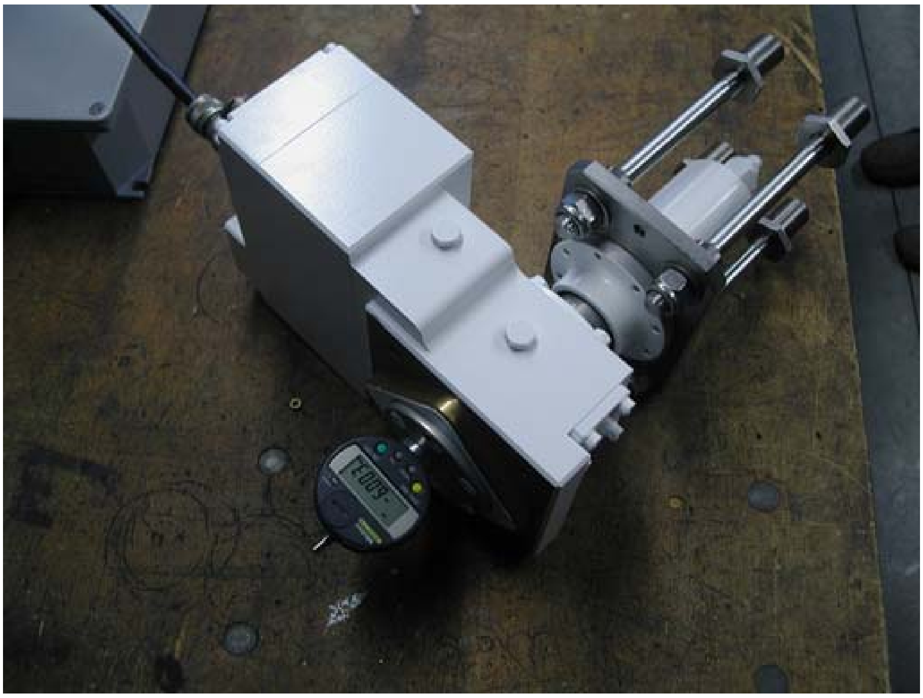


Fig. 3.2 Arrangement of the dial indicator on the moving axis of the actuator

4. MEASUREMENTS RESULTS

All the components affecting the positioning accuracy were measured: backlash, linearity, stiffness, hysteresis.
Since the position of the actuator isn't directly measured, but calculated through the steps of the motor, the actuator position accuracy is influenced by the backlash of the mechanical system, by the positioning accuracy of the ball screw and by the stiffness.

The axial backlash is affected by mechanical tolerances of these components:

- The tolerance on the distance between wormshaft and wormwheel axles
- The tolerance on the distance between wormshaft bearings
- The axial clearance of the wormshaft bearings
- The tolerance on the coupling between the teeth of the spline, used for avoiding the rotation of the ball screw spindle.

The linearity is affected by mechanical tolerances of these components:

- The nominal gear ratio versus effective gear ratio.
- An eccentricity on the rotation of the wormwheel.
- The tolerance on the ball screw spindle stroke (pitch accuracy).

Stiffness and hysteresis are a property of solid body and are affected by the material and the shape of all actuator mechanical components supporting the load.

4.1 Backlash statistics

The manufacturer was instructed to produce the measure of the backlash for the majority of the actuators. We got results of 757 over 1159 produced. The limit tolerance for the backlash of each actuator was given ≤ 30 micron. Following are the statistics,

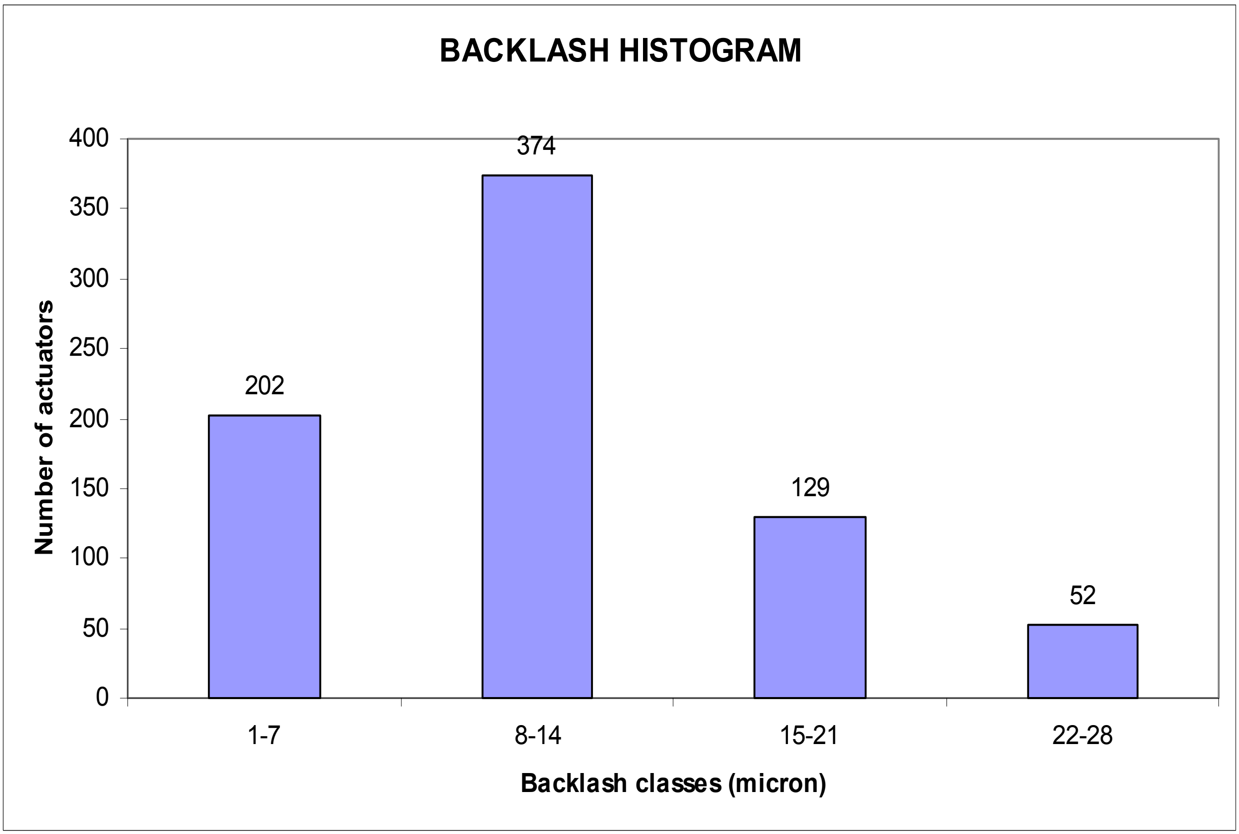


Fig. 4.1.1 Classes of backlash yield in quartiles (absolute number of actuators)

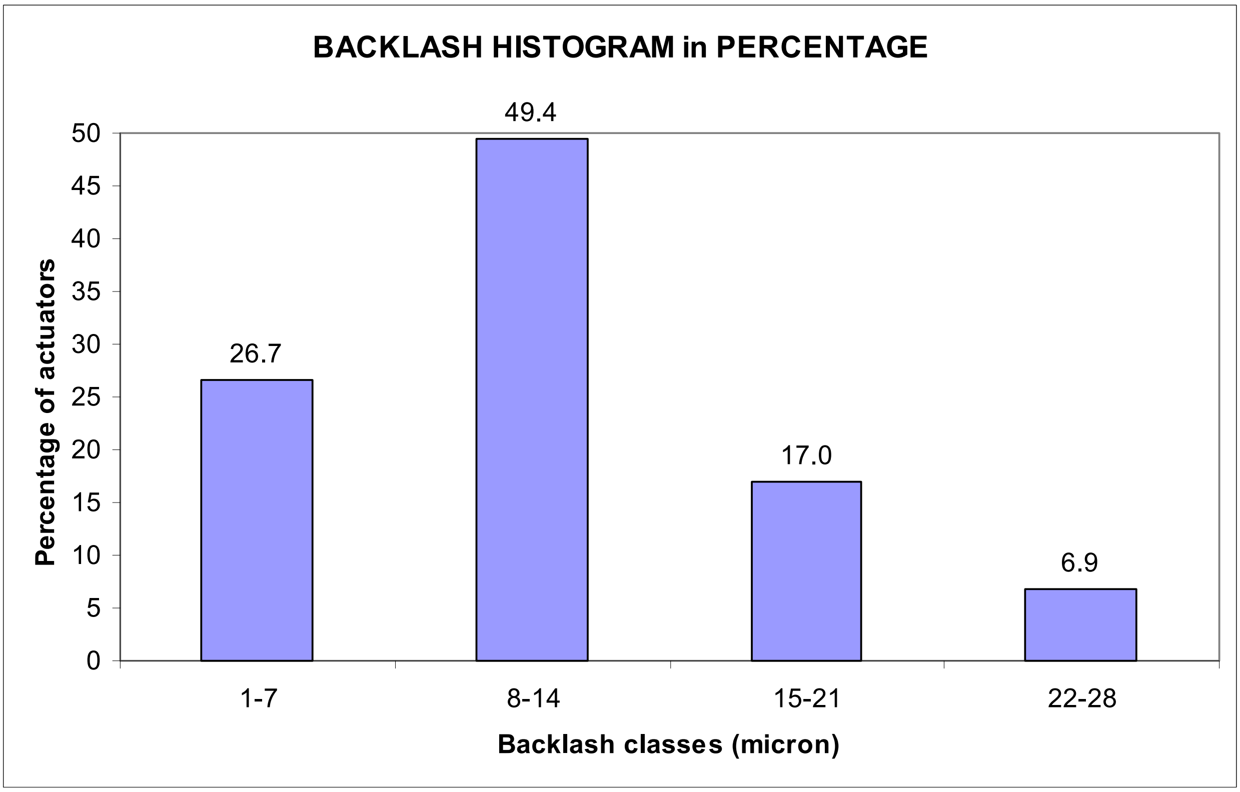


Fig. 4.1.2 Classes of backlash yield in quartiles (% of actuators)

Despite of the tolerance of 30 microns, most of the actuators have less than 16 micron (607 actuators over 757, i.e. about 80% of the measured production). In fig. 4.1.3 the distribution of the population is shown,

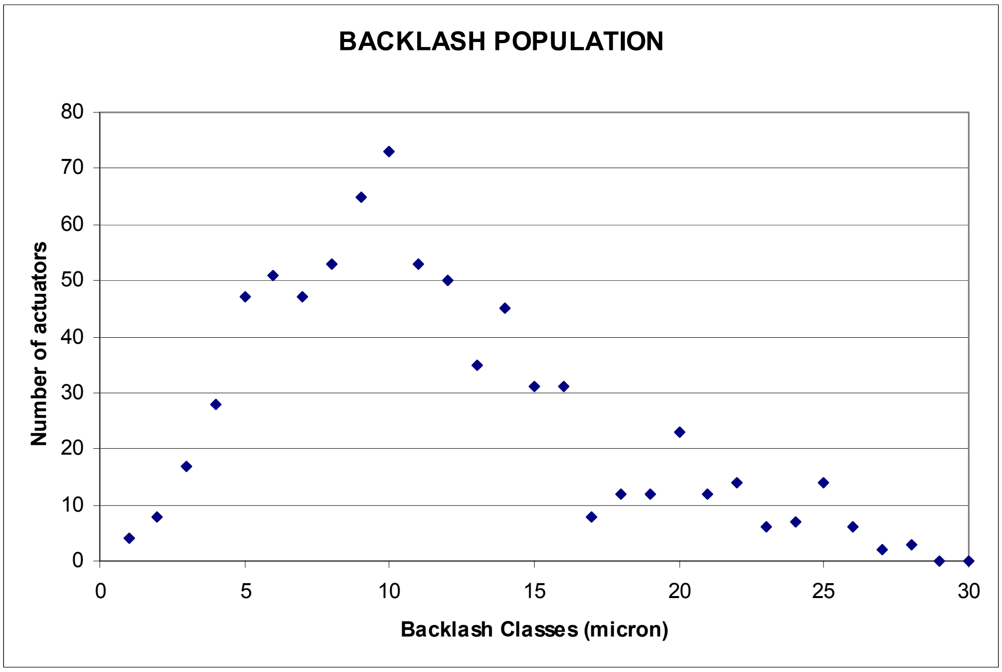


Fig. 4.1.3 Backlash Population Distribution

4.2 Backlash, Linearity, Stiffness and Hysteresis

Some actuators were then measured in house by the authors of this report in order to determine other important features of the device, such as the linearity, the stiffness and hysteresis.

