MERLAB, PC **David R. Smith, Ph.D., PE**
Mechanical Engineering Research Laboratory David_Smith@merlab.com
357 S. Candler St. (404)378-2138
Decatur, GA 30030-3746 FAX: (404)378-0822

TO: Alfonso Serrano, Pete Schloerb (LMTO)
Kamal Souccar (UMass)
FROM: David R. Smith, MERLAB
DATE: September 24, 2004
RE: Initial Actuator Test Results

1.0 Summary

In mid-March, we began a series of tests on the LMT/GTM surface segment prototype actuators. The purpose of the testing was to confirm the manufacturers' performance predictions and to obtain familiarity with operation of the actuators. Following the initial tests, on-going testing has continued to better understand these findings. These more recent data are beyond the scope of this report. Instead, this report is intended to provide a reference document for the later tests.

According to the initial tests, neither actuator meets the positioning specifications without additional compensation. However, both actuators show promise that they may be able to reach the required performance given additional characterization.

The Moog actuator had problems with the limit switch circuits, which caused the actuator to reverse direction unexpectedly. Additionally, there is an apparent initial transient that resulted in offset errors of as much as 75 μm. Once the initial behavior was complete, however, the actuator showed ripple of about 1 μm about the mean and an input side backlash or windup of about 7 μm. Except for the initial transient, these values are acceptable and can likely be improved. Initial stiffness measurements showed some variation between positive and negative loading directions and even some variability between tests. This should be verified in additional testing.

The ADS actuator functioned very reliably, and did not show the same initial transient response problem as the Moog unit. However, it did not meet the same level of accuracy reached by the Moog actuator. The error ripple was repeatable within tests, but varied from about 9 μm about the mean in initial tests to 3 μm about the mean in later tests. The input side backlash and windup is of order 20–30 μm. Some initial attempts were made to compensate for this in software, but there were problems with the lookup table generation routine, so this approach has not yet been successful. Additional tests

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using lookup tables will be necessary for this actuator to meet the specifications. Initial stiffness measurements for the ADS actuator were baffling. In addition to having poor repeatability, the qualitative behavior did not match what would be expected for this type of mechanical design. Whether this is due to the loading mechanism, a mounting issue, or some feature internal to the actuator is unknown. Additional testing will be required in order to characterize this.

2.0 Introduction

The LMT/GTM design relies on an active surface system on the primary reflector to make open loop corrections for gravitational and thermal deformations. To implement this active surface, an actuator is needed that can meet a wide variety of specifications. While there are requirements concerning environment, weight, size, and mounting geometry, some of the most difficult specifications are the performance specifications. These are summarized in Table 1.

To obtain better cost information on such an actuator, the LMT/GTM US Project Office funded the construction of two prototype actuators. One from Moog, Inc., in California, and the other from ADS in Italy. Additionally, the project procured an actuator testbed from ADS and instrumented it with a load cell and linear position sensors. In March of 2004, the initial tests were performed on the prototype actuators to determine if they could meet the positioning requirements. The initial testing included position accuracy measurements for triangular motion patterns (full cycle extension and retraction). The motion tests were conducted unloaded, as well as under normal operation loads (250 kg) and degraded operation loads (400 kg). Some stiffness tests in the positive and negative directions were also conducted. Survival testing was not performed in this initial set of experiments because it is necessary to develop a database of performance data so the performance after a survival event can be compared with it later.

Table 1: Summary of Actuator Specifications

Specification	**Value**
Normal Operation	
Load	± 2.5 kN
Stroke	± 5 mm
Motion increment	≤ 2.5 μm
Position error	± 5 μm
Speed	≥ 0.03 mm/s
Profile	Min steps of 40 μm, 5000 steps/yr
Lifetime travel	<1 km
Degraded Operation	
Load	± 4.0 kN
Stroke	± 5 mm
Motion increment	≤ 2.5 μm
Position error	Degraded
Speed	≥ 0.03 mm/s
Drive to Stow	
Load	± 4.0 kN
Stroke	± 5 mm
Motion increment	Degraded
Position error	± 0.25 mm
Speed	≥ 0.03 mm/s
Profile	Max step of 10 mm, 5 steps/yr
Survival	
Load	± 16.0 kN, at static, locked position
Load	± 2.5 kN static, ± 11.0 kN pulsating
General	
Backlash at rod	Zero
Position lock	Self-locking
Position sensor	Internal, absolute or incremental with a home position
Range limiter	Mechanical at both ends of stroke
Mass	≤ 9 kg

3.0 Testing Information

3.1 Test Equipment

Table 2: Test Equipment

ADS Prototype Actuator
Moog Prototype Actuator
Actuator Test Bench
Load Cell
- Manufacturer: HBM
- Model: S9
- Capacity: 10 kN
- Serial #: 411759a
- Calibration Factor: 102 kgf/V

Linear sensors
- Manufacturer: Heidenhain
- Model: MT2581
- Serial #'s: 12682576D, 12682577D

LMT/GTM Monitor and Control general-purpose A/D system

3.2 Tests Conducted

During the initial evaluation, a series of tests were conducted using both the Moog and ADS actuators.

3.2.1 Tests with the Moog Actuator

The Moog actuator tests are summarized in Table 3. In addition to tests in which the actuator was cycled back and forth under different loading conditions, the tests also include stiffness tests to determine the effects of changing load on the actuator position.

3.2.2 Tests with the ADS Actuator

The ADS actuator tests are summarized in Table 4. As with the Moog tests, the data include tests in which the actuator was cycled back and forth under different loading conditions as well as stiffness tests.

Table 3: Moog Actuator Tests

Filename	Date	Time	Comments
MOOG.txt	2004-03-15	13:24	Unloaded, 10 mm and return
MOOG2.txt	2004-03-15	16:11	Unloaded, 10 mm one way
MOOG3.txt	2004-03-15	17:39	Unloaded, 10 mm cycle, limit switch problems
MOOG4.txt	2004-03-16	09:16	Unloaded, 10 mm cycle, 9 cycles, limit switch problems
MOOG5.txt	2004-03-16	11:48	Unloaded, one 10 mm cycle
MOOG6.txt	2004-03-16	12:11	Operational load (250 kg) from right (−direction), towards retraction, typ current 0.91 A, 1 cycle, limit switch issues
MOOG7.txt	2004-03-16	12:42	Degraded load (400 kg) −, typ current 0.91 A, one cycle, limit switch issues
MOOG8.txt	2004-03-16	13:09	Stiffness test at home position. Note: different file format – B
MOOG9.txt	2004-03-17	13:25	Unloaded test during lunch, 5 full cycles, using position reading. Another new table format – C
MOOG10.txt	2004-03-17	13:25	Stiffness check, +, various weights, 5 mm position, another table format to add TruePos – D
MOOG11.txt	2004-03-17	15:04	Stiffness check, +, DRS applied loads, increase and decrease, 5 mm position, D
MOOG12.txt	2004-03-17	15:11	Stiffness check, +, DRS applied loads, increase and decrease, 0 mm position, D
MOOG13.txt	2004-03-17	15:20	Up/down, operational load, 2 large weights, one of next size Original table format – A
MOOG14.txt	2004-03-17	16:22	Up/down and chatter, degraded load, all weights. A

Table 4: **ADS Actuator Tests**

Filename	Date	Time	Comments
ADS.txt	2004-03-15	09:32	Unloaded, 10 mm and return, many cycles, original file format
ADS2.txt	2004-03-15	11:19	Unloaded, 10 mm one cycle,
ADS3.txt	2004-03-17	17:17	Stiffness test @0 mm, +, MOOG10 file format
ADS4.txt	2004-03-17	17:22	Stiffness test @5 mm, +
ADS5.txt	2004-03-17	17:34	Stiffness test @0 mm, +? TruePos column corrected to be the sum of actual and reference
ADS6.txt	2004-03-17	17:40	Same as ADS5, up to 200 kgf, Belleville springs don't open
ADS7.txt	2004-03-18	10:13	Unloaded, 2 cycles of up/down to generate lookup table. New lookup table (LUT) consistent with original file format
ADS8.txt	2004-03-18	10:41	Repeat ADS7 based on LUT
ADS9.txt	2004-03-18	11:10	Operational load +, w/ LUT from ADS8, one cycle
ADS10.txt	2004-03-18	12:19	Operational load +, no LUT, home off by 5 μm, 2 cycles
ADS11.txt	2004-03-18	12:47	Degraded load +, no LUT, home off by 56 μm, 3 cycles
ADS12.txt	2004-03-18	13:29	Degraded load +, LUT from ADS7, Peak current 1.6 A, 1 cycle, Note: ADS8 and ADS9 have bad LUT
ADS13.txt	2004-03-18	14:08	Operational load +, no LUT, 7 cycles
ADS14.txt	2004-03-18	16:21	Operational load +, LUT from ADS13
ADS15.txt	2004-03-18	16:43	Operational load +, LUT from ADS13, 1 cycle
ADS16.txt	2004-03-18	17:10	Same as ADS15
ADS17.txt	2004-03-18	17:44	Same as ADS16

4.0 Calculations

In reducing the raw data, there are several calculations that must be performed to obtain meaningful results. These include determination of the true position of the actuator, calculation of the actuator step size, accounting for force variations, and combining these results to obtain a measure of commanded versus actual performance.

4.1 Calculating True Position

There are two linear encoders on the test setup. One measures the position of the actuator rod with respect to the test bench. The other measures the position of the actuator mounting flange with respect to the test bench. The encoders are in opposite directions, so the true position x_{true} is related to the two sensor readings by the equation:

$$x_{\text{true}} = x_{\text{actuator}} + x_{\text{reference}}. \tag{1}$$

It is worth noting that the mounting flange is very stiff, so the value of $x_{\text{reference}}$ is generally very small.

4.2 Step Size Calculation

Generally, the step size is calculated as the average of the absolute value of all of the step sizes in the sample. That is,

$$\Delta x =< |x_{i+1} - x_i| > . \tag{2}$$

However, during reversal of direction, the backlash in the system is sometimes such that the system appears to take a partial step followed by a double step. To keep isolated events from affecting the estimate of the overall step size, outliers are removed before calculating the average. The step size is then given by

$$\delta = \frac{\Delta x}{n}, \tag{3}$$

where n is the number of motor encoder counts commanded. The result gives the step size of the motor in μm traveled versus motor encoder steps commanded.

4.3 Calculating Commanded vs Actual Position

Once the step size has been calculated, the commanded position is given by the equation

$$x_{\text{commanded}} = n\delta, \tag{4}$$

where δ and n are as defined in section 4.1. This commanded position can then be subtracted from the actual position as measured by the sensors in order to investigate the error behavior of the actuator.

4.4 Force Effects

As shown in the stiffness tests, changing the static load on the system changes the measurement of the true position. This is due to the stiffness of the actuator and the stiffness of the mounting flange on the test bench. The gear reducer used on the test bench generates a force characteristic that varies with the direction of actuator motion. Since the loads in the field will vary and will not be measurable, it is necessary to consider the performance of the actuator without removing the force variation effects. However, from the testing point of view, it is useful to understand the magnitude of such effects. While the force characteristic is not linear, it is approximated as a linear relation. That is,

$$\Delta x_{\text{force}} = \frac{k_{\text{eff}}}{F}. \tag{5}$$

From the stiffness test data, an approximate k_{eff} is determined by a linear least-squares fit.

5.0 Conclusions and Recommendations

The tests on both actuators have revealed that there are still open issues with each of the designs. However, both demonstrated high repeatability within a given test, and both demonstrated a very stable average step size over all tests. This suggests that with proper characterization, both may still meet the performance specifications.

For the Moog actuator, the two most important shortcomings were the problem with the limit switches and the initial errors in the first cycle of the actuator. The limit switch problem can be addressed by insisting on non-contact limit switches. Further tests will be necessary to understand the source of the initial transient error. An additional area of interest for the Moog actuator is the stiffness behavior. The initial tests suggest high stiffness, but perhaps not to the level required by the specification, at least in one loading direction. This also warrants further testing.

For the ADS actuator, the large ripple and input side backlash/windup are the two most important issues. If these cannot be addressed with a lookup table, the actuator cannot meet the position specifications. However, the stiffness behavior of this actuator is still not well understood. The initial tests reveal a slope opposite what was expected for small loads, and a hysteresis-like behavior for large loads. Additional tests should be made with this actuator to determine the source of this effect.

Appendix A: Test Results

For future reference, each of the tests conducted is summarized here, along with relevant plots.

A.1 Moog Actuator

A.1.1 Filename: MOOG, One Cycle

This initial test is unloaded, so there are no force effects to be taken out. Investigation of the force plot confirms that the peak force is less than 6 lbf. However, there is an unusual behavior to this test, shown in Figure 1. On the outbound stroke, there is a steady increase in error between the commanded position and the actual position. Such behavior would normally correspond to an incorrectly-calculated step size. However, after reversal, the behavior is essentially flat. This could be explained by a different step size in each direction. However, after another reversal the actuator begins to move in the initial direction again without following the original trend. While there is not a complete second cycle, this suggests that the initial motion command removed some initial transient of 75 μm. There is not sufficient data from this test alone to show whether this was a sensor effect or some real effect in the actuator. The average step size was 125.4 μm for an average commanded motor step of 5000 counts. This corresponds to 25.08 nm/motor-step.