Linearity means how much the actual position of the actuator stay around the commanded values throughout the whole stroke; ideally we would like that the deviation between the commanded and actual position is zero. In the real world we would like that the straight lines fitting the positioning error points show both slope and offset as near to zero as possible.

Stiffness means the resistance of an elastic body to deformation by an applied force. In fact, the stiffness is typically measured in newton per micron.

Hysteresis means a property of a system that does not instantly follow the forces applied to them, but react slowly. For instance, if you load a device it will assume a new shape, and when you remove the load it will not return immediately to its original shape. Hysteresis phenomena occurs in the elastic behaviour of materials, in which a lag occurs between the application and the removal of a force and its subsequent effect. In fact if the displacement of a system with hysteresis is plotted on a graph against the applied force, the resulting curve is in the form of a loop. In contrast, the curve for a system without hysteresis is a single, not necessarily straight, line.

All of these parameters come out from the measures, together with, again, the *Backlash* value.

The label identifying the actuator is composed by the number of the row of the primary mirror and the sequential number of the actuator inside that row; for example 03-30 means that we are dealing with the 30th actuator of the third row.

In the following graphs we show the performances of a sample of six actuators, randomly selected. For each of them all the parameters are measured.

Initially the characterization has been done measuring *Backlash* and *Linearity.* The actuator was driven in a “step-by-step” mode, 1mm wide, over the travel range of ±6mm with repect to the mid range of actuator travel. The actuator is with no load, i.e. no additional force from the pneumatic cylinder was applied.

In the tests the actuator is moved starting from one limit, reaching the opposite side and coming back to the starting point. The *Backlash/Linearity* curves are shown in figures 4.2.1,4,7,10,13,16. In these charts we can see:

- the *Linearity*, all actuators show a constant behaviour, at least within the dial indicator error of about 1 micron. The 12-09 actuator is an exception, but with a very small value,
- the *Backlash*, i.e. the positioning error when the actuator motion is reversed. The actuators show a behaviour ranging in 1 ÷ 27 microns.

The results in Fig. 4.2.19 is obtained in the same way, but by loading the actuator by pneumatic cylinder in compression and tensile strength at two different values. Again, reversing the actuator motion and the load the difference between the two positioning errors is essentially the *Backlash* + *Stiffness*.

- the *Stiffness* is shown in figures 4.2.2,5,8,11,14,17. An evaluation of the effect of the loading in compression and tensile give values between 40÷50 N/µm. These values are much better than estimated in the document GAI-01-TM-003.0 dated September 2006 (20 N/µm). The 07-98 actuator is an exception, at least when loaded in compression, because it shows a stiffness behaviour twice as other actuators.
- the *Hysteresis* values for each actuator is directly shown in the figures 4.2.3,6,9,12,15,18. It appears symmetric for each actuator and mostly ranging in 7÷10 microns.

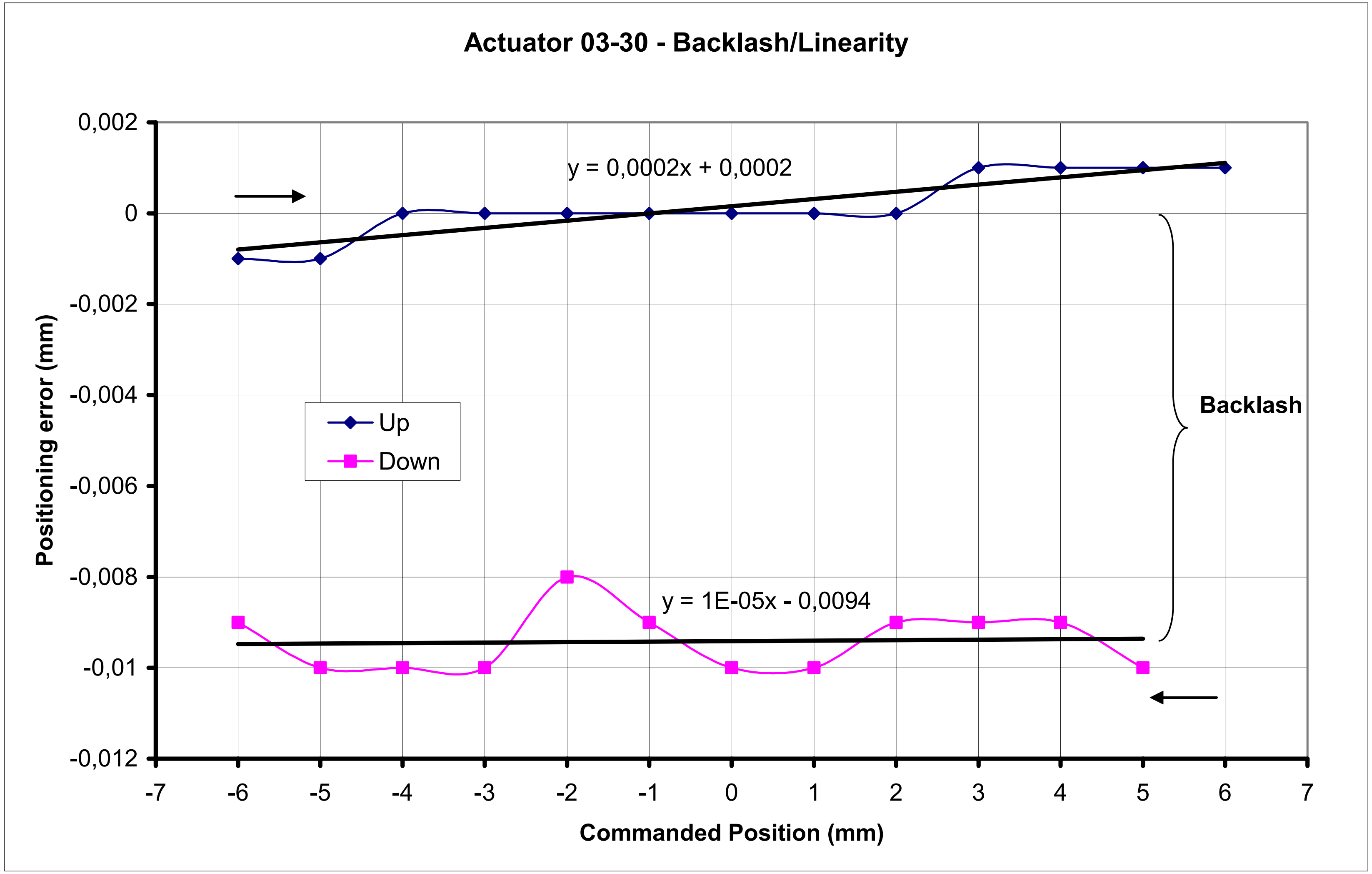

Actuator 03-30 - Backlash/Linearity
0,002
0
-0,002
-0,004
-0,006
-0,008
-0,01
-0,012
Positioning error (mm)
y = 0,0002x + 0,0002
y = 1E-05x - 0,0094
Up
Down
Backlash
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Commanded Position (mm)

Fig. 4.2.1

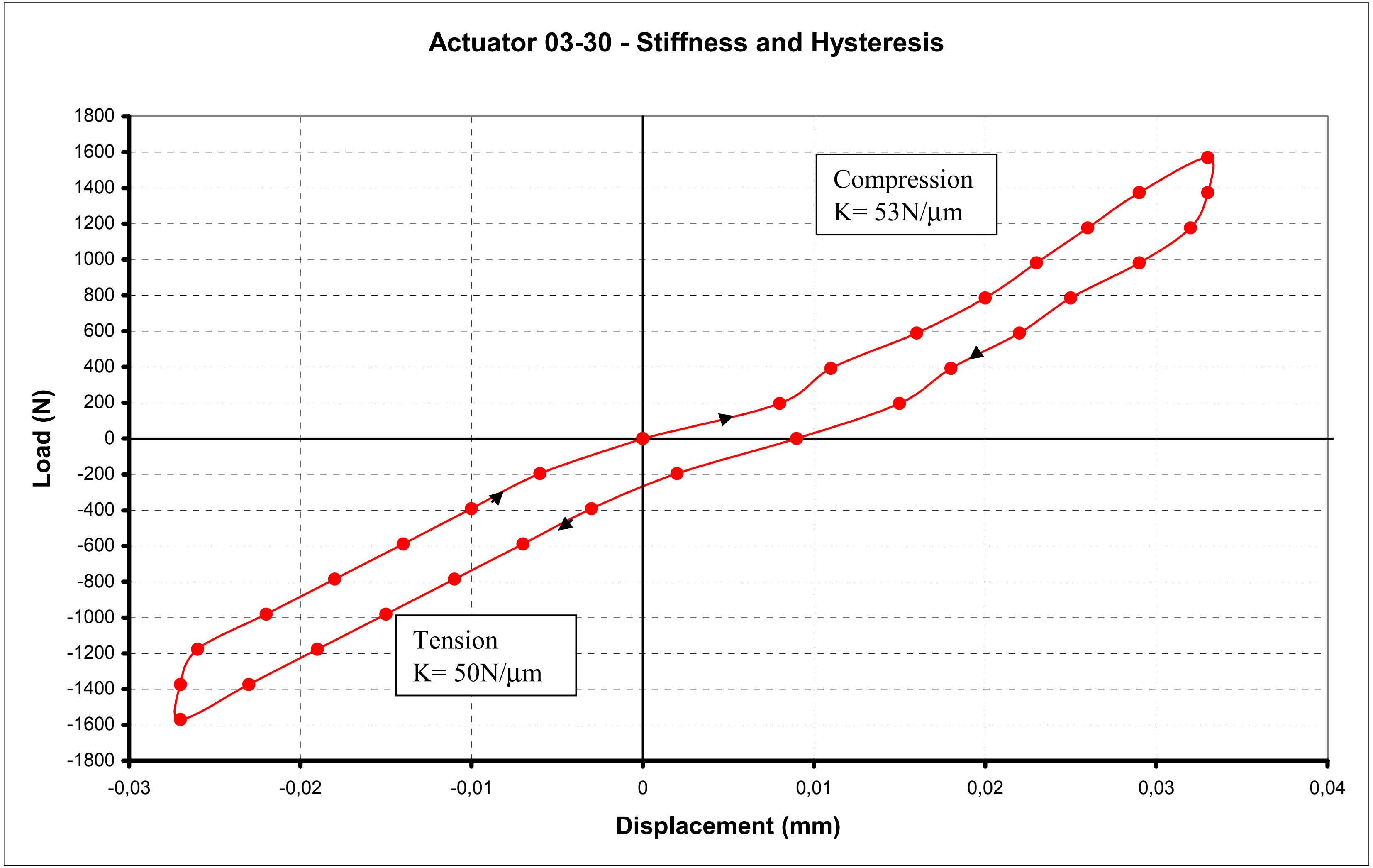

Actuator 03-30 - Stiffness and Hysteresis
Compression
K= 53N/µm
Tension
K= 50N/µm
Load (N)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-0,03
-0,02
-0,01
0
0,01
0,02
0,03
0,04
Displacement (mm)

Fig. 4.2.2

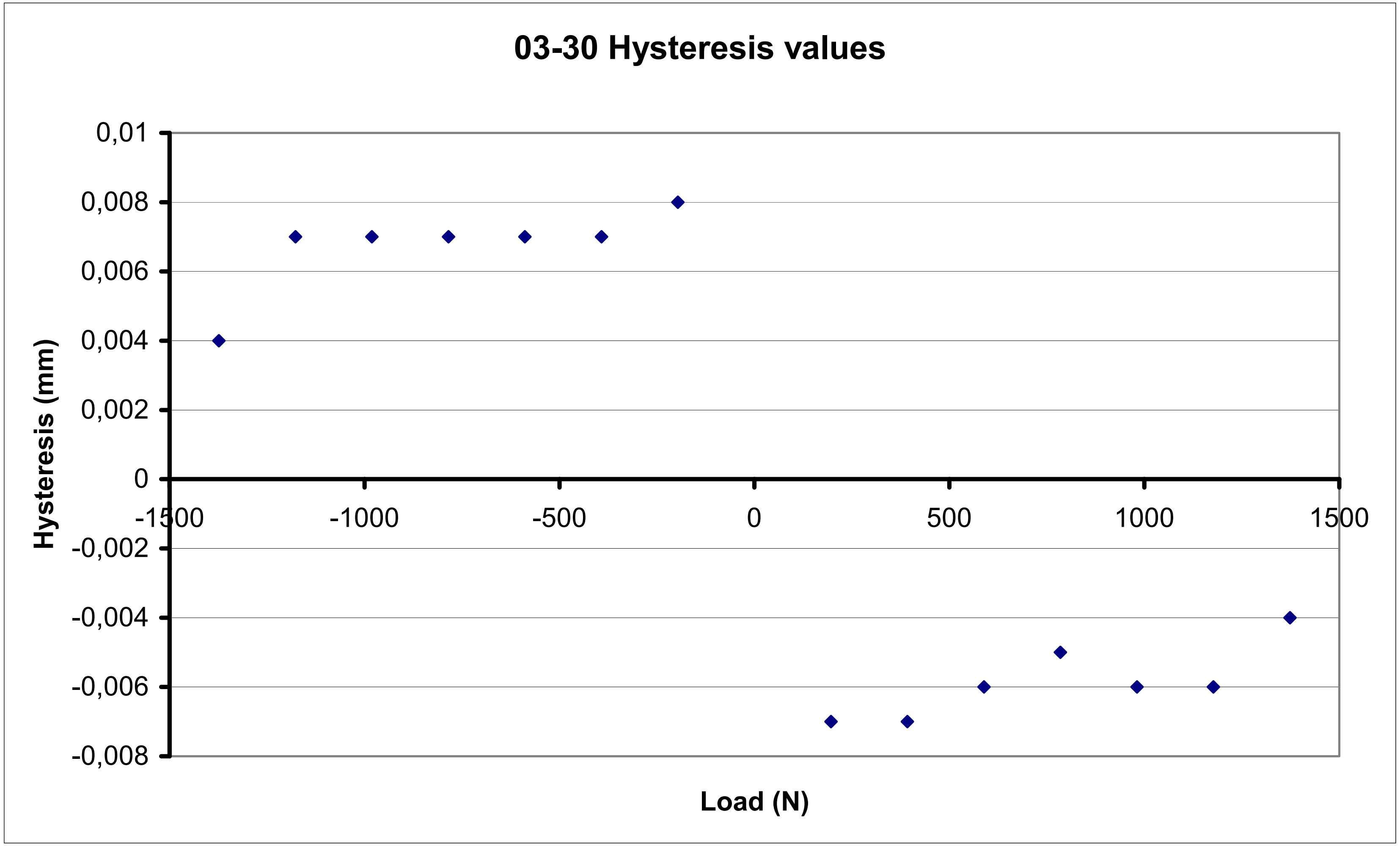
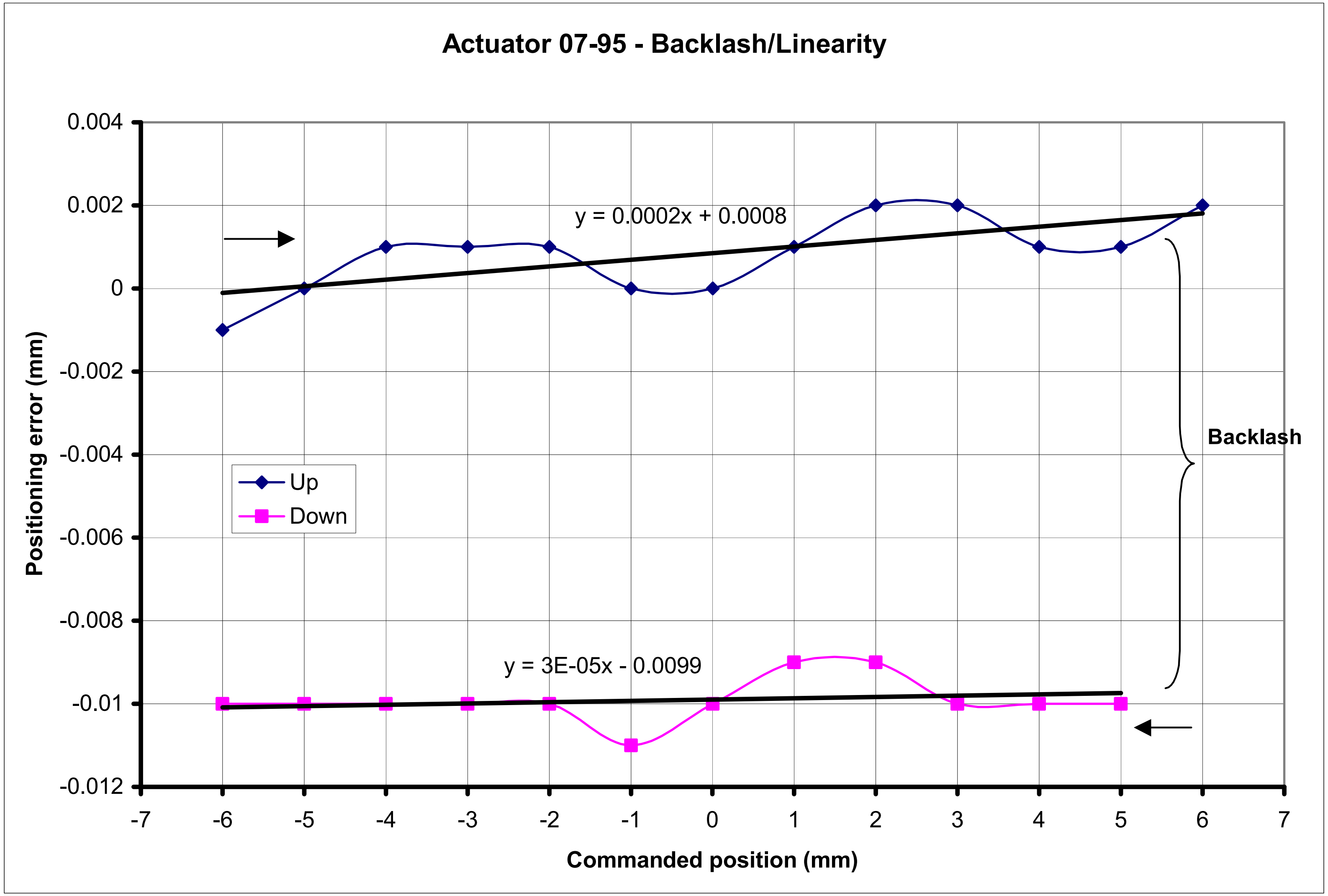

03-30 Hysteresis values
Hysteresis (mm)
0,01
0,008
0,006
0,004
0,002
0
-0,002
-0,004
-0,006
-0,008
-1500
-1000
-500
0
500
1000
1500
Load (N)

Fig. 4.2.3



Actuator 07-95 - Backlash/Linearity
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
Positioning error (mm)
y = 0.0002x + 0.0008
y = 3E-05x - 0.0099
Up
Down
Backlash
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Commanded position (mm)

Fig. 4.2.4

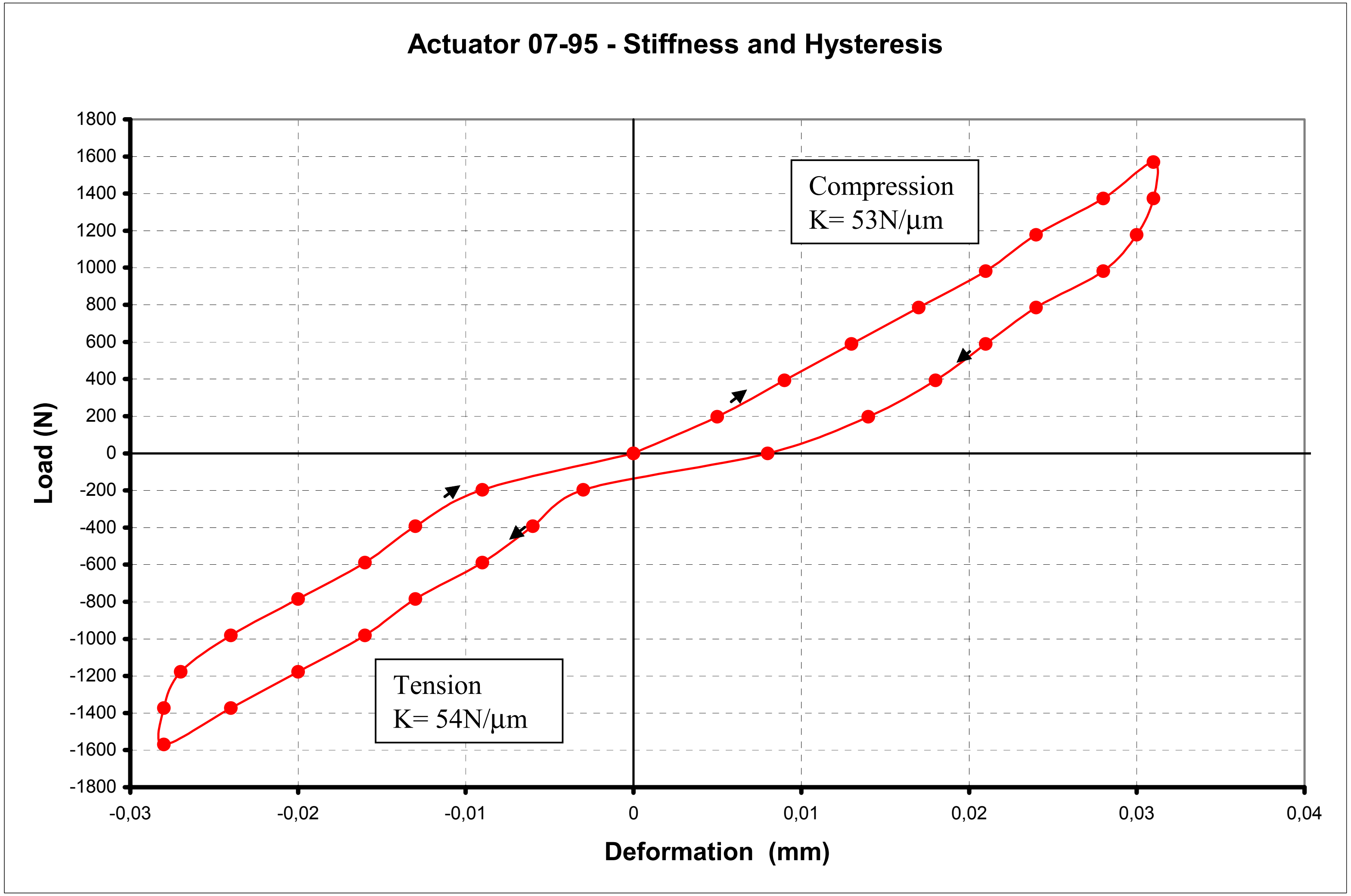

Actuator 07-95 - Stiffness and Hysteresis
Compression
K= 53N/µm
Tension
K= 54N/µm
Load (N)
Deformation (mm)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-0,03
-0,02
-0,01
0
0,01
0,02
0,03
0,04