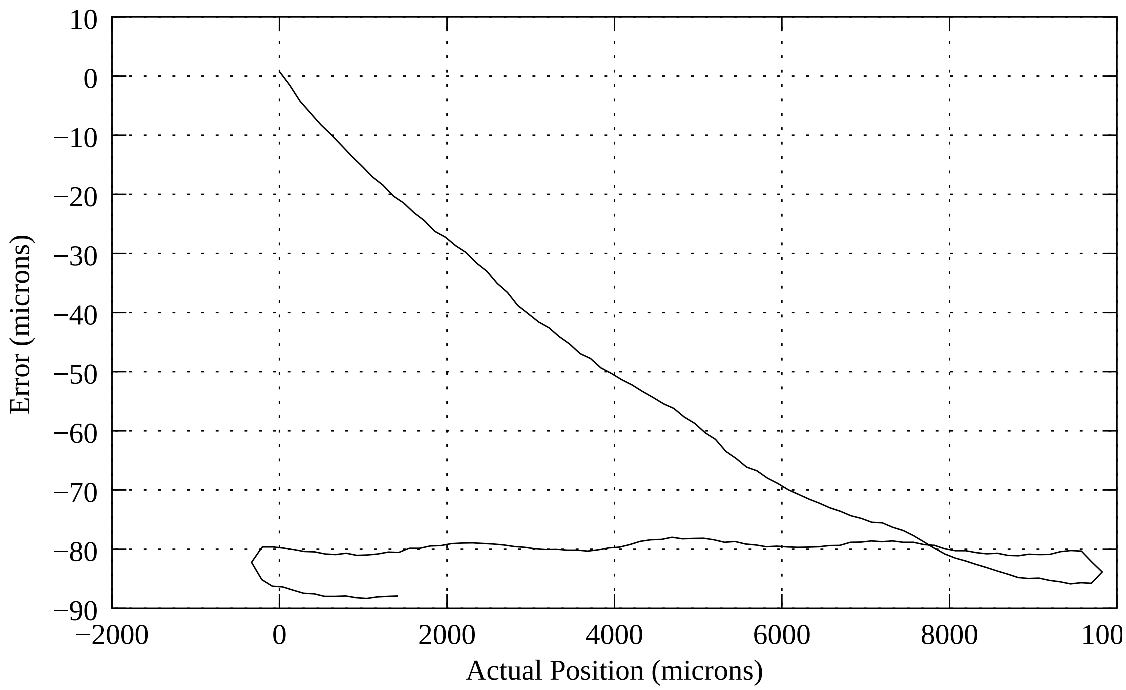

Figure 1: Error vs Actual Position for MOOG

A.1.2 Filename: MOOG2, Small Steps

In the second MOOG test, small steps were taken in order to confirm the ability of the actuator to make the required 2.5 μm steps. The motion range began at 0 and proceeded unidirectionally to 10 mm. The results are shown in Figure 2. In this test, the actuator shows outstanding behavior. The error is generally of order 1 μm, which is well within the specifications. The ripples as the actuator moves from 0 to 10 mm are most likely screw thread variations, as they repeat in form. Upon reaching the maximum commanded position, near 10 mm, the actuator reverses. The load on the actuator during the reversal is constant, because it is in an unloaded condition. Thus, the reversal reveals input backlash, or, equivalently, input-side windup in the system of about 7 μm. The average step size was 2.5138 μm for an average commanded motor step of 100.19 counts. This corresponds to 25.09 nm/motor-step.

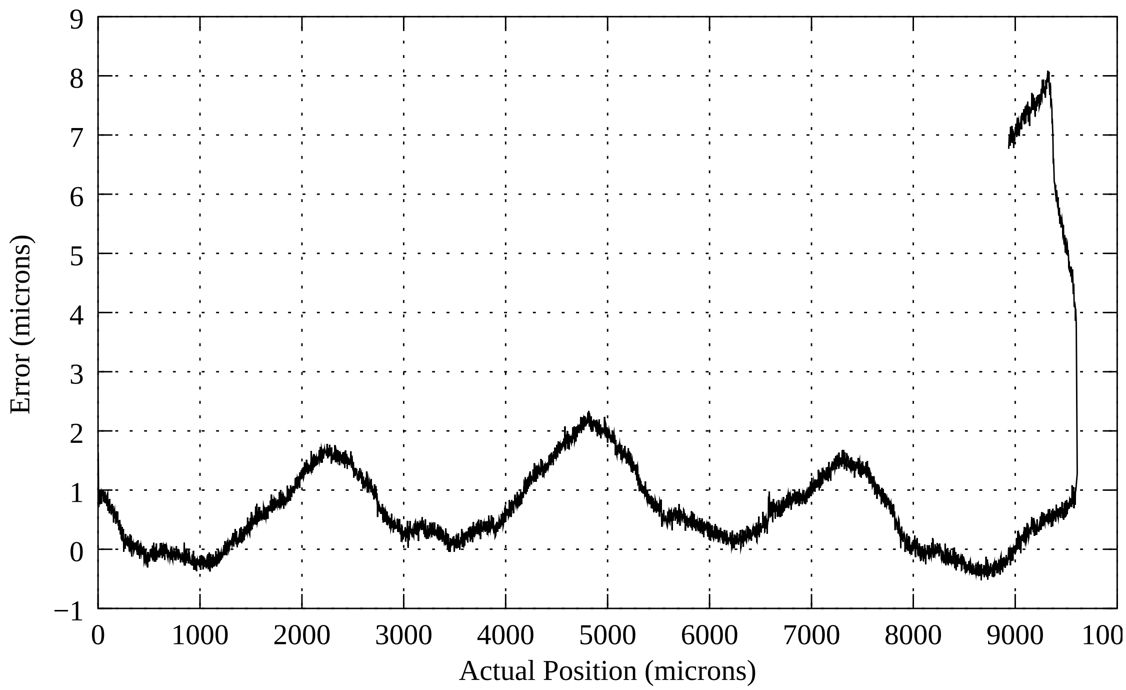

Figure 2: Error vs Actual Position for MOOG2

A.1.3 Filename: MOOG3

This test was intended to have the actuator move, unloaded, in multiple cycles by driving to the limit, then reversing. However, as shown in Figure 3, the actual motion profile was quite different. The actuator did the first cycle as commanded, but thereafter reversed direction almost at random. The source of the reversals appeared to be unexpected triggering of the contact limit switches.

The error versus the commanded position is shown in Figure 4. Like the MOOG2 test result, there is a small, distinct ripple with an amplitude of about 1 μm about the mean. When the actuator reverses, there is about 7 μm of input-side backlash. It then returns, again following the screw thread ripple of about 1 μm amplitude. The smaller loops at the left side of the plot correspond to the short stroke random reversals that occurred due to the limit switch problems. The average step size was 62.64 μm for an average commanded motor step of 2497.4 counts. This corresponds to 25.08 nm/motor-step.

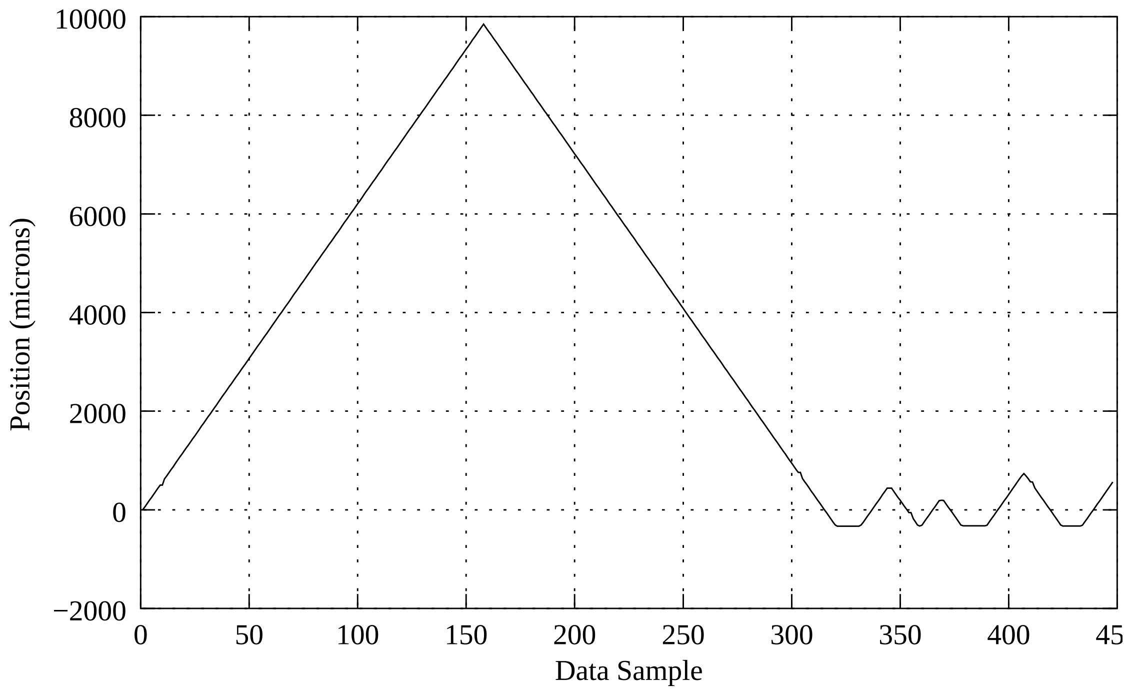

Figure 3: Actual Position vs Time, MOOG3

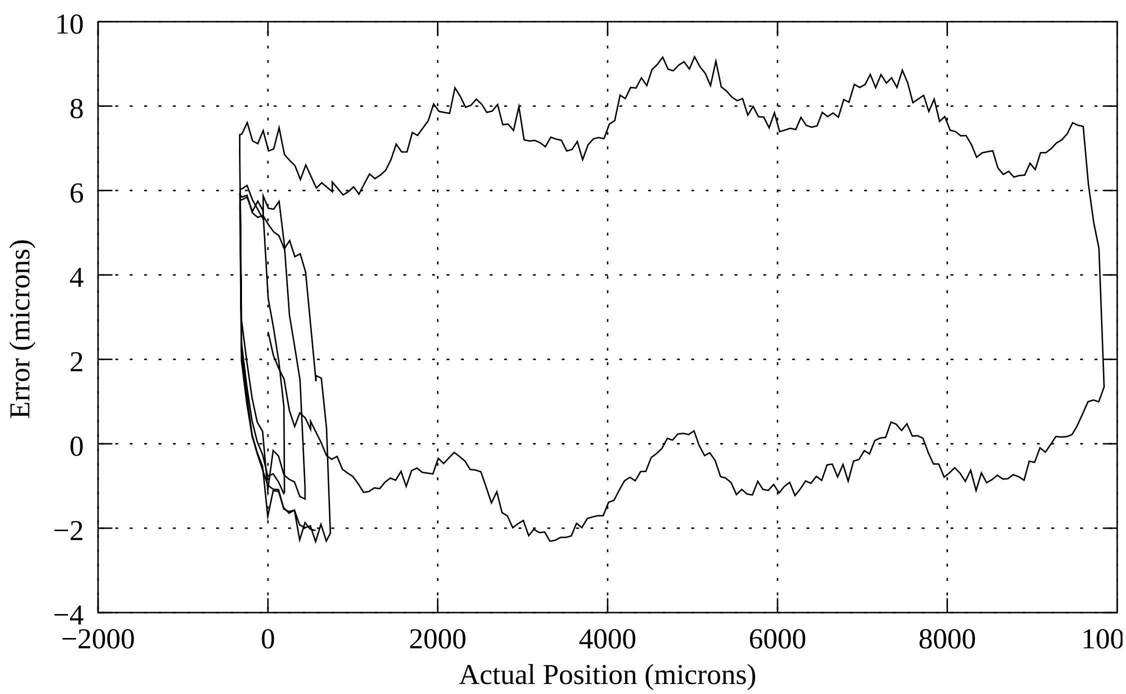

Figure 4: Error vs Actual Position, MOOG3

A.1.4 Filename: MOOG4

The purpose of this test was to repeat the attempt to obtain many full cycles of the actuator in its unloaded condition. The actual motion profile obtained is shown in Figure 5. While reasonably long strokes were maintained, only two full strokes resulted from the command sequence. The source of the problem was the unexpected triggering of the limit switches.

The error versus the commanded position is shown in Figure 6. Like the MOOG test result, the entire first outward stroke has a substantially different step size than the rest of the cycles, resulting in an offset of about 80 μm. Following that initial transient, the familiar pattern emerges of a 1 μm screw thread ripple and 7 μm input backlash. It is worth noting that some of the shorter cycles do not quite repeat, but the variation is smaller than the screw thread ripple. There is also a single point spike in the data. It is not known whether this was stiction at the actuator or a glitch in the data acquisition system. The average step size was 62.73 μm for an average commanded motor step of 2500.7 counts. This corresponds to 25.08 nm/motor-step.

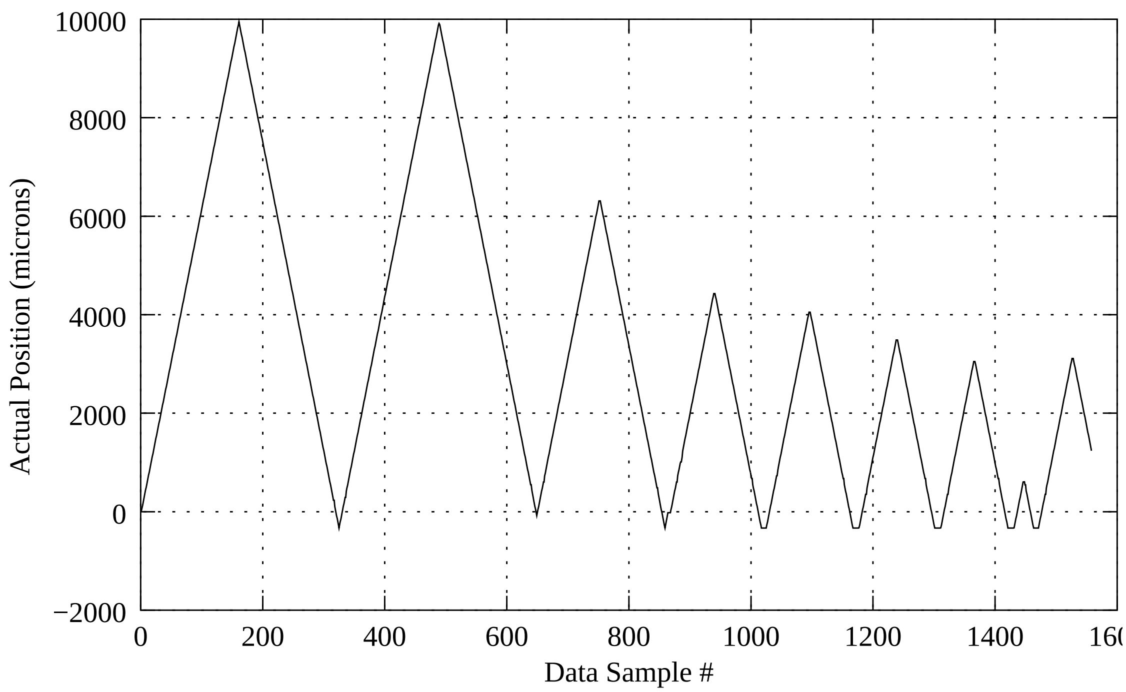

Figure 5: Actual Position vs Time, MOOG4

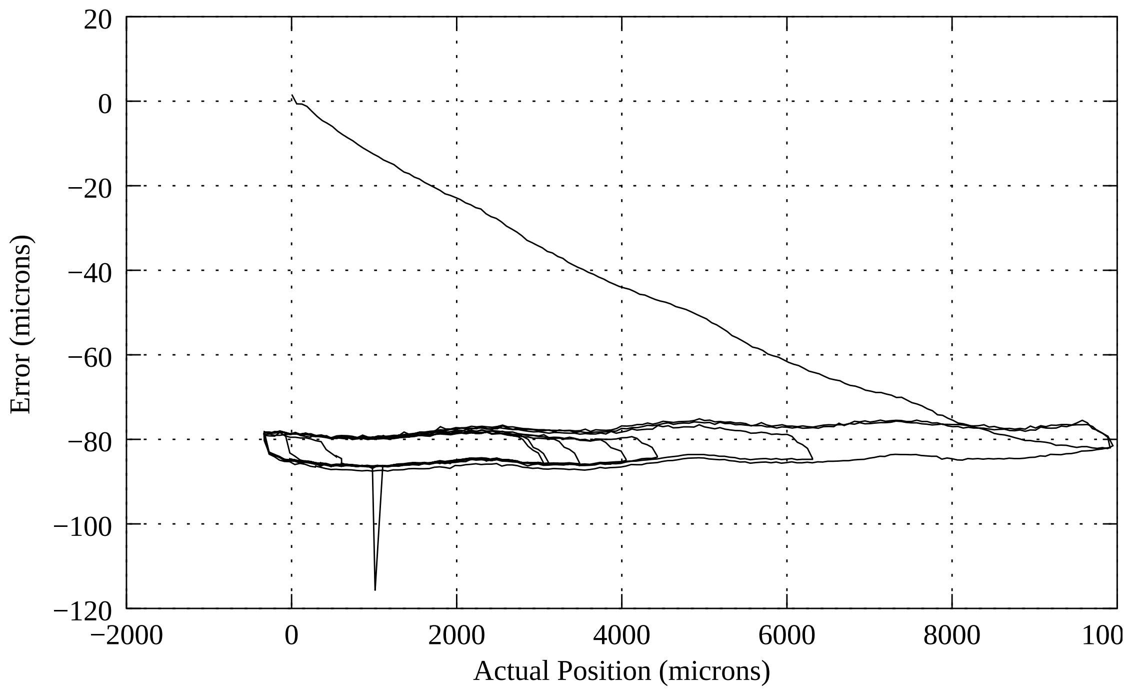

Figure 6: Error vs Actual Position, MOOG4

A.1.5 Filename: MOOG5

In an attempt to understand the limit switch issue and the initial transient, another unloaded test was repeated for one cycle. The error versus the commanded position is shown in Figure 7. Like the previous (MOOG4) test result, there is apparently a different step size on the outbound cycle. However, in this case, it results in only a 15 μm error over the entire stroke. The behavior thereafter is as seen in previous tests. The average step size was 62.57 μm for an average commanded motor step of 2494.7 counts. This corresponds to 25.08 nm/motor-step.

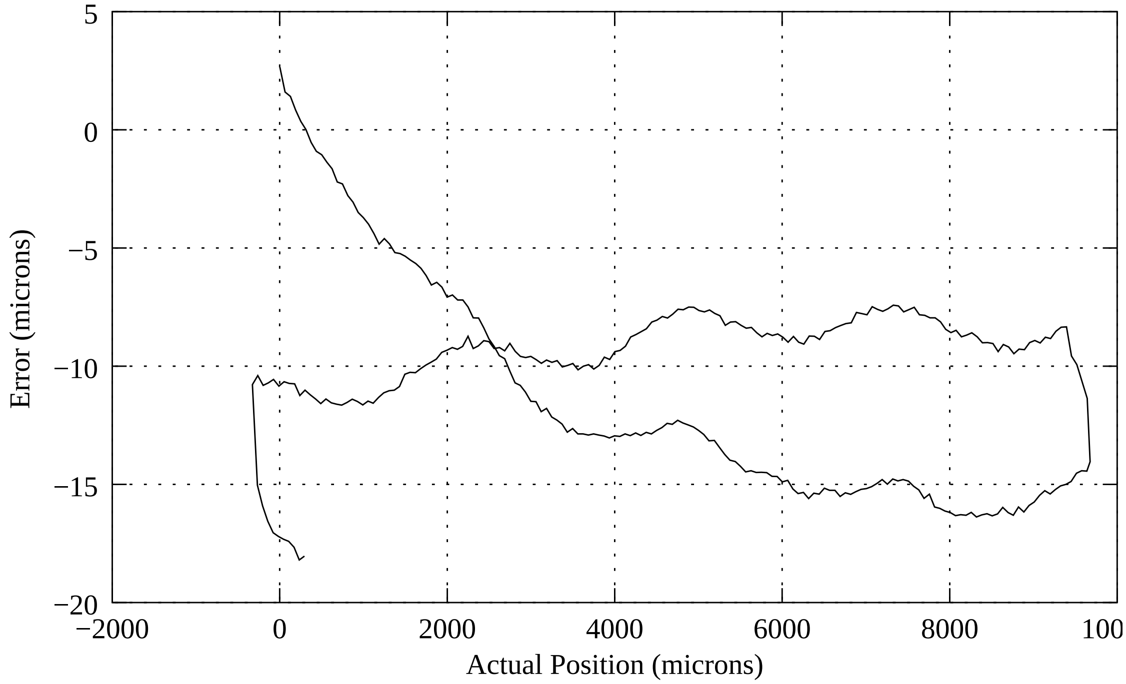

Figure 7: Error vs Actual Position, MOOG5

A.1.6 Filename: MOOG6

The MOOG6 test was the first test under load. An operational (250 kg) load was applied so that it acted in the − direction. That is, the external force was trying to force the actuator to retract. This was a one cycle test, followed by the usual issues with the limit switches. It is worth noting that the typical motor current was monitored for this test, and was found to be 0.91 A.

The error versus the commanded position is shown in Figure 8. The results differ from the previous ones in that the normal pattern has been changed. The outbound cycle shows the screw thread ripple, followed by the input backlash at the reversal. However, the return stroke shows a slightly different effective step size, resulting in an error increase of 8 μm over the stroke. This is presumably due to the external force, and may be due to a slight change in the thread pitch under load. It is important to note that the choice of slope is somewhat arbitrary. One could just as easily choose the typical step size so that the return would appear flat and the extension would be at a slight angle. The relevant feature is the change in slope versus direction. It is also interesting that the input backlash has changed. When the load reverses from opposing the load to going with the load, the apparent input backlash is about 10 μm. When reversing at the other end of the stroke, the value is 17 μm. Not only are these values different, but they both differ from the value measured in the unloaded condition.

The average step size was 62.635 μm for an average commanded motor step of 2497.3 counts. This corresponds to 25.08 nm/motor-step. It is encouraging that the average step size did not change, even under the operational load.

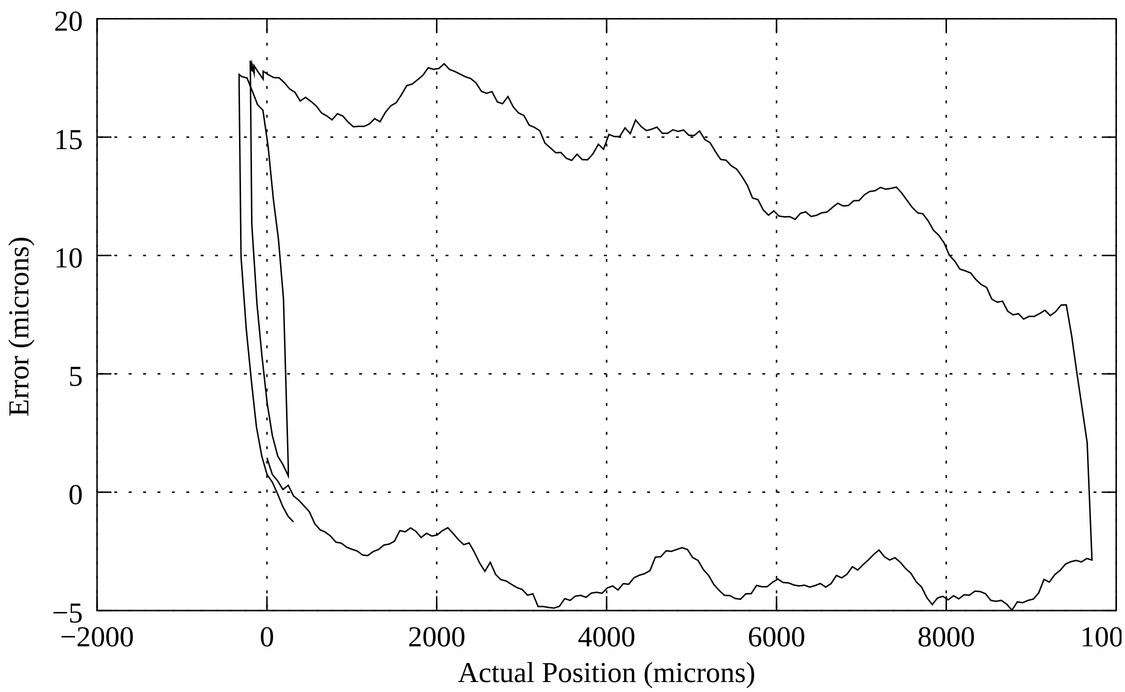

Figure 8: Error vs Actual Position, MOOG6

A.1.7 Filename: MOOG7

The MOOG7 test repeated MOOG6, but with the degraded load (400 kg) applied in the same direction. This was a one cycle test, followed by the usual issues with the limit switches. The typical motor current was also monitored for this test, and was still found to be 0.91 A. This suggests that the power required to operate and move the actuator dominates over the additional requirements imposed by external loads.

The error versus the commanded position is shown in Figure 9. The results are qualitatively similar to the MOOG6 test. The outbound cycle shows the screw thread ripple, followed by the input backlash at the reversal, and the return stroke shows a slightly different step size. In this case, the error increase on the return is about 14 μm. The apparent input backlash on the first reversal was about 15 μm, and at the second reversal it was about 23 μm. Since all of these values are greater than measured in the MOOG6 test, it appears that they are load dependent. This is consistent with a load-dependent change in windup at the input side.

The average step size was 62.62 μm for an average commanded motor step of 2496.4 counts. This corresponds to 25.08 nm/motor-step. Again, it is encouraging that the average step size did not change, even under the increased load, though this average is for two different values on the outward and return stroke.