Fig. 4.2.5

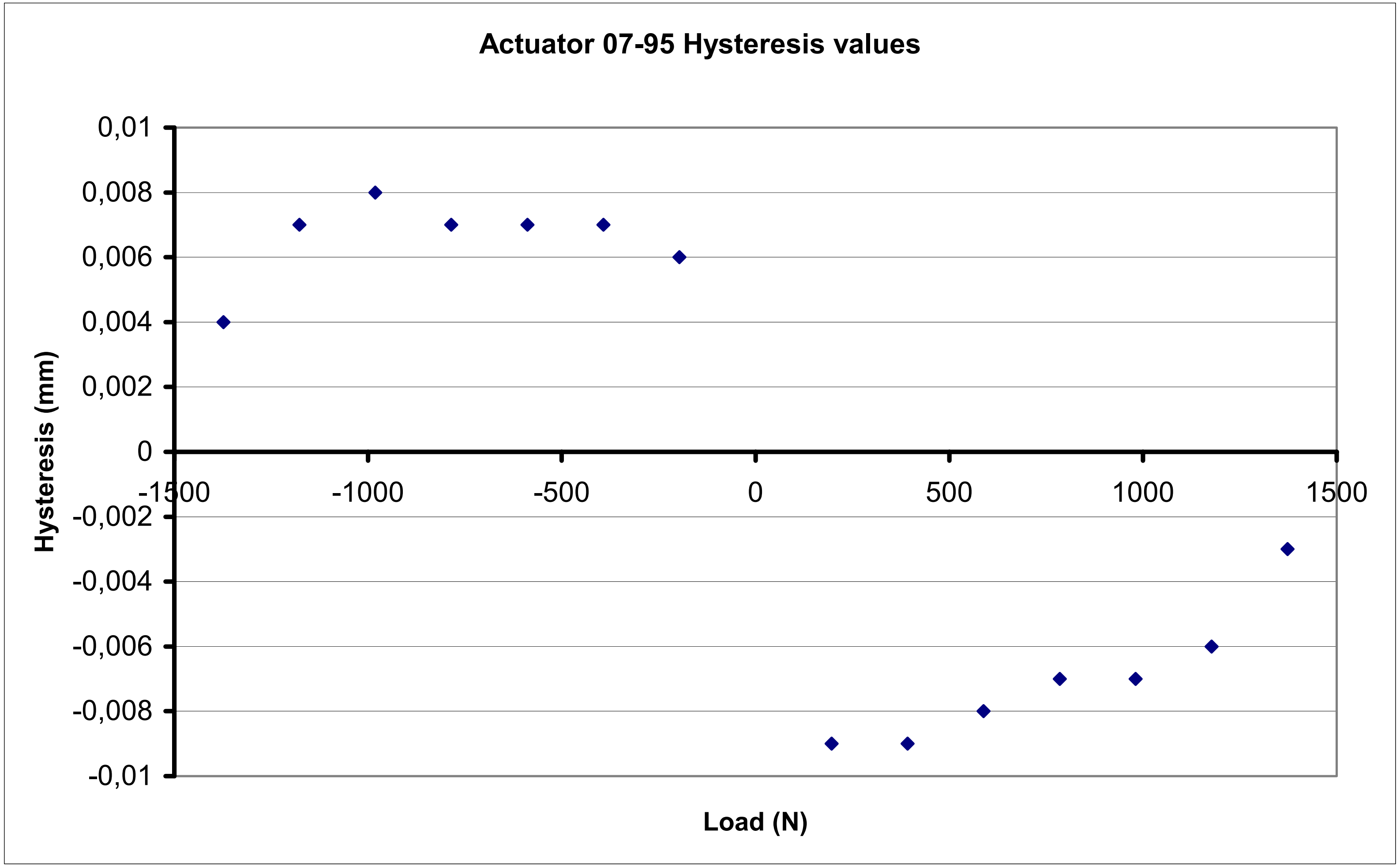

Actuator 07-95 Hysteresis values
Hysteresis (mm)
0,01
0,008
0,006
0,004
0,002
0
-0,002
-0,004
-0,006
-0,008
-0,01
-1500
-1000
-500
0
500
1000
1500
Load (N)

Fig. 4.2.6

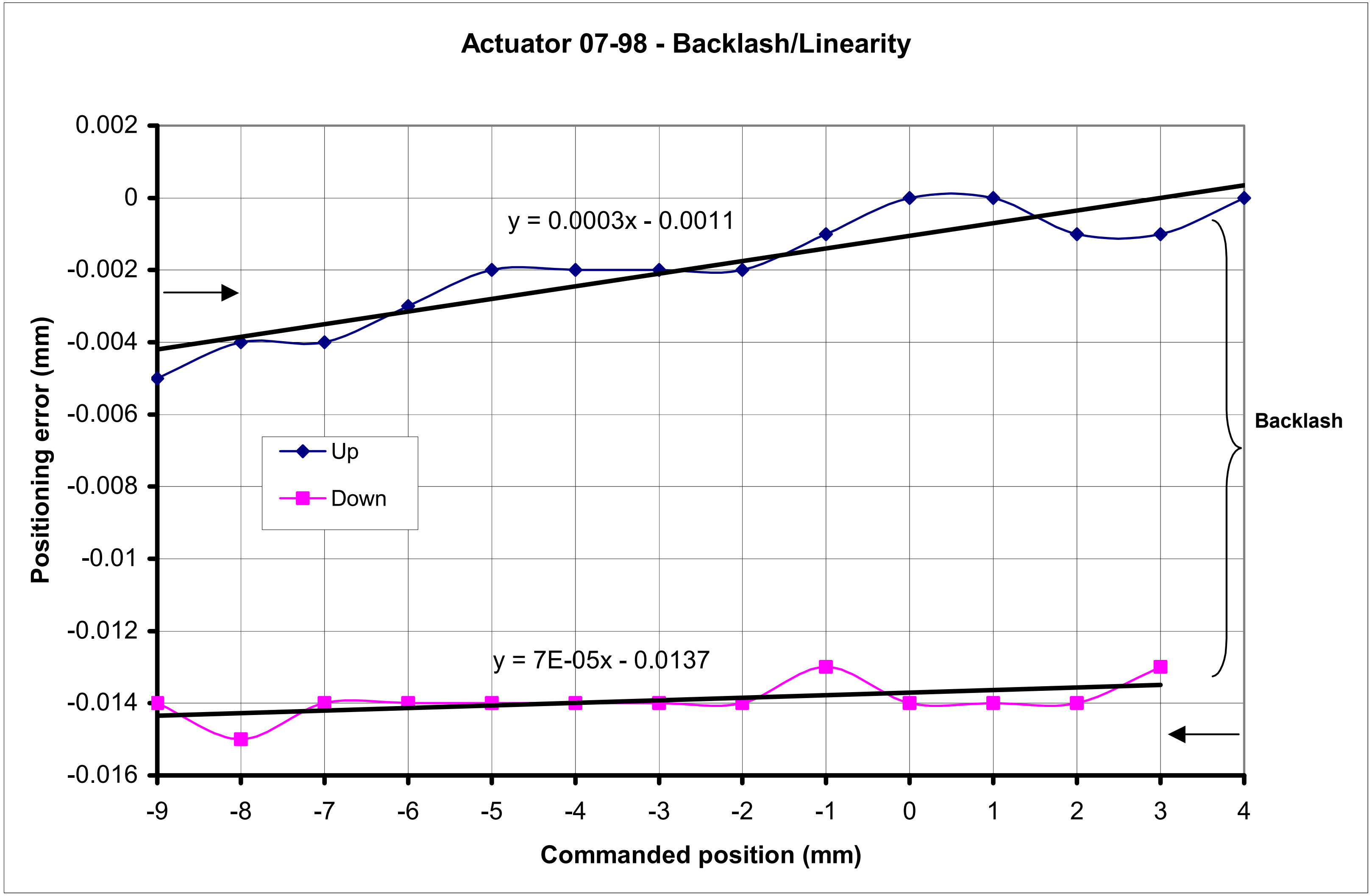

Actuator 07-98 - Backlash/Linearity
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
Positioning error (mm)
y = 0.0003x - 0.0011
y = 7E-05x - 0.0137
Up
Down
Backlash
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
Commanded position (mm)

Fig. 4.2.7

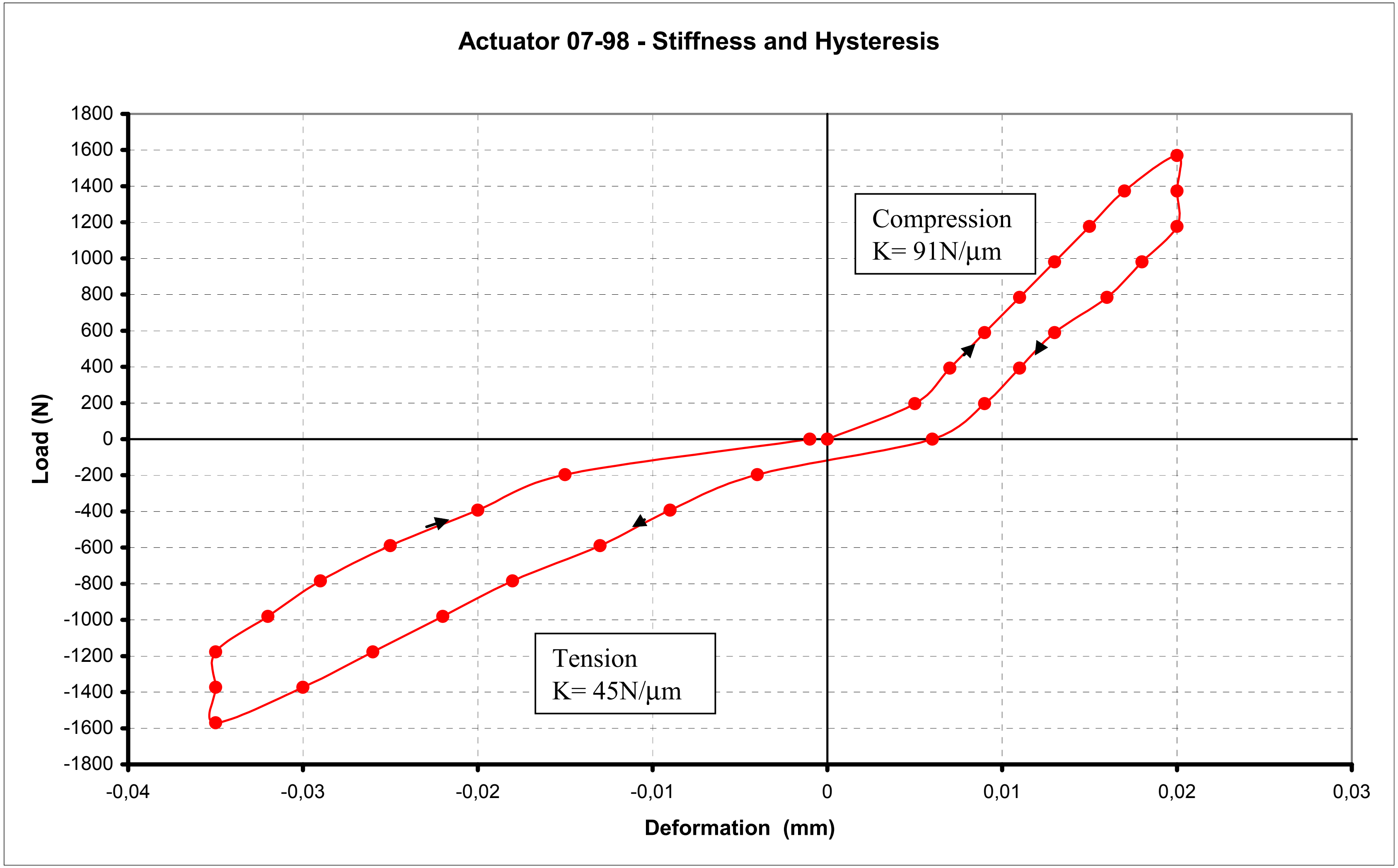

Actuator 07-98 - Stiffness and Hysteresis
Compression
K= 91N/µm
Tension
K= 45N/µm
Load (N)
Deformation (mm)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-0,04
-0,03
-0,02
-0,01
0
0,01
0,02
0,03