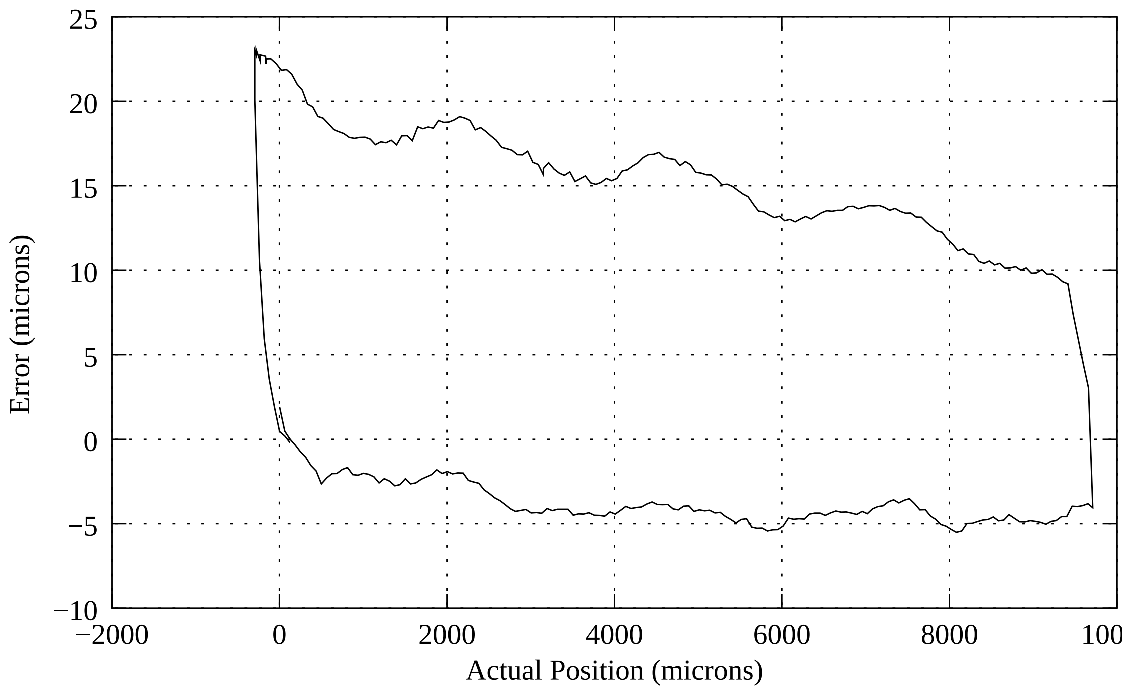

Figure 9: Error vs Actual Position, MOOG7

A.1.8 Filename: MOOG8

To investigate the difference in measured position due to the external load on the system, the MOOG8 test was performed as a stiffness test at the home position of the actuator. In this test, the load was varied and the actual position measured in order to calculate an effective stiffness k_{eff} of the test setup. This would allow removal of the effects due to variation of the load. The stiffness test is shown in Figure 10. The results show some hysteresis, but can be well approximated by a slope of 2.022 kgf/μm, or 19.815×10^6 N/m.

This suggests that operational load condition of the actuator could still change the true position by 126 μm. While these effects are presumably included in the overall structural FE model, this number is large enough to be a concern.

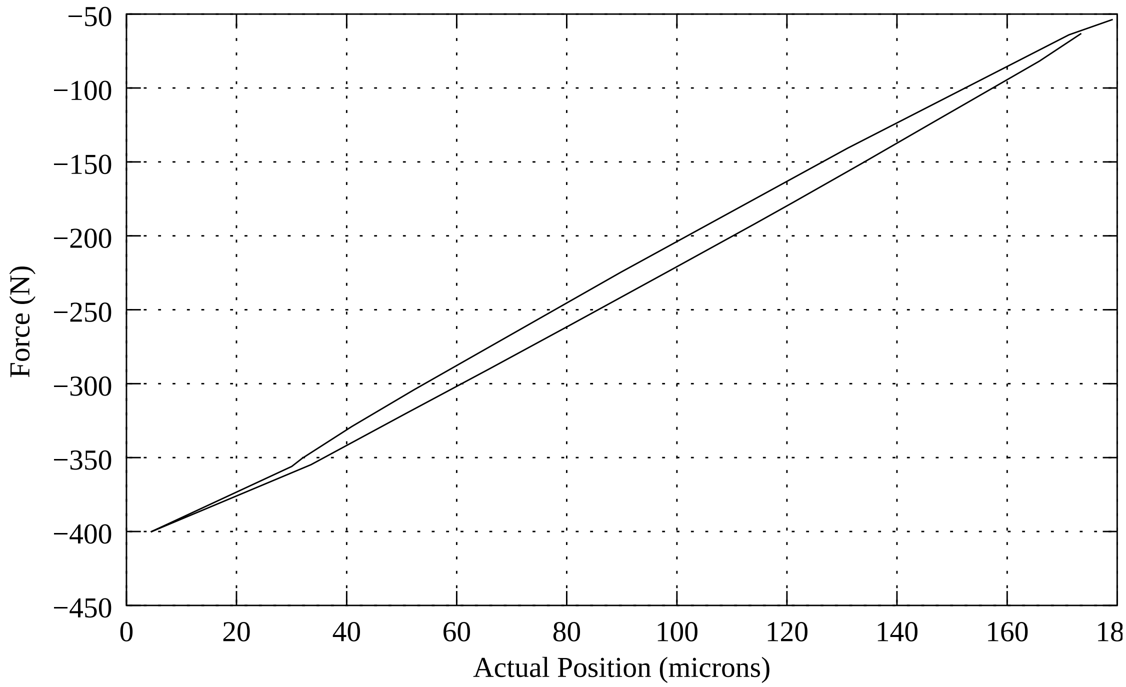

Figure 10: Load vs Actual Position, MOOG8

A.1.9 Filename: MOOG9

In attempting to obtain more data on the Moog actuator without the limit switch problem, the MOOG9 test was conducted by disabling the limit switches and running the cycle using the command position reading. The actuator was unloaded for this test, and the resulting motion profile is shown in Figure 11.

The error versus the commanded position is shown in Figure 12. Like the earlier tests, MOOG9 shows the familiar screw thread ripple and input backlash. However, the ripple now appears to have an amplitude of 1.5–2 μm, and the backlash is in the range of 10–12 μm. Additionally, the entire pattern drifts slightly, moving by perhaps 1 μm over the five cycles. The cause of the apparent 50% increase in both input backlash and thread ripple is not known. The average step size was 62.685 μm for an average commanded motor step of 2500.0 counts. This corresponds to 25.07 nm/motor-step.

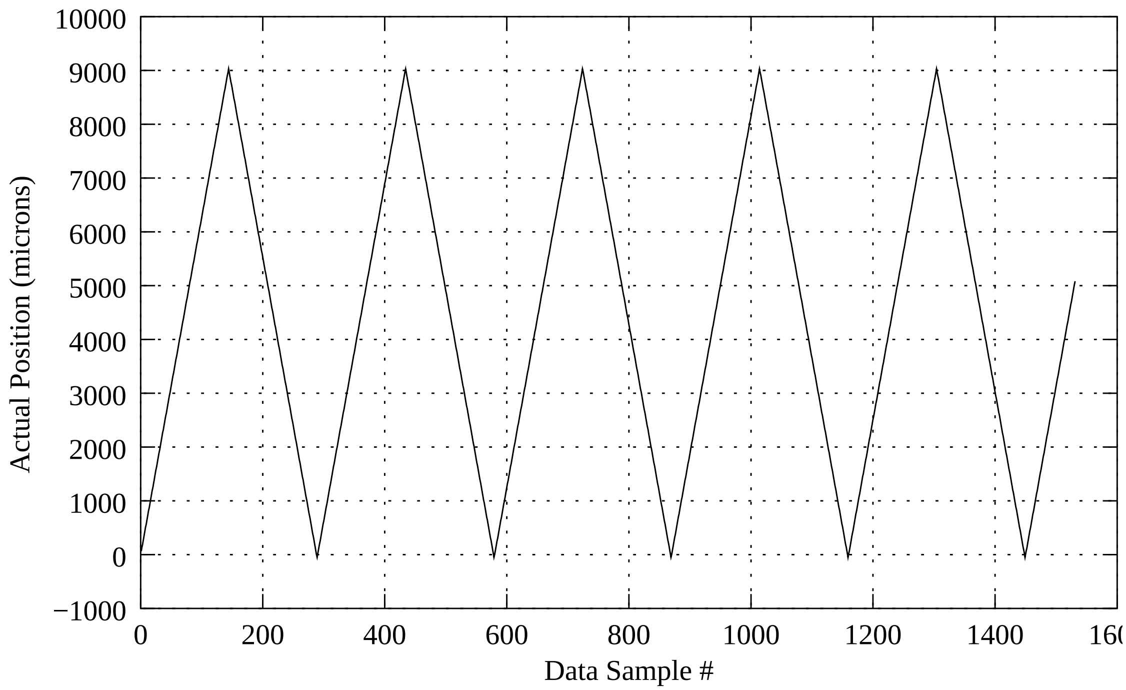

Figure 11: Actual Position vs Time, MOOG9

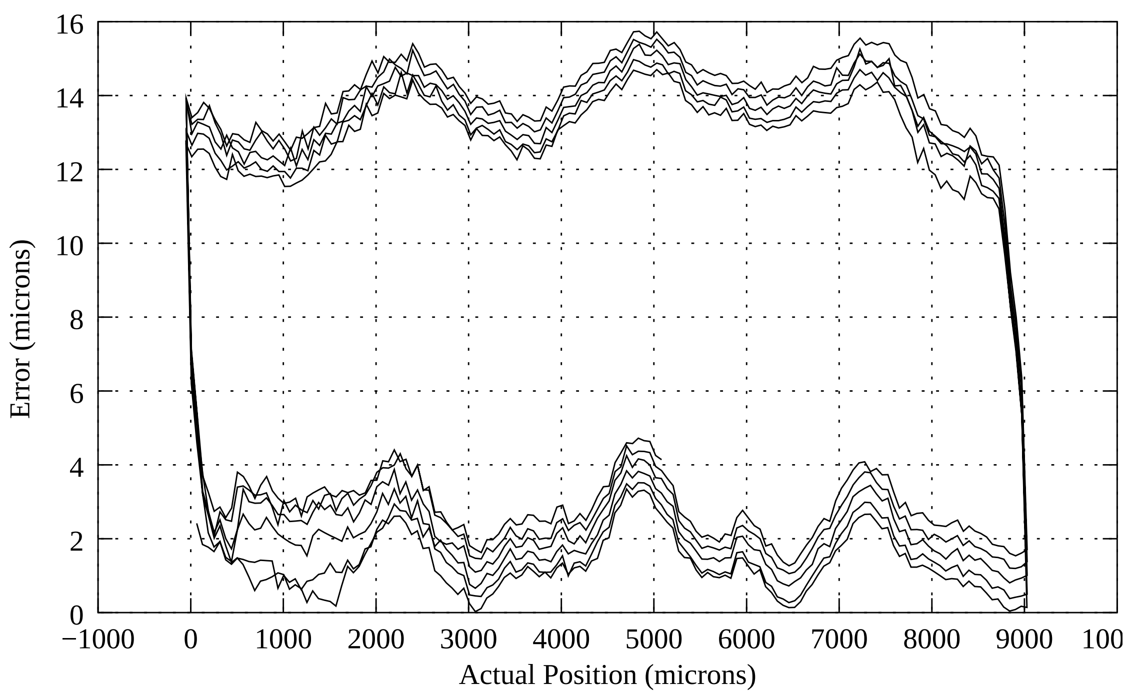

Figure 12: Error vs Actual Position, MOOG9

A.1.10 Filename: MOOG10

Before continuing the tests with the load in the opposite direction, stiffness tests were performed in different positions. The first of these tests was MOOG10. The load was provided via static weights on the loading setup and the actuator was set at the center of its stroke (5 mm). The stiffness test is shown in Figure 13. The best-fit slope of the data is 7.787 kgf/μm, or 76.362×10^6 N/m. This is markedly different from the test in the other direction at the home position.

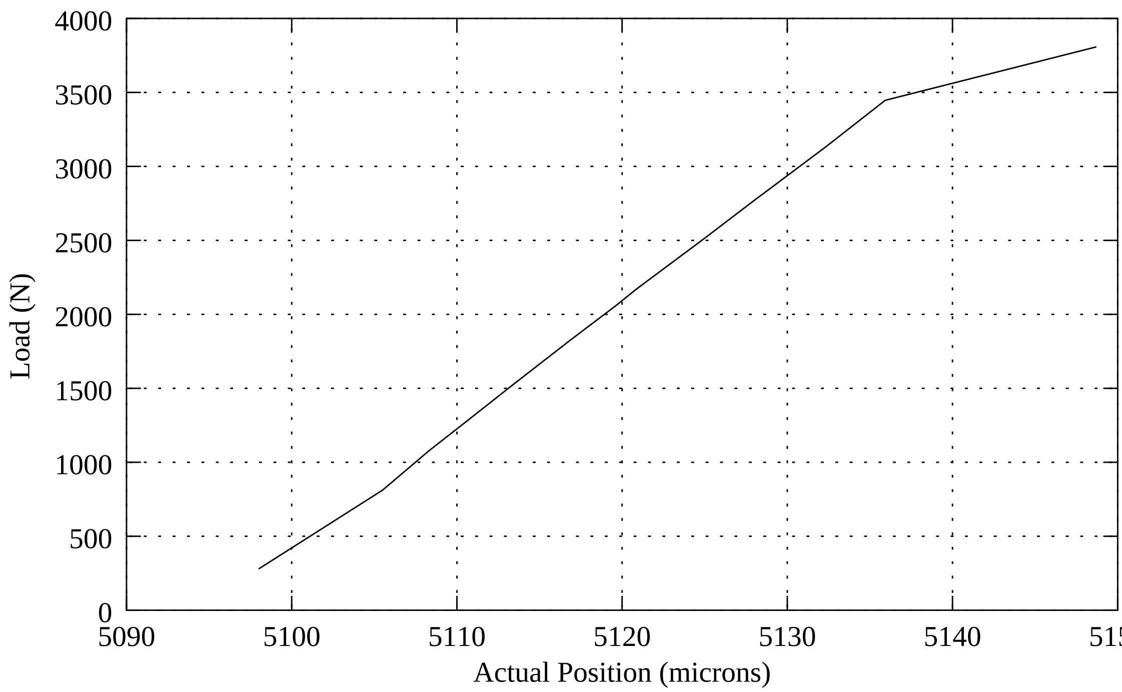

Figure 13: Load vs Actual Position, MOOG10

A.1.11 Filename: MOOG11

To speed up the stiffness tests, MOOG11 was a repeat of MOOG10, but using one of the operators to load the apparatus with their own weight. Because the data acquisition system is able to measure position and load simultaneously, this was a more convenient way of measuring stiffness. The results are shown in Figure 14. The best-fit slope of the data is 8.283 kgf/μm, or 81.224×10^6 N/m. This value differs by about 6.5% from the previous identical test, but is possibly affected by the wider range of forces used in this test.

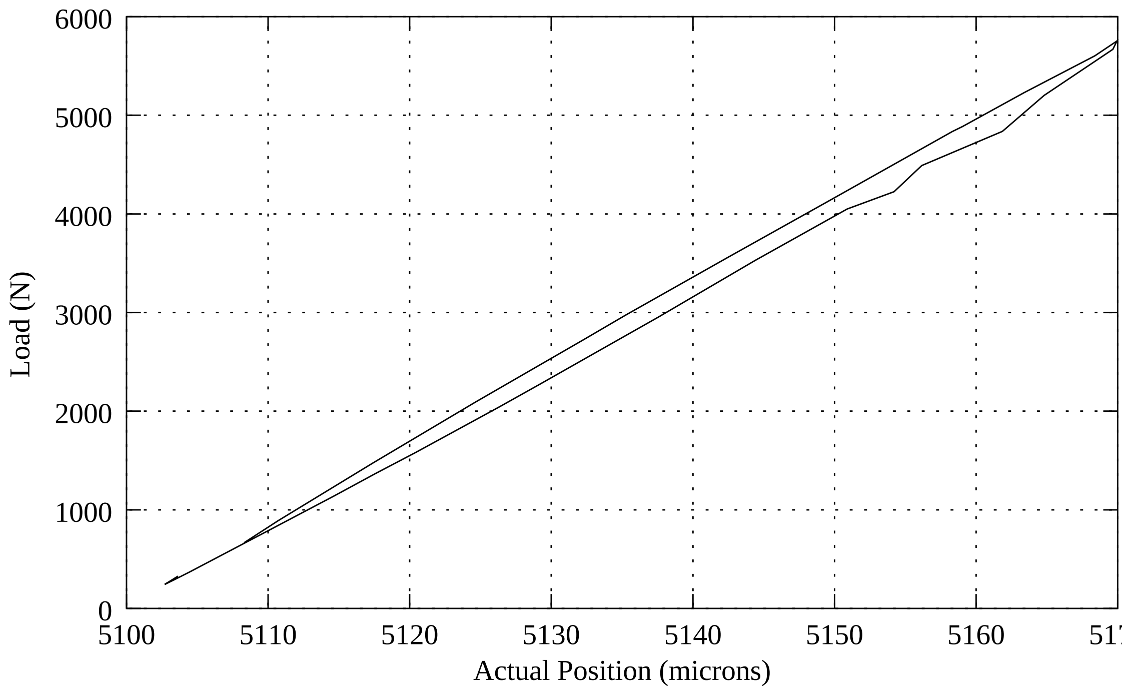

Figure 14: Load vs Actual Position, MOOG11

A.1.12 Filename: MOOG12

Because the results in the + direction at 5 mm were dramatically different than those in the − direction at the home position, the MOOG12 test was a repeat of MOOG11, but taken at the home position. This would allow separation of the direction effect from the position effect. The results are shown in Figure 15. The best-fit slope of the data is 8.729 kgf/μm, or 85.605×10^6 N/m. This value is an additional 5.4% higher than the MOOG11 test, but this could be due to the shorter length of the actuator rod. In any event, the value is consistent with the other tests in the + direction.

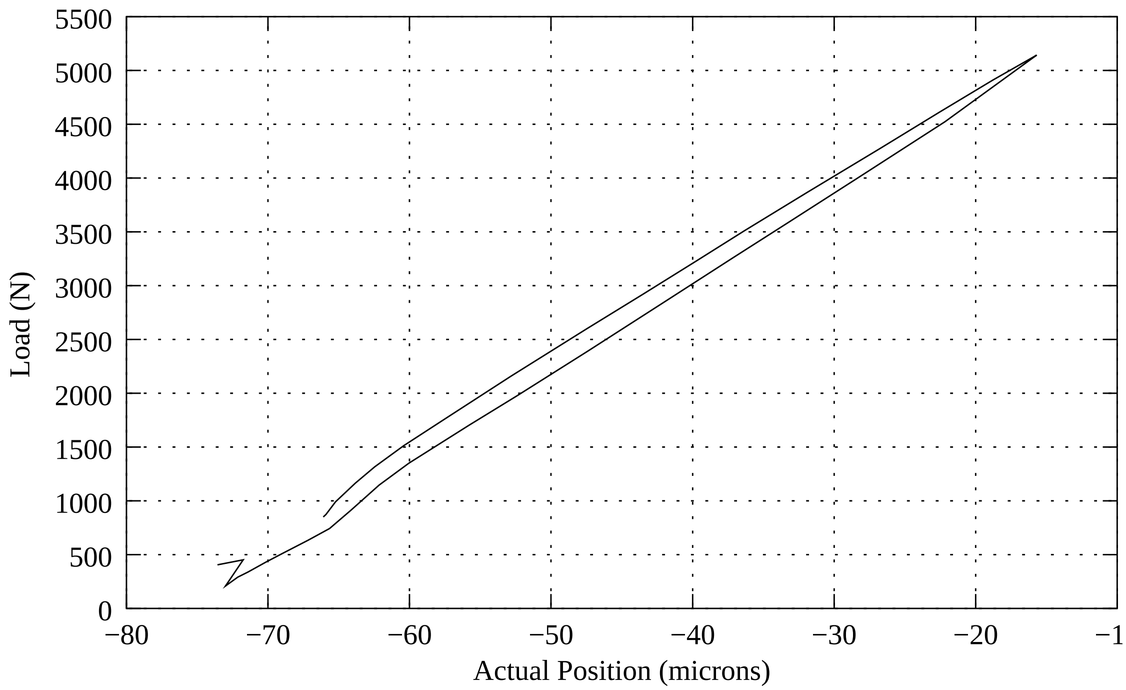

Figure 15: Load vs Actual Position, MOOG12

A.1.13 Filename: MOOG13

The MOOG13 test was a test under operational load (250 kg) from the + direction, covering two cycles. There were some unexpected glitches near the reversal of the second cycle, as shown in Figure 16.

The error versus the commanded position is shown in Figure 17. Like some of the earlier tests, MOOG13 shows the familiar pattern of an initial transient (in this case, 20 μm), followed by the screw thread ripple and input backlash. The ripple in this test has returned to its original value of of 1 μm, and the backlash is about 12 μm. The average step size was 62.71 μm for an average commanded motor step of 2500.0 counts. This corresponds to 25.08 nm/motor-step.

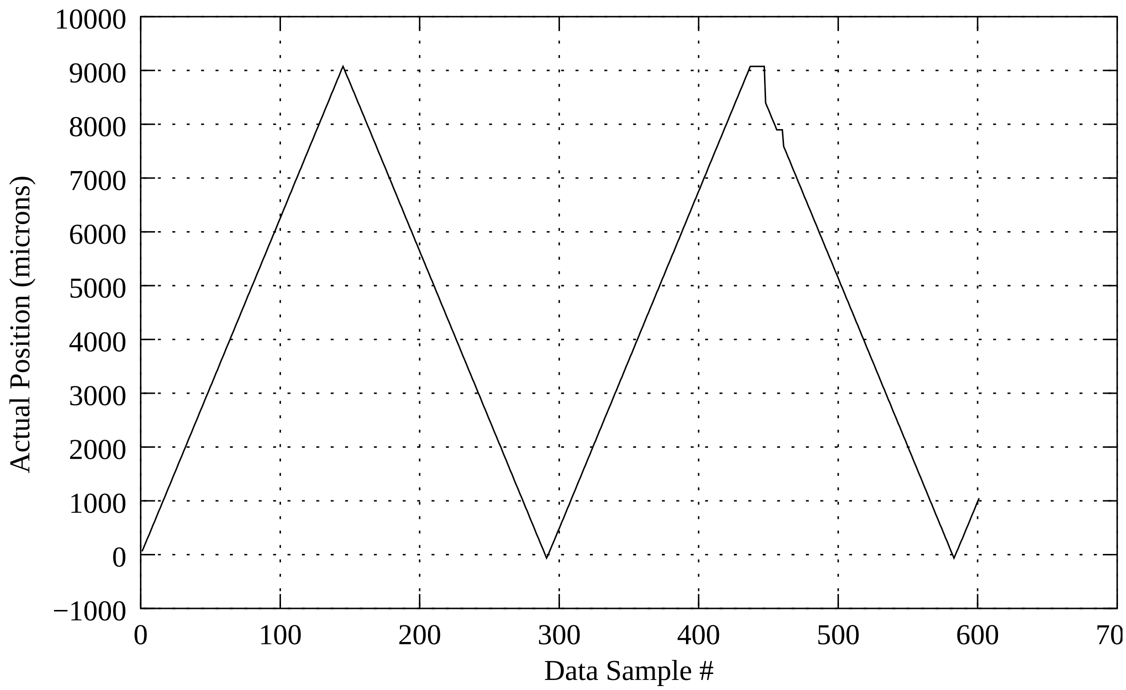

Figure 16: Actual Position vs Time, MOOG13

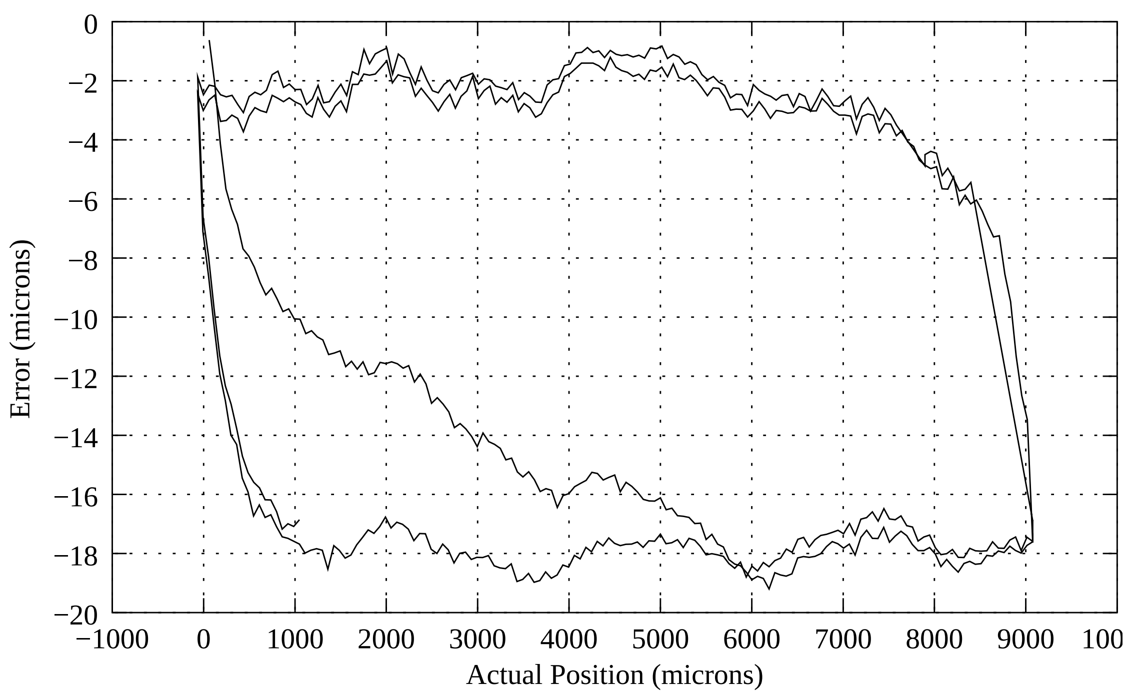

Figure 17: Error vs Actual Position, MOOG13

A.1.14 Filename: MOOG14

The MOOG14 test was a test under degraded load (450 kg) from the + direction, covering two cycles. Again, it operated on the limit switches (with additional circuitry to de-bounce the connection). As shown in Figure 18, there were again unexpected motion reversals.

More worrisome than the reversals is the behavior of the error, shown in Figure 19. In this test, the first cycle behaved nominally. The abbreviated cycles then shifted with respect to the initial cycle, but repeated reasonably well between themselves. However, on the final cycle, the actuator appears to be on an entirely different curve. This suggests that something in the actuator or the sensors is changing in a way that could add considerable error (of order 10 μm) to the actuator.

In spite of the problems with this test, the average step size was 62.459 μm for an average commanded motor step of 2492.5 counts. This corresponds to 25.06 nm/motor-step.