Fig. 4.2.8

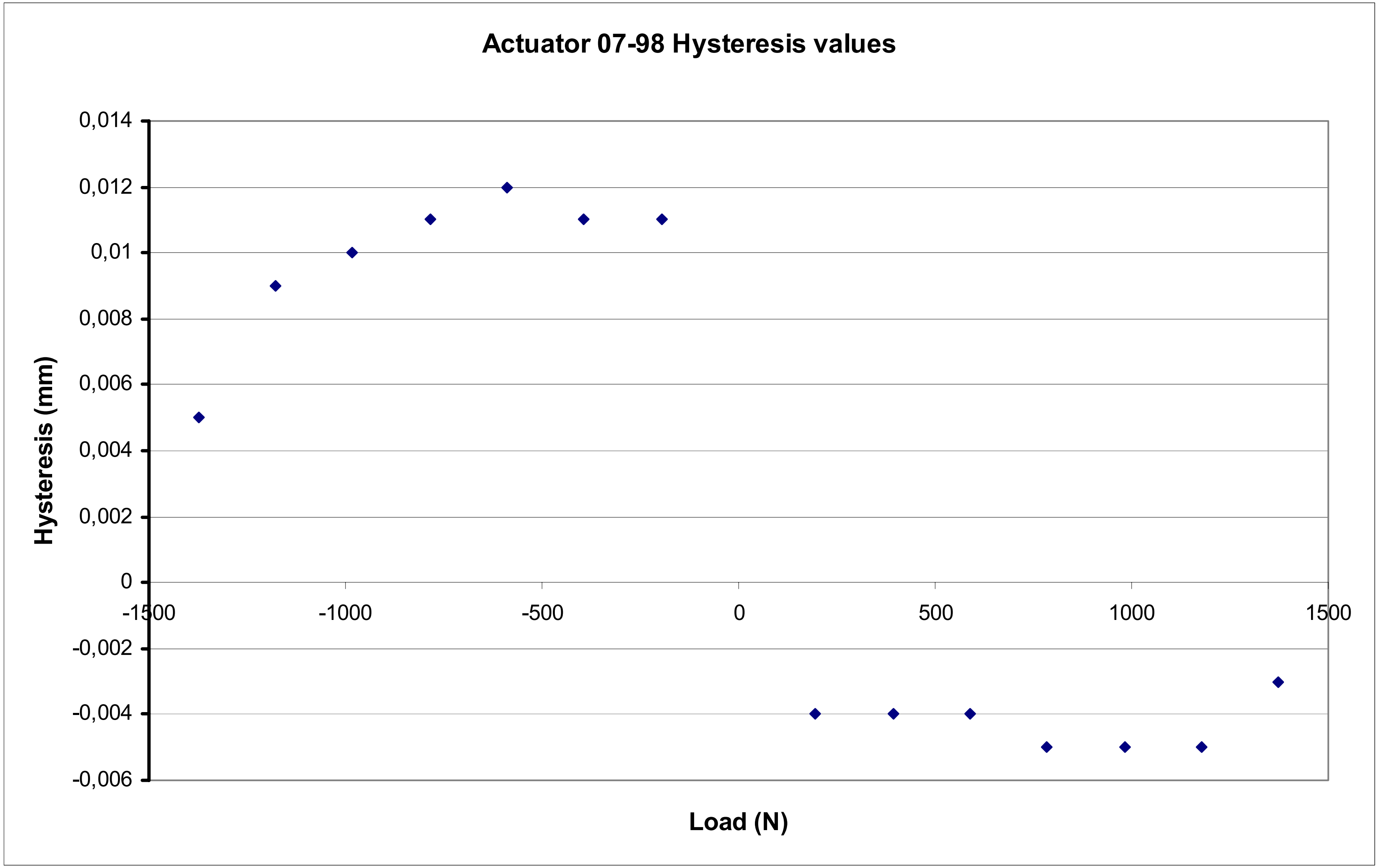
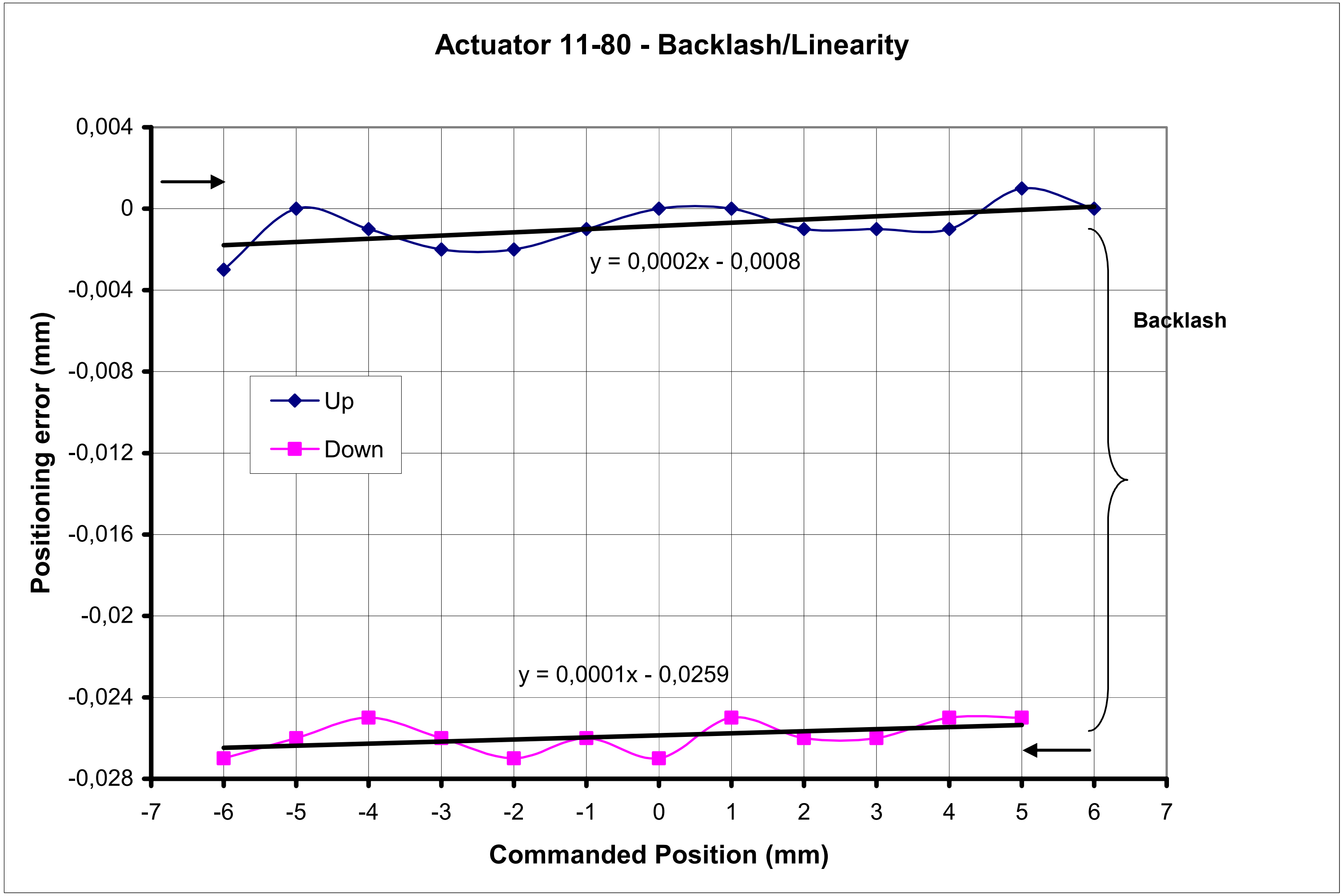

Actuator 07-98 Hysteresis values
Hysteresis (mm)
0,014
0,012
0,01
0,008
0,006
0,004
0,002
0
-0,002
-0,004
-0,006
-1500
-1000
-500
0
500
1000
1500
Load (N)

Fig. 4.2.9



Actuator 11-80 - Backlash/Linearity
0,004
0
-0,004
-0,008
-0,012
-0,016
-0,02
-0,024
-0,028
Positioning error (mm)
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Commanded Position (mm)
Up
Down
y = 0,0002x - 0,0008
y = 0,0001x - 0,0259
Backlash

Fig. 4.2.10

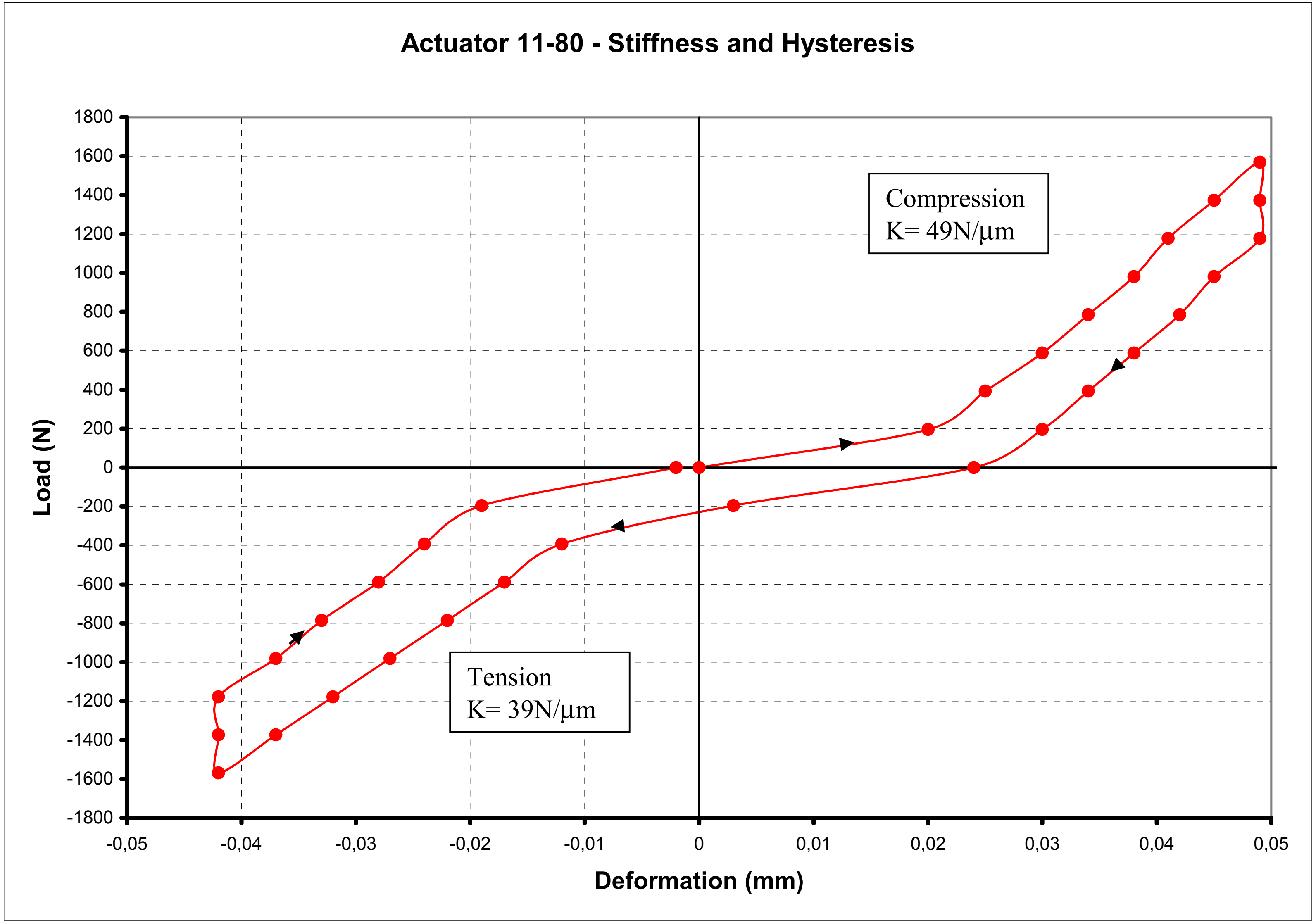

Actuator 11-80 - Stiffness and Hysteresis
Compression
K= 49N/µm
Tension
K= 39N/µm
Load (N)
Deformation (mm)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-0,05
-0,04
-0,03
-0,02
-0,01
0
0,01
0,02
0,03
0,04
0,05