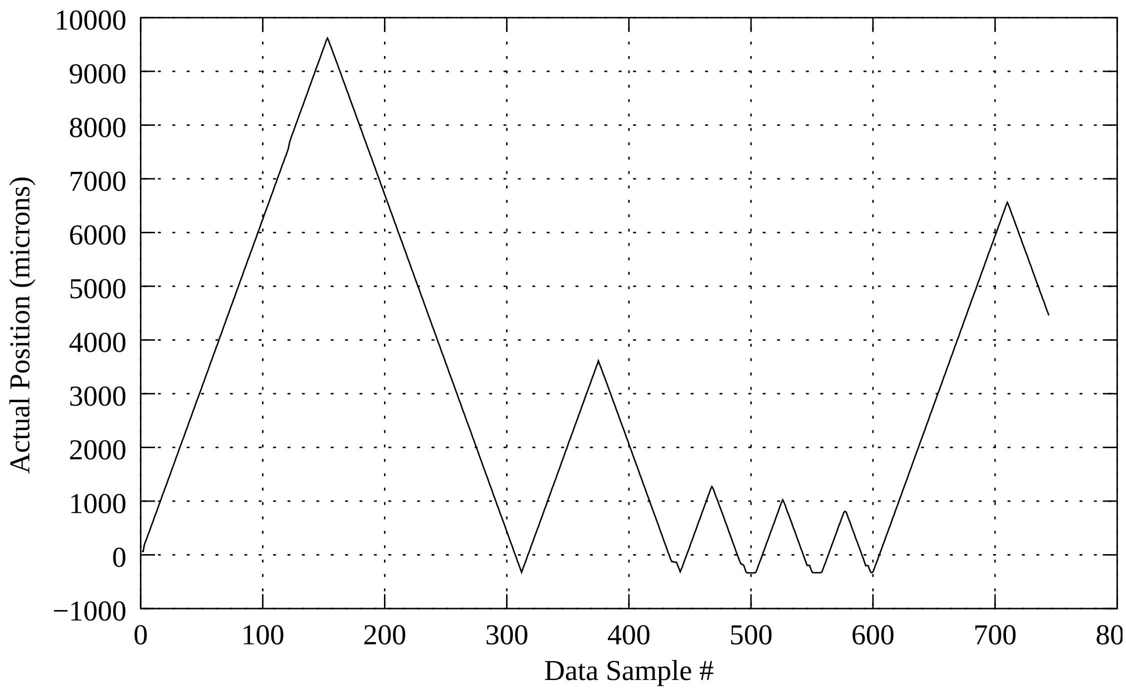

Figure 18: Actual Position vs Time, MOOG14

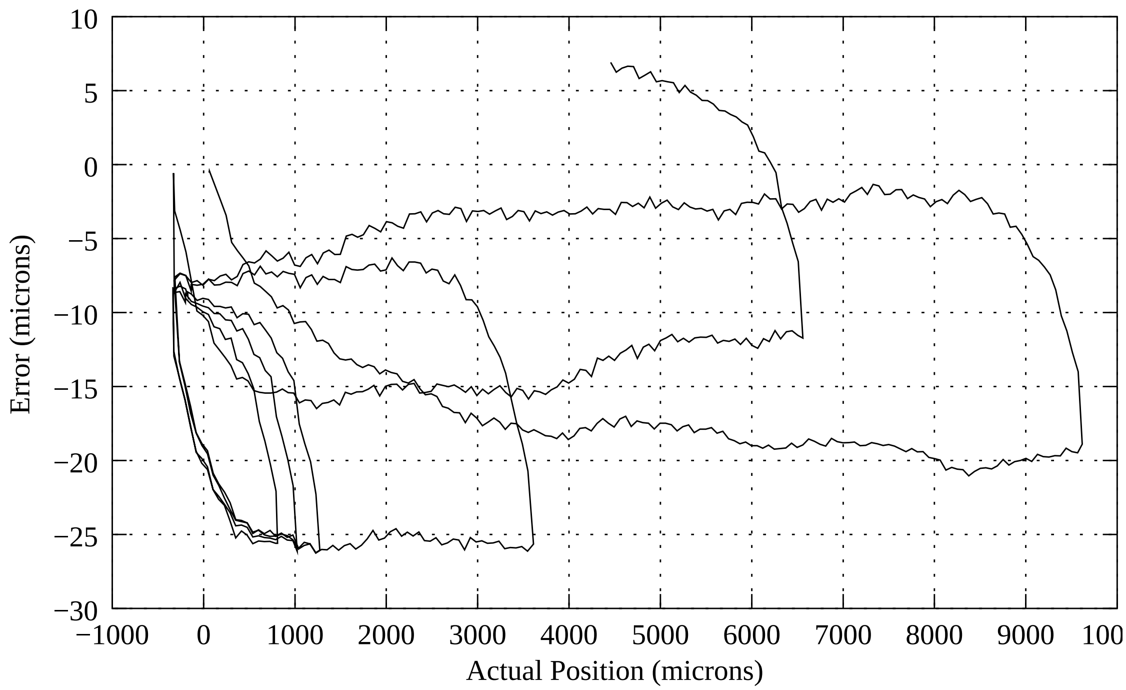

Figure 19: Error vs Actual Position, MOOG14

A.2 ADS Actuator

A.2.1 Filename: ADS

The initial ADS test was an unloaded test run for many (21) cycles. While this actuator was also commanded to drive to the limits, there were no problems with the limit switches, so this mode worked reliably. The motion profile is shown in Figure 20.

By plotting the error against the actual position, it is clear that the actuator behaved in a highly repeatable manner (Figure 21). The 21 cycles are identical within a couple of microns. However, there are two substantial error sources for this actuator. The first is the obvious screw thread ripple. This ripple has an amplitude of about 9 μm, or a peak-to-peak deviation of twice that value, and the ripple has about 7 cycles over the 10 mm stroke. Additionally, there is some obvious input-side backlash and windup. This results in an error change of about 30 μm when reversing from the positive to negative direction, and about 20 μm when reversing in the other direction. The 10 μm difference is not fully explained, but is likely due to the change in windup torque when driving with or against the preload spring.

The average step size for this test was 60.923 μm for an average commanded motor step of 4994.7 counts. This corresponds to 12.20 nm/motor-step.

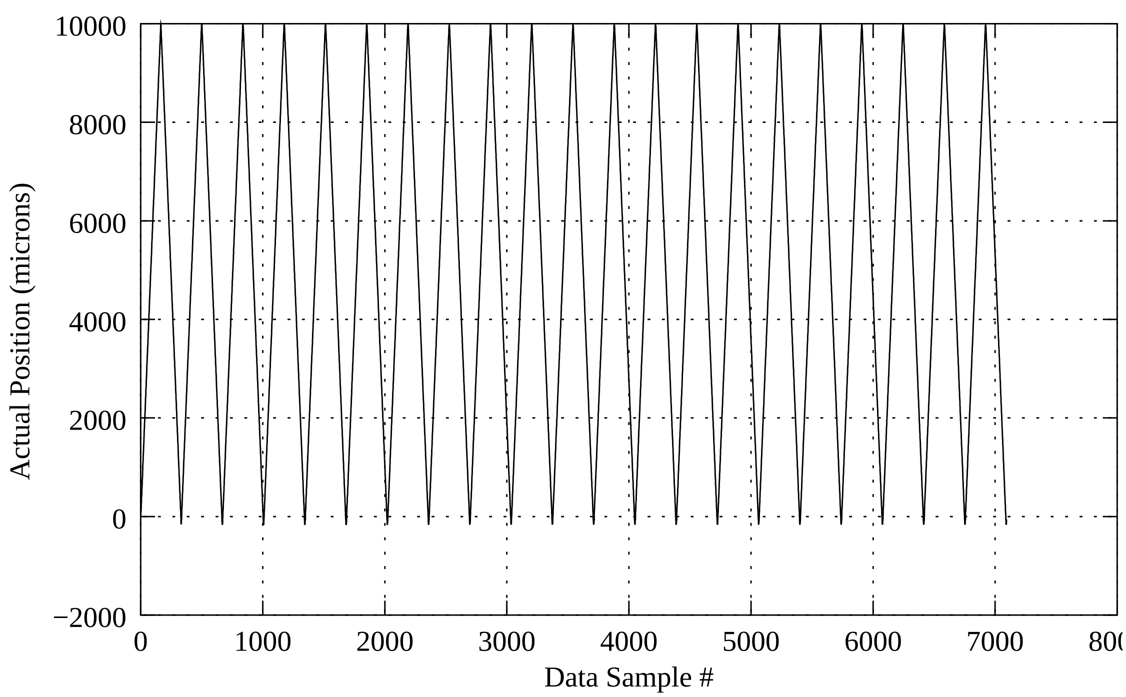

Figure 20: Actual Position vs Time, ADS

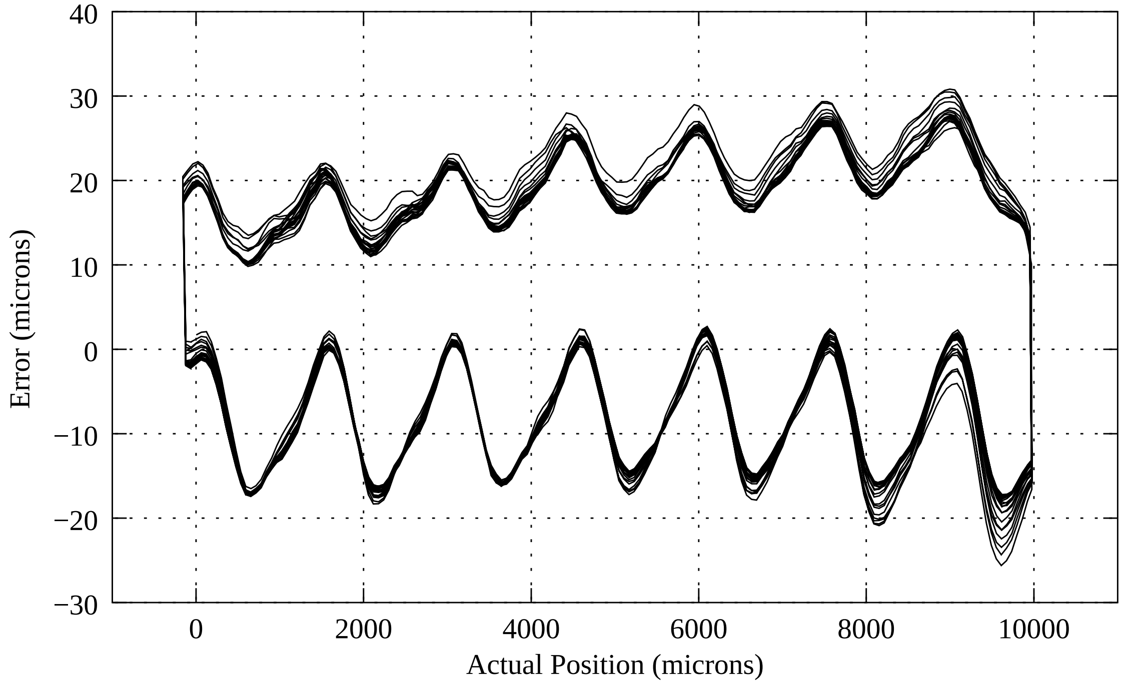

Figure 21: Error vs Actual Position, ADS

A.2.2 Filename: ADS2

This test is a repeat of the ADS test, but with only one cycle. As shown by the error plot in Figure 22, there are no substantial differences between this test and the previous one. The average step size for this test was 60.978 μm for an average commanded motor step of 4998.1 counts. This corresponds to 12.20 nm/motor-step.

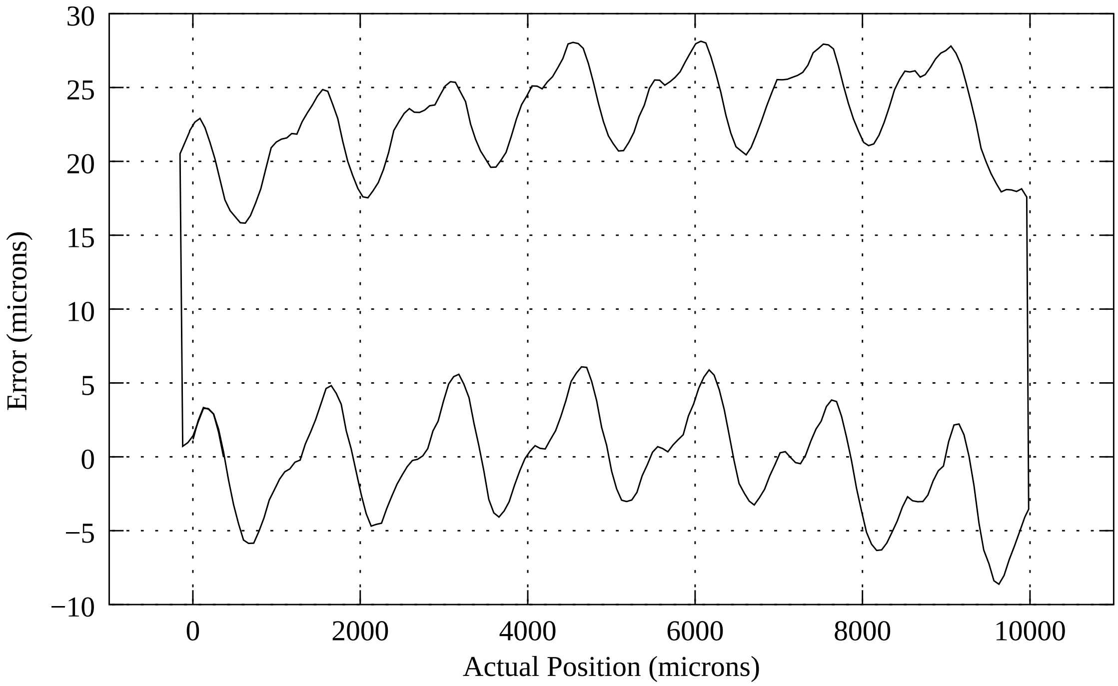

Figure 22: Error vs Actual Position, ADS2

A.2.3 Filename: ADS3

This test was conducted after the series of tests on the Moog actuator, so it was clear that a stiffness test would be useful. ADS3 is a stiffness test with the load in the + direction (extending the actuator), at the home position. The load profile for this test was not unusual, and is shown in Figure 23.

However, the stiffness plot is completely nonsensical (Figure 24). As the load increases, there is almost no motion. That is, the stiffness appears to be nearly infinite. Then, as the load is released, there is a substantial motion. To date, the only credible explanation offered for this behavior is that the loading apparatus itself must not have been transferring the load properly to the actuator. That is, something in the cable run from the force multiplying gearbox to the positive side force connection must have been stuck.

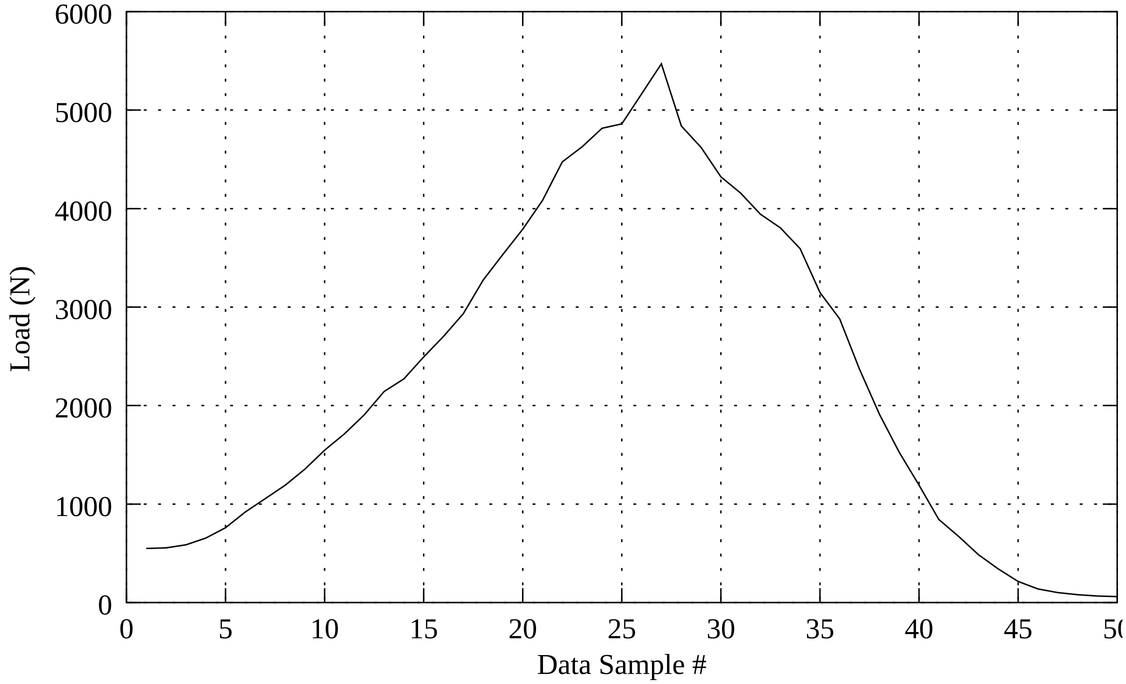

Figure 23: Load Profile, ADS3

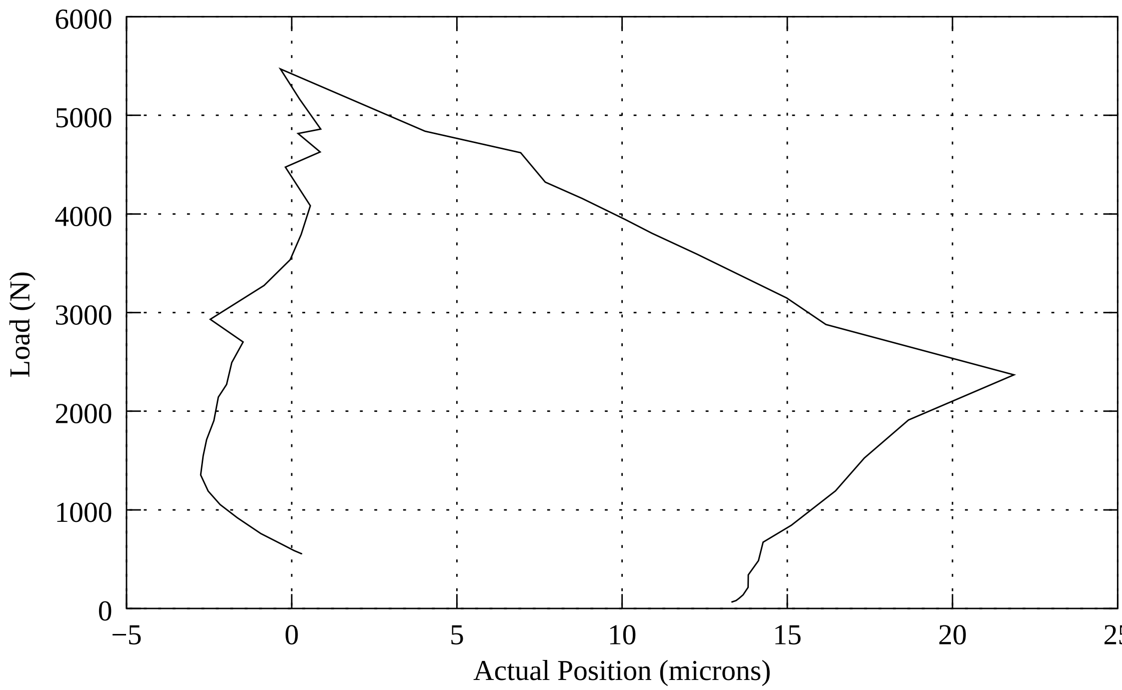

Figure 24: Load vs Actual Position, ADS3

A.2.4 Filename: ADS4

Because of the unusual results on ADS3, the test was repeated at the 5 mm position, still in the + direction. However, it showed exactly the same type of unusual behavior. In the load vs position plot in Figure 25, the application of the load has almost no effect on the position. As the load is slowly released, however, there is a sudden change of position, which increases to the point that by the end of the load cycle there has been a change of about 10 μm. Again, this is not the behavior that was expected. The expected behavior was that there would be a change at one slope until the internal springs opened, then a change at another slope thereafter.

Examination of the individual linear sensors reveals that each of them correlates better with the force than their linear combination. However, since the sensors are measuring the rod position and flange position, the actuator behavior should be the relative position of the two. The behavior is still unexplained.

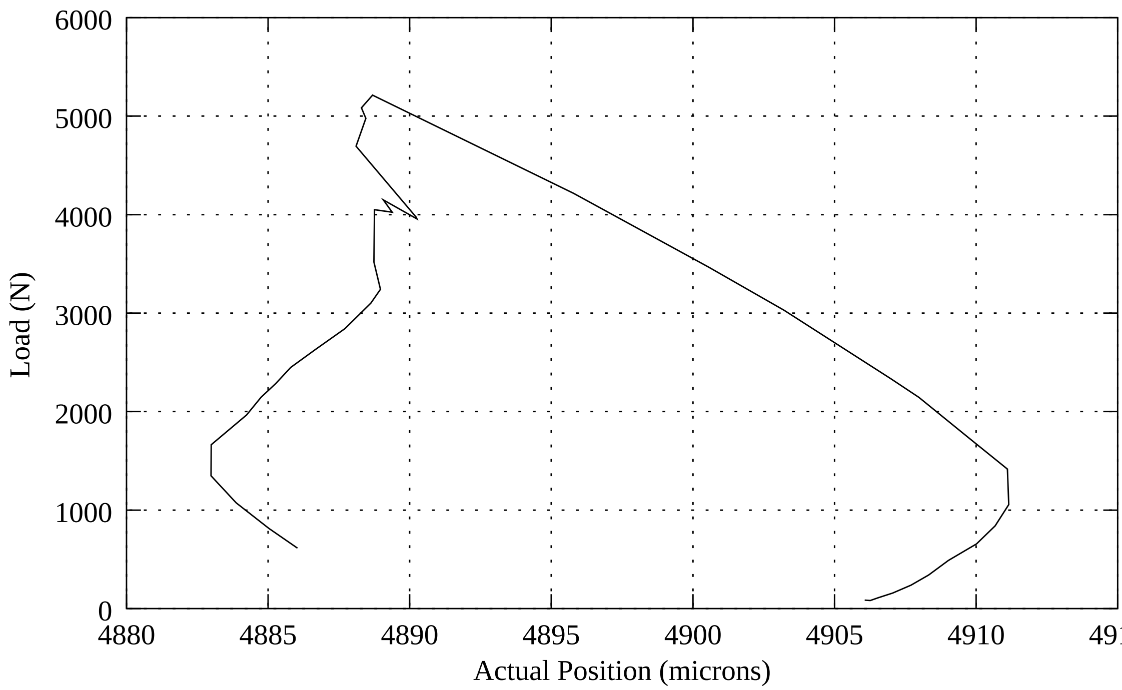

Figure 25: Load vs Actual Position, ADS4

A.2.5 Filename: ADS5

In an attempt to understand the stiffness behavior, ADS5 was conducted as an exact repetition of ADS3. That is, a stiffness test at the home position (0 mm) in the + loading direction. While the results (Figure 26) are still unusual, they are closer to the expected behavior. Specifically, when the load is applied, there is a change in position with load. When the load reaches about 3 kN, the preload spring is overcome and the stiffness changes substantially. However, as the load relaxes, it should retrace this behavior. Instead, it follows the initial slope until the force is almost completely relaxed, then follows the sharper slope. Further, the slopes are in the wrong direction. A positive slope was expected, as seen with the Moog actuator.

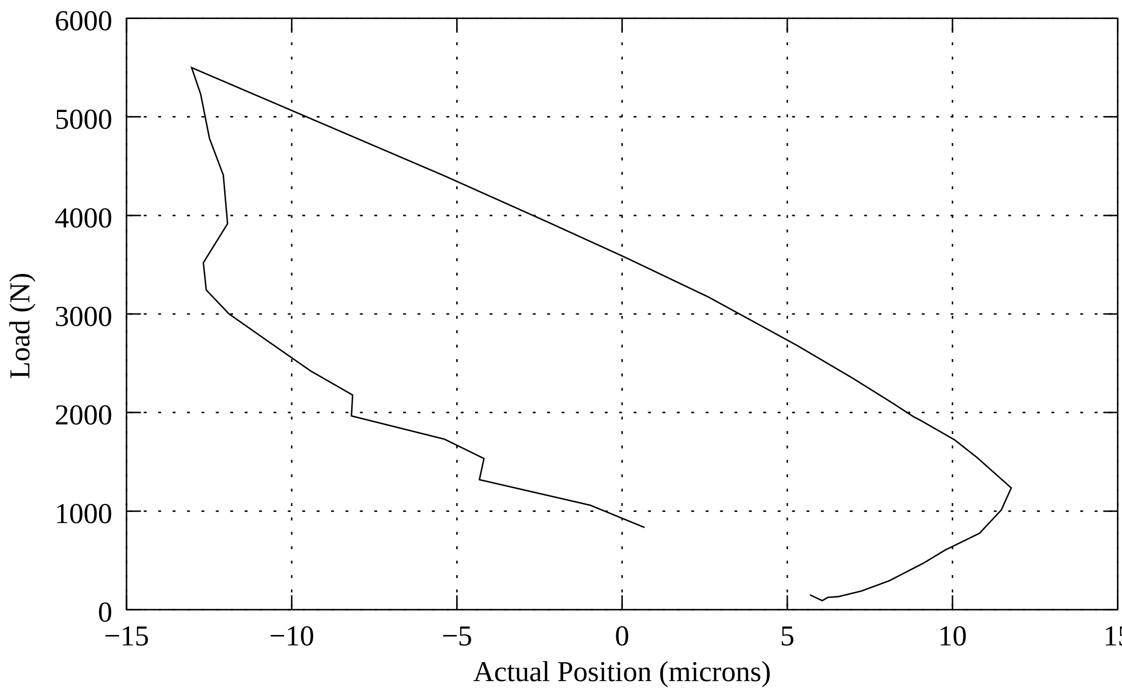

Figure 26: Load vs Actual Position, ADS5

A.2.6 Filename: ADS6

Since the stiffness behavior of the ADS actuator still made no qualitative sense, the ADS6 test was performed. This test loaded the actuator only to 200 kg. The goal was to stay within the range before the springs opened. As shown in Figure 27, the response is very linear, though the slope is still in the opposite direction from expected. The best-fit slope of the data is -14.928 kgf/μm, or 146.39×10^6 N/m.