Fig. 4.2.11

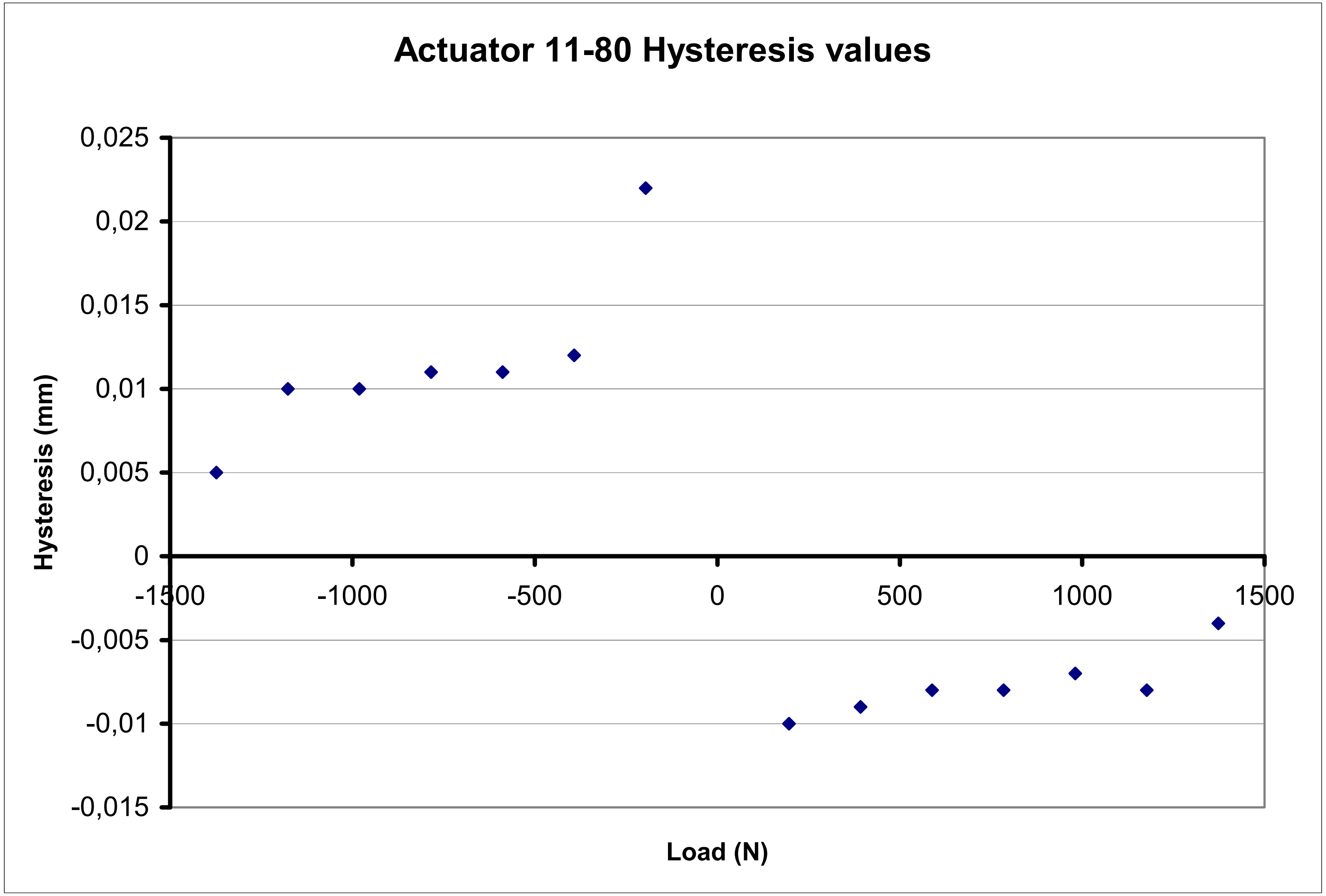

Actuator 11-80 Hysteresis values
0,025
0,02
0,015
0,01
0,005
0
-0,005
-0,01
-0,015
Hysteresis (mm)
-1500
-1000
-500
0
500
1000
1500
Load (N)

Fig. 4.2.12

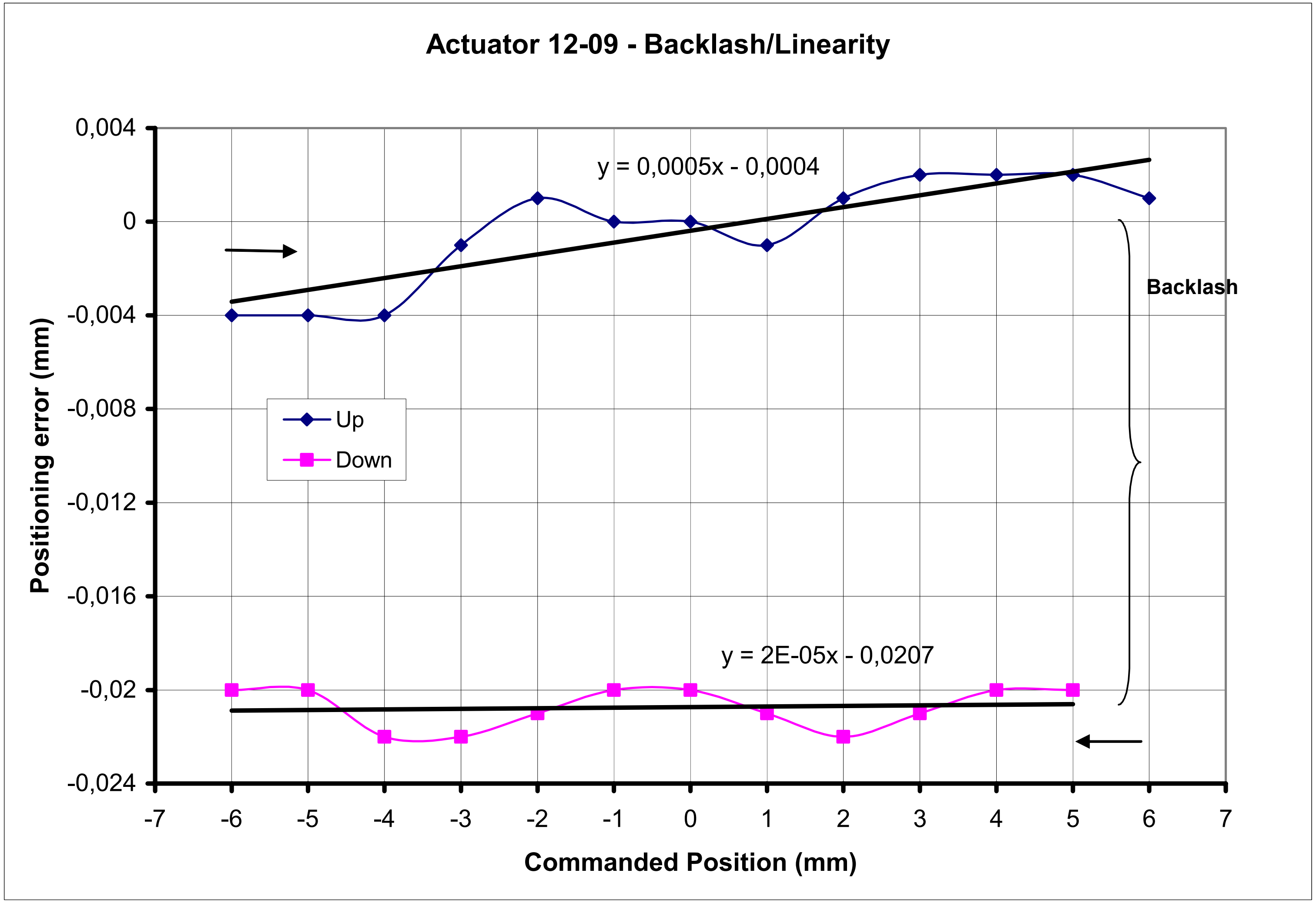

Actuator 12-09 - Backlash/Linearity
0,004
0
-0,004
-0,008
-0,012
-0,016
-0,02
-0,024
Positioning error (mm)
y = 0,0005x - 0,0004
Backlash
Up
Down
y = 2E-05x - 0,0207
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Commanded Position (mm)

Fig. 4.2.13

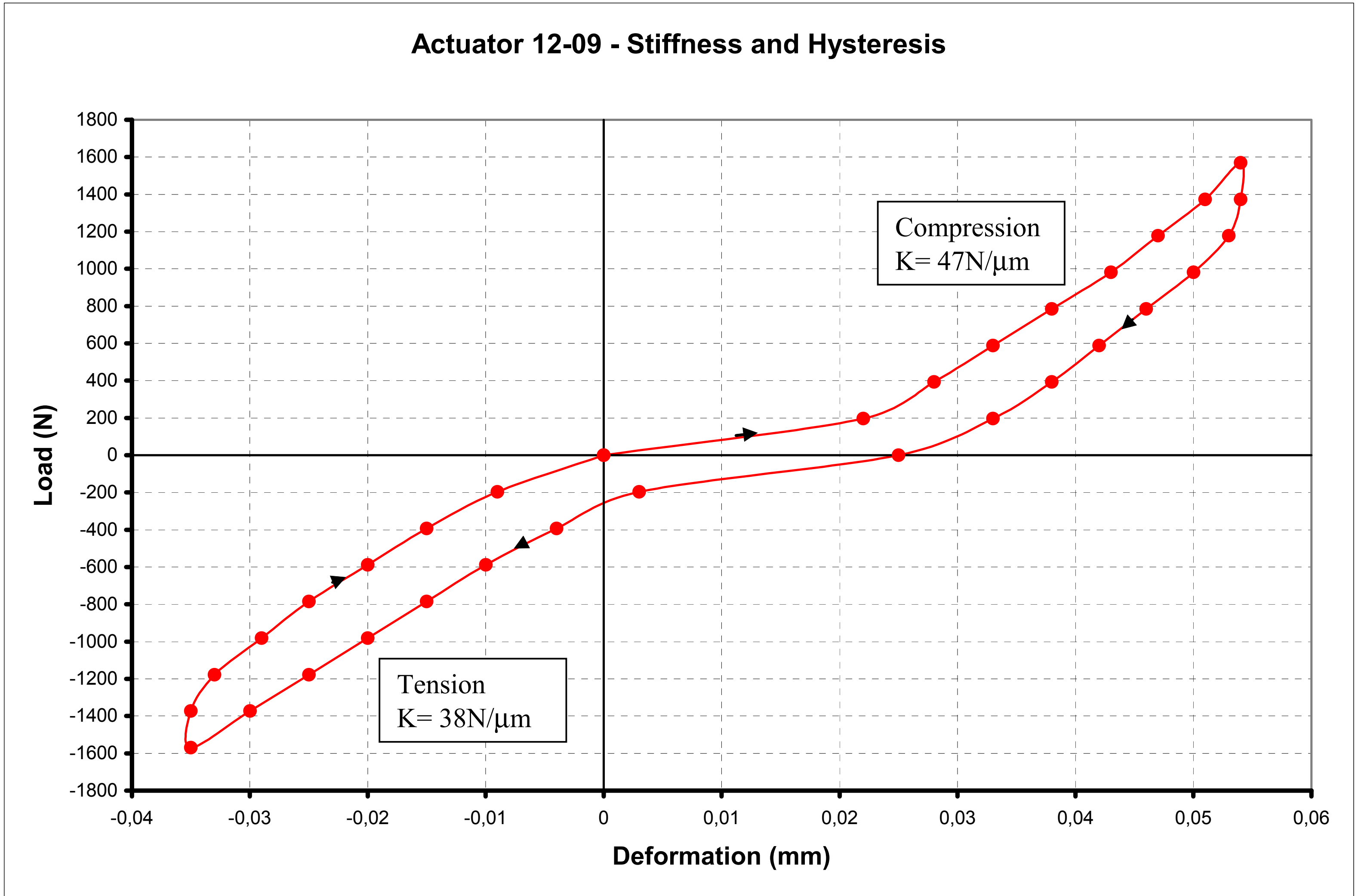

Actuator 12-09 - Stiffness and Hysteresis
Compression
K= 47N/µm
Tension
K= 38N/µm
Load (N)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-0,04
-0,03
-0,02
-0,01
0
0,01
0,02
0,03
0,04
0,05
0,06
Deformation (mm)

Fig. 4.2.14

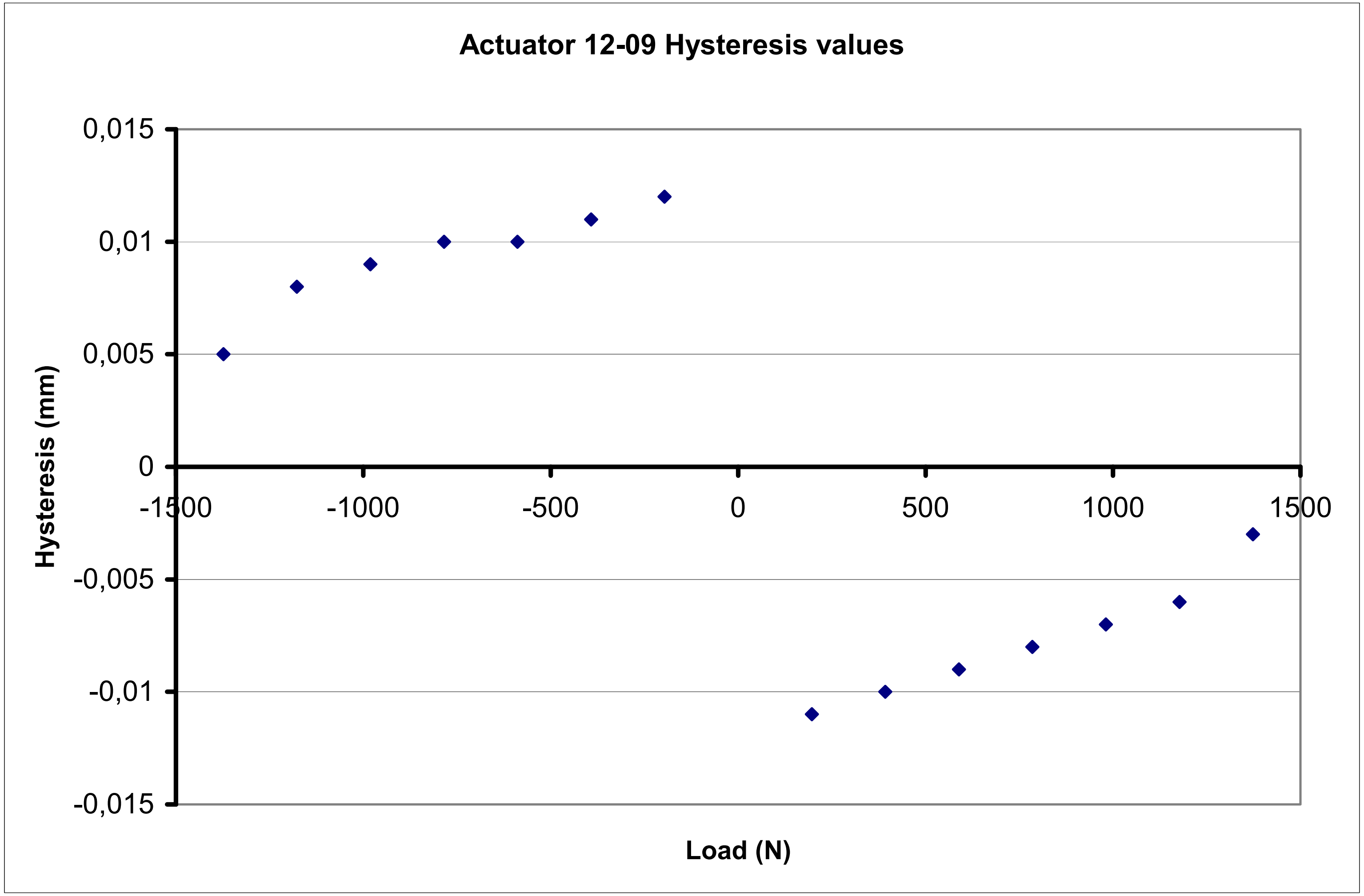

Actuator 12-09 Hysteresis values
0,015
0,01
0,005
0
-0,005
-0,01
-0,015
Hysteresis (mm)
-1500
-1000
-500
0
500
1000
1500
Load (N)

Fig. 4.2.15

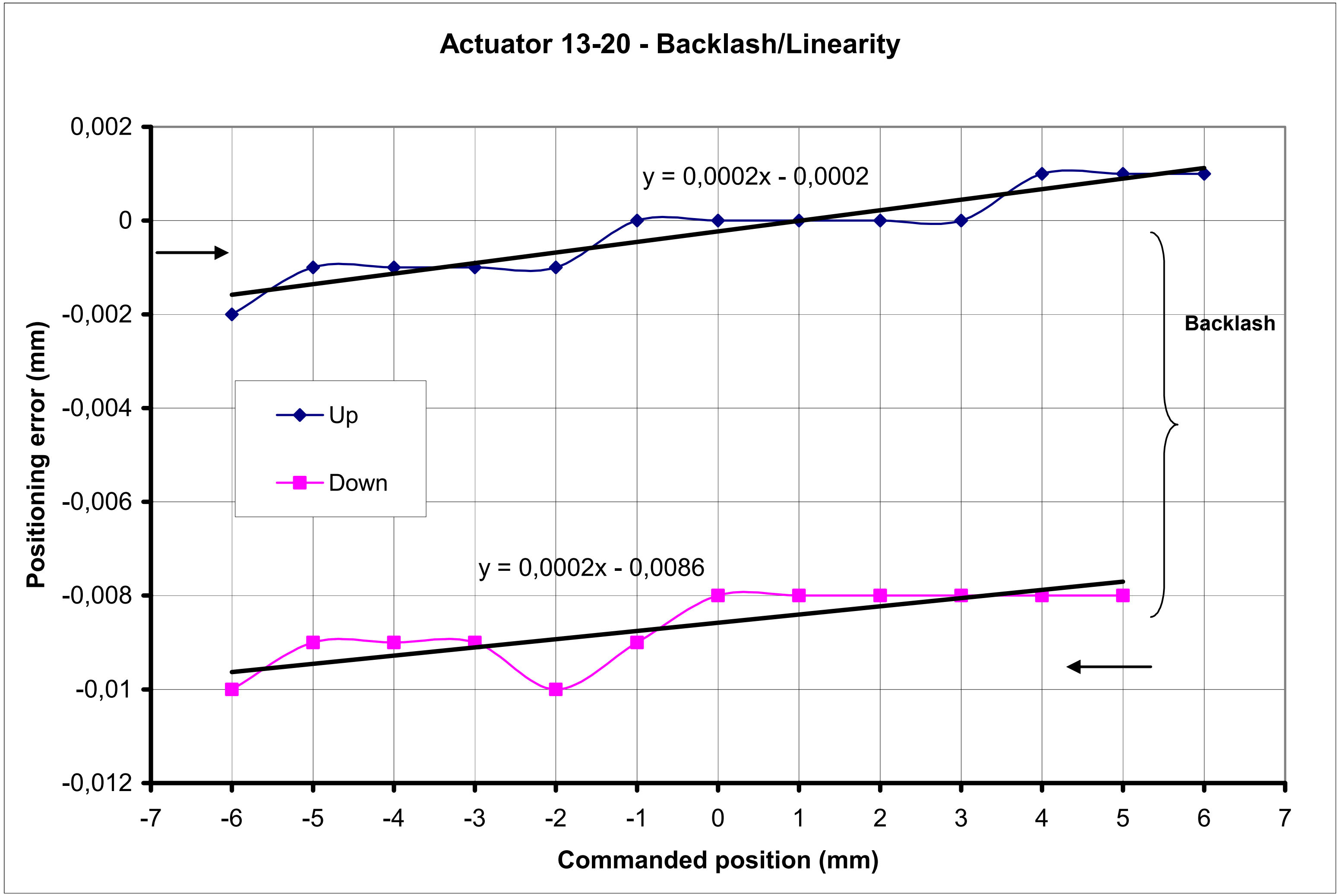
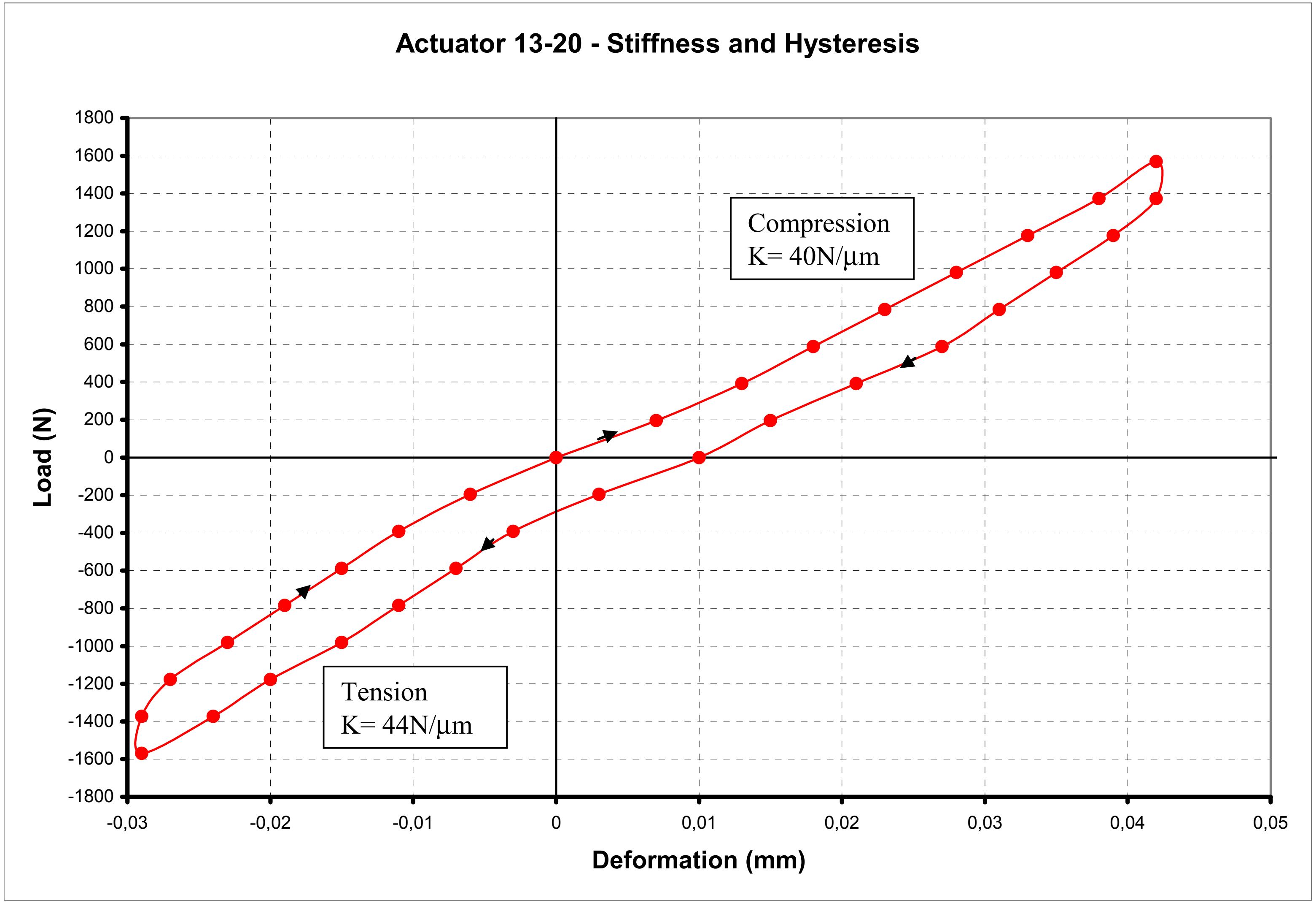

Actuator 13-20 - Backlash/Linearity
0,002
0
-0,002
-0,004
-0,006
-0,008
-0,01
-0,012
Positioning error (mm)
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Commanded position (mm)
y = 0,0002x - 0,0002
y = 0,0002x - 0,0086
Up
Down
Backlash

Fig. 4.2.16



Actuator 13-20 - Stiffness and Hysteresis
Compression
K= 40N/µm
Tension
K= 44N/µm
Load (N)
Deformation (mm)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-0,03
-0,02
-0,01
0
0,01
0,02
0,03
0,04
0,05

Fig. 4.2.17

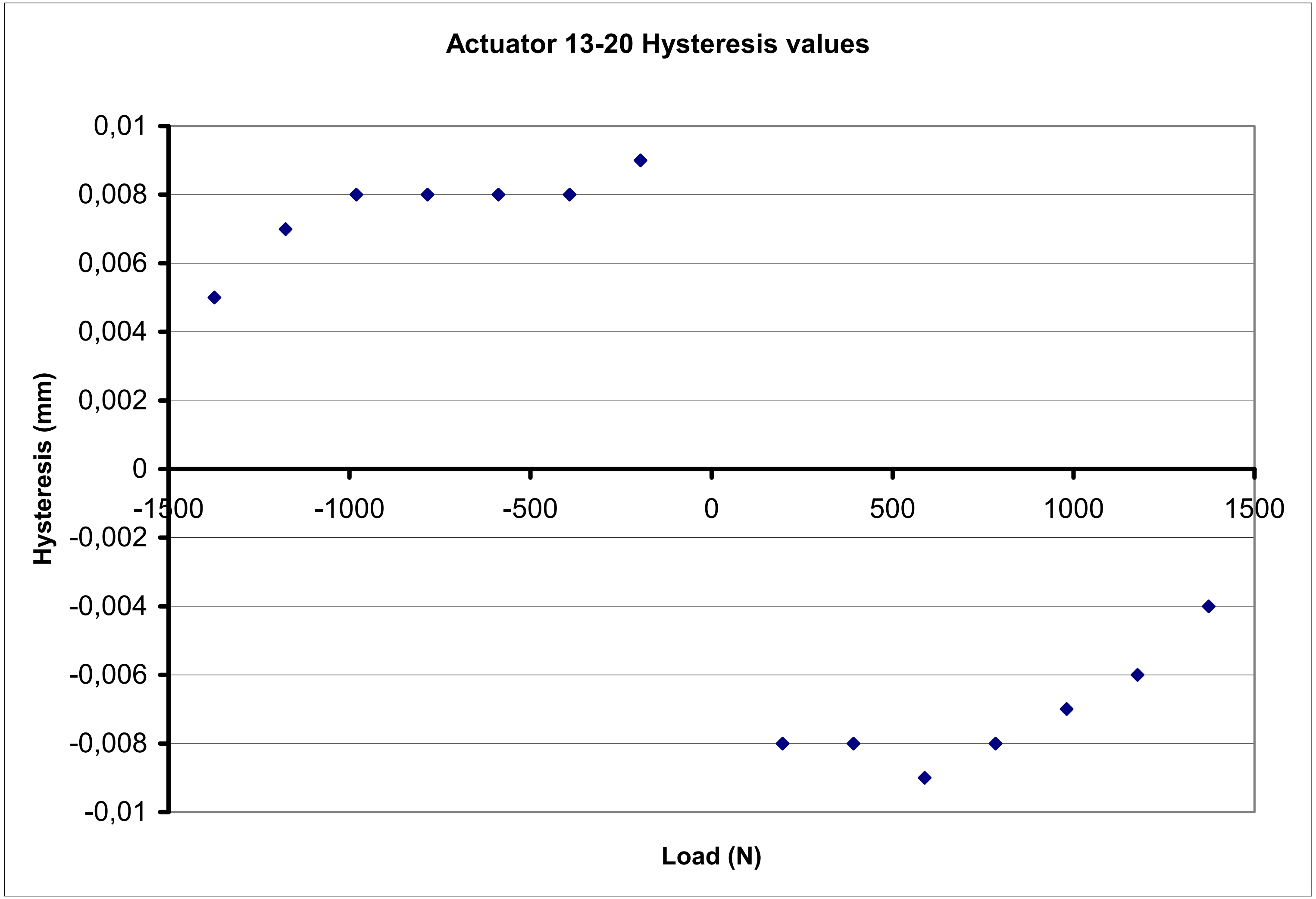

Actuator 13-20 Hysteresis values
Hysteresis (mm)
0,01
0,008
0,006
0,004
0,002
0
-0,002
-0,004
-0,006
-0,008
-0,01
-1500
-1000
-500
0
500
1000
1500
Load (N)

Fig. 4.2.18

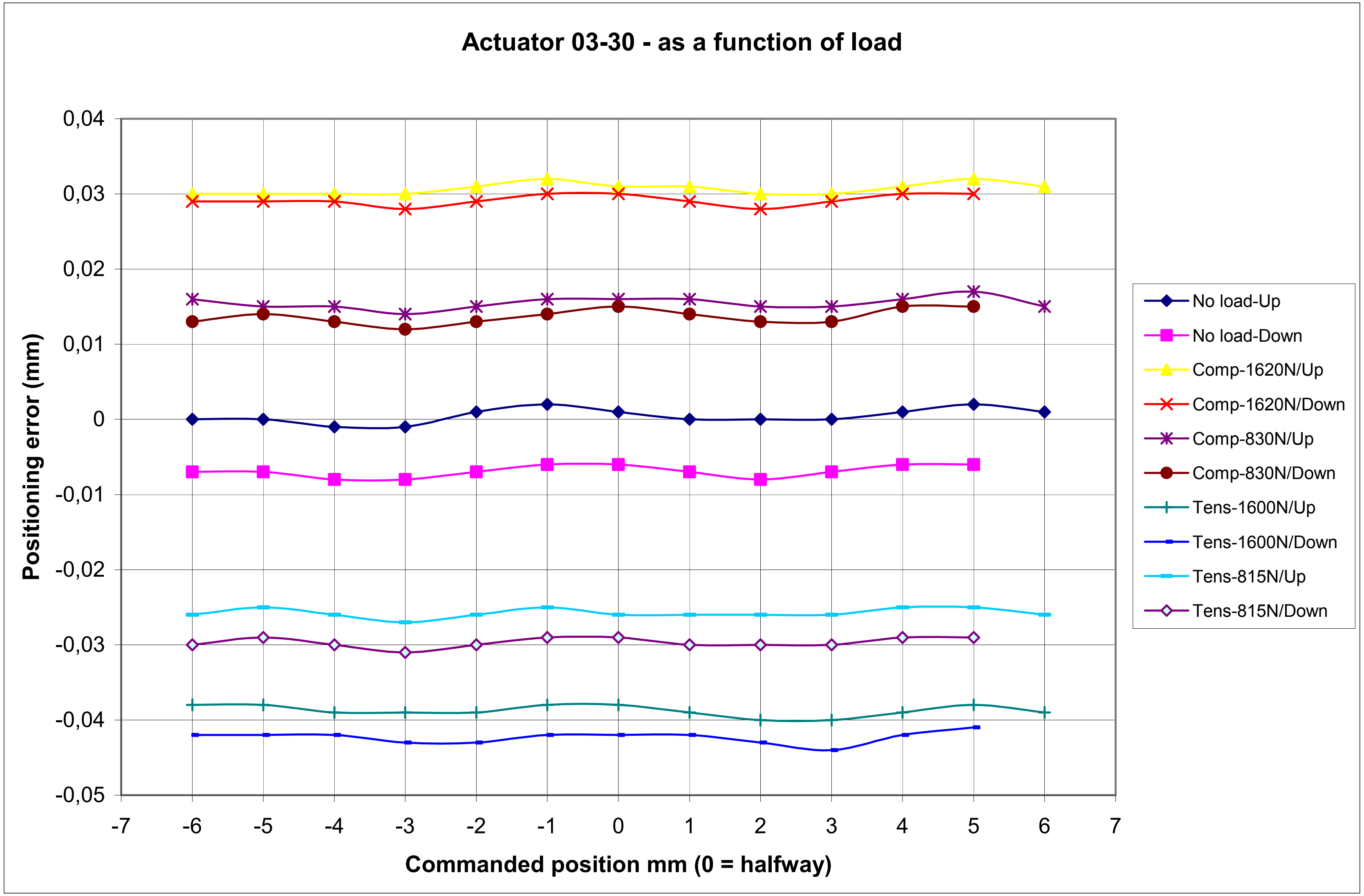

Actuator 03-30 - as a function of load
Positioning error (mm)
0,04
0,03
0,02
0,01
0
-0,01
-0,02
-0,03
-0,04
-0,05
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Commanded position mm (0 = halfway)
No load-Up
No load-Down
Comp-1620N/Up
Comp-1620N/Down
Comp-830N/Up
Comp-830N/Down
Tens-1600N/Up
Tens-1600N/Down
Tens-815N/Up
Tens-815N/Down

Fig. 4.2.19

5. CONCLUSIONS

On the basis of the tests reported in this memo and the previous ones typically devoted to get a knowledge on loads, speed and temperature range we can summarize the characteristics for the SRT version of the electromechanical actuator, in Table 5.1

Weight	**12 / 9.5 Kg** with / without panels interface
Dimension (W-D-H)	**185x280x330/294 (mm)** with / without panels interface
Stroke	**±15mm**
Axial Operating Load	**3000N**
Radial Operating Load	**1500N**
Axial Survival Load	**10000N**
Radial Survival Load	**7000N**
Axial Stiffness	**40-50N/μm**
Backlash	**15μm (11μm mean)**
Linearity	**≤ 0.5μm/mm**
Speed	**21.5mm/minute**
Power Supply	**115VAC**
Communication	**RS485 + LAN Gateway**
Power Consumption: -Operating (min/max) -Standby	 **16 / 23 VA** **4 VA**
Operating Temperature Range	**-10°C ÷ 60°C**
Protection Class	**IP 65**
EMC certification	**YES**
Lifetime	**20 years**

Tab. 5.1 Measured actuator characteristics

The *stroke* needed to compensate the gravity deformations is ±6mm, and the actuators have been characterised only in this interval, although we believe that the performances found can be extended to the full stroke of (±15mm).

The *axial operating load* and the *radial operating load* takes into account the largest panel (72kg weight and 5.3m^2 area) and 80 Km/h wind.

The *axial survival load* must be regarded as the maximum load we tested without any damage of the actuator, which corresponds to the load for wind speed of 160Km/h. For wind speed equal to 200Km/h (survival wind specification of the SRT antenna) the axial load rises to 16KN for a very small amount of actuators, about 2% of the total, and calculations show that these actuators should have a permanent damage.

The *radial survival load* must be regarded as the maximum load we tested without any damage at the actuator, which corresponds to the load for wind speed equal to 200Km/h (survival wind specification of the SRT antenna).

The <u>*backlash*</u> is the peak value shown by the 80% of the actuators measured. The average value from the measure made on 65% of the 1159 actuators produced is 11 microns. These two values, 11 and 15 microns, characterize the class of mechanics of this kind of actuator. We believe that with only small and no-cost variation in the construction and mounting procedure all actuators can show a backlash less than 15 microns. Requiring better than this figure is not achievable because the manufacturing tolerances should be such that a lot of actuators will have to be discarded in the assembling phase.

The <u>*stiffness*</u> range comes from a measured sample of actuators.

The <u>*linearity*</u> value is the worst case from a measured sample of actuators.

The <u>*temperature range*</u> specified is conservative with respect to the range tested, but it takes into account that the controller/driver is a 0 ÷ 70°C component.

As a final remark about possible extreme applications of this kind of actuator note that we could obtain a backlash *peak* value of 15 microns (worst case, may be better), a *peak to peak* value of 6 microns with regards the linearity (assuming a stroke of ±6mm, like usual in all kinds of large reflector antennas regardless the diameter) and a residual hysteresis *peak* value of about 10 micron. Besides, for antenna operating in precision environmental condition (i.e. wind speed ≤15Km/h), the actuator stiffness shouldn't affect the positioning accuracy because the actuator elastic deformation due to panels weight must be measured in the alignment phase of the primary mirror and it will be taken into account in the look-up table of the active surface system.

Now a question arises, which should be the overall accuracy of the best fit shaped contour when more than one thousand actuators, or some hundred in medium size antenna, move the panels. If the sources of errors above mentioned should be considered to follow a gaussian noise law they could be composed by root sum squaring the rms values of the different non-accuracy causes. This should result in about 5 micron RSS and should be largely compatible with an application also on a submillimeter antenna!

This is not the case in practice, see for example fig. 4.1.3 about backlash, but we have not made enough investigation in order to unveil the statistical properties of an active surface.

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