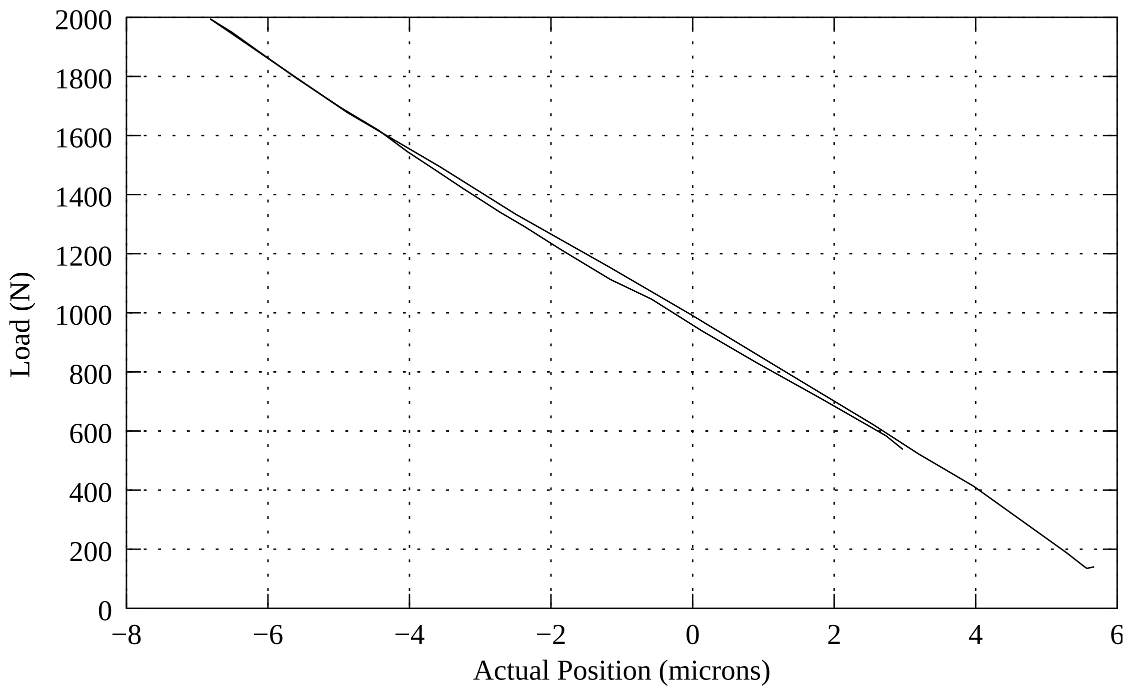

Figure 27: Load vs Actual Position, ADS6

A.2.7 Filename: ADS7

This test is a repeat of the AD2 test, but with two cycles. The goal of this test was to generate a lookup table (LUT) in order to remove the repeatable effects seen in the previous experiments. The error plot (Figure 28) is similar to the previous tests, but with smaller amplitude on the ripple due to the threads. The average step size for this test was 61.005 μm for an average commanded motor step of 5000.0 counts. This corresponds to 12.20 nm/motor-step.

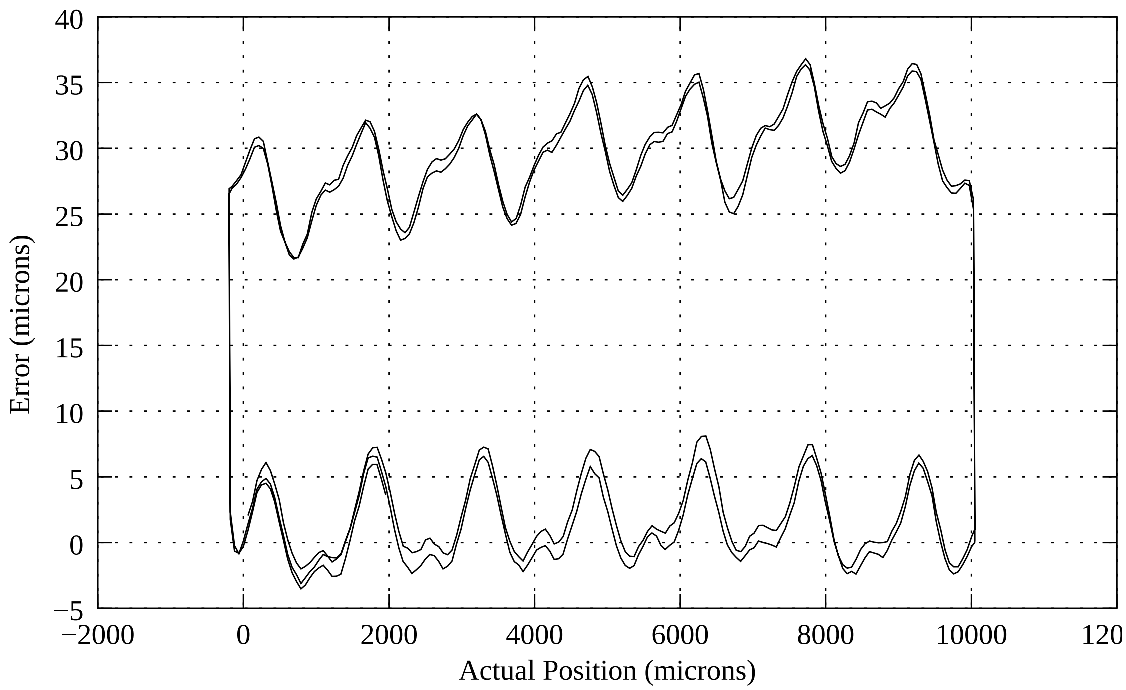

Figure 28: Error vs Actual Position, ADS7

A.2.8 Filename: ADS8

This was an attempt at correcting for the repeatable errors by using the results from ADS7 as a lookup table. While there is an improvement in the ripple, there was a problem with the LUT generation algorithm, resulting in an invalid test. The error plot (Figure 29) shows comparable behavior to ADS7. The average step size for this test was 90.098 μm for an average commanded motor step of 7382.0 counts. This corresponds to 12.20 nm/motor-step.

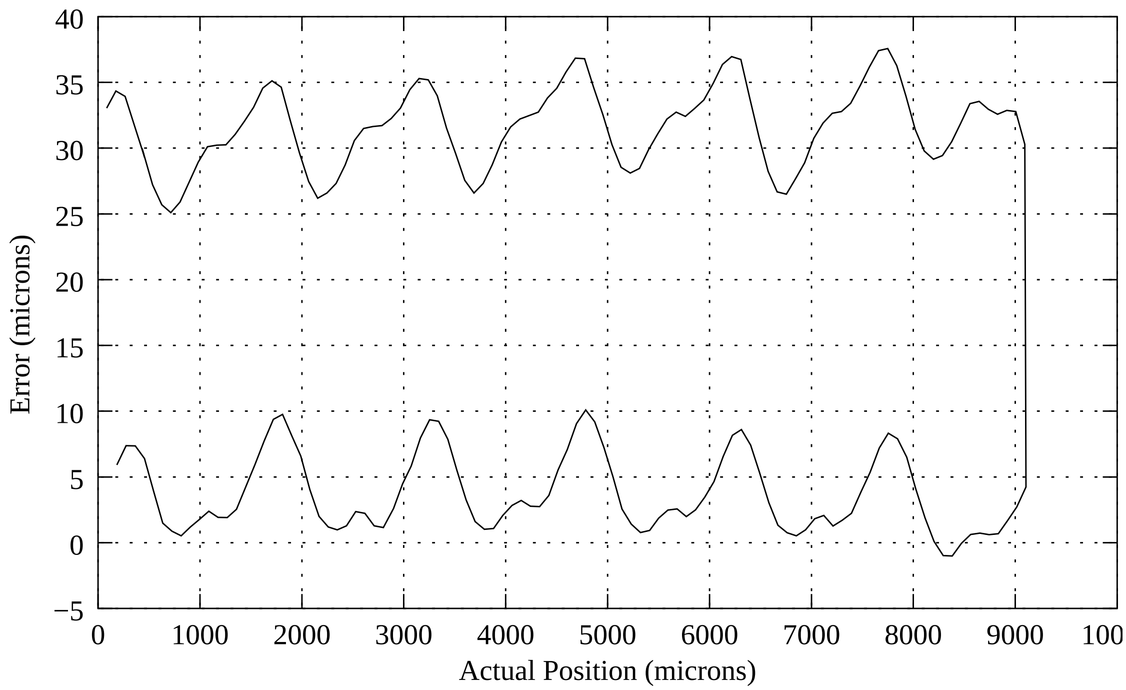

Figure 29: Error vs Actual Position, ADS8

A.2.9 Filename: ADS9

This was another attempt at correcting for the repeatable errors by using the results from ADS7 as a lookup table. Again, there is an improvement in the ripple, reducing it to about 6 μm peak-to-peak, but there was still a problem with the LUT generation algorithm. The error plot is shown in Figure 30. The average step size for this test was 90.142 μm for an average commanded motor step of 7381.4 counts. This corresponds to 12.21 nm/motor-step.

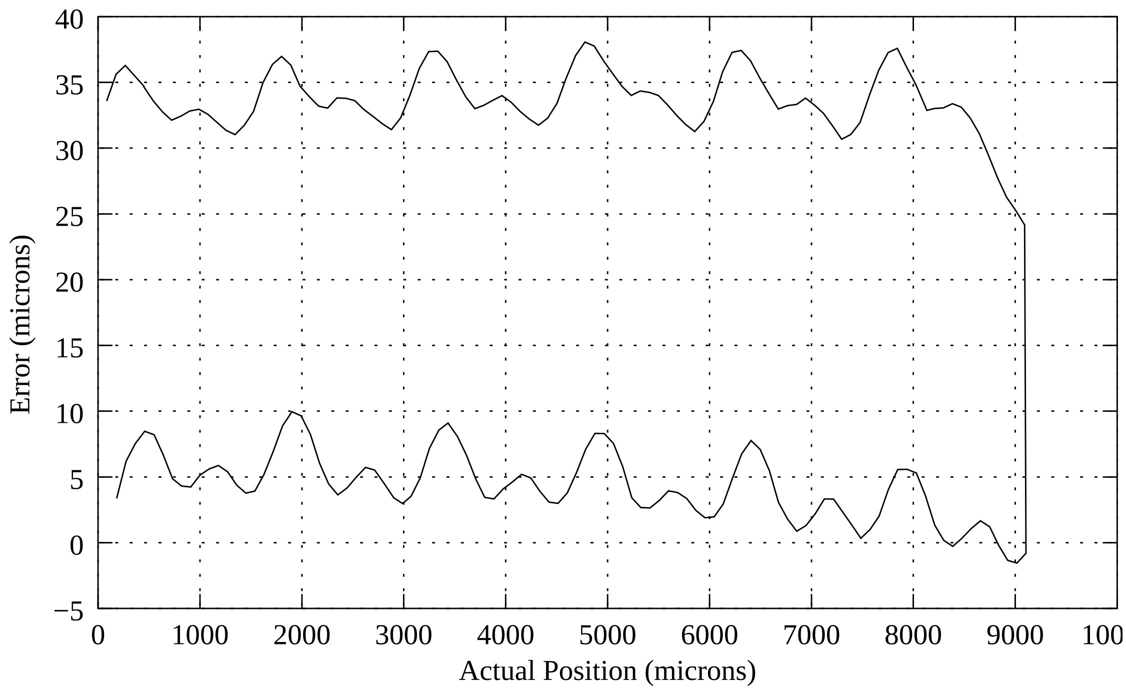

Figure 30: Error vs Actual Position, ADS9

A.2.10 Filename: ADS10

The ADS10 test was the first loaded test for the ADS actuator. The loading was at the operational load level (250 kgf) in the + direction. No lookup table was used. It is also worth noting that the initial home position was off by 5 μm, suggesting that the homing is not fully repeatable.

The error plot is shown in Figure 31. Interestingly, the ripple is still as low as in ADS9, and the input side backlash is still of order 30 μm. The average step size for this test was 60.92 μm for an average commanded motor step of 4989.8 counts. This corresponds to 12.21 nm/motor-step.

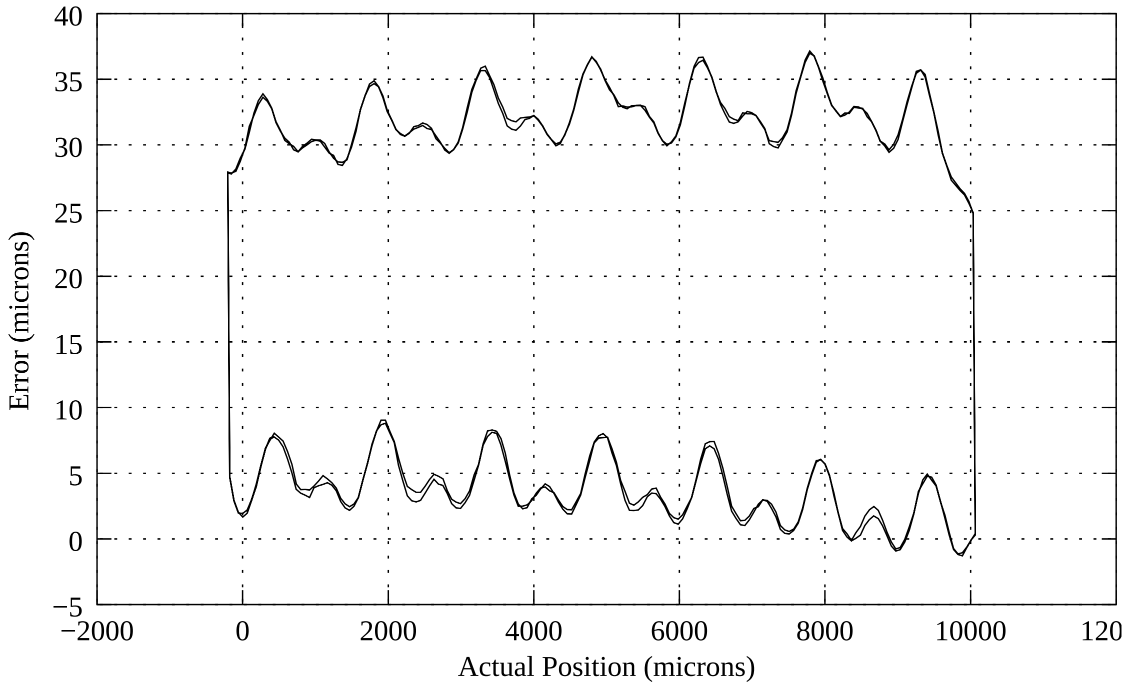

Figure 31: Error vs Actual Position, ADS10

A.2.11 Filename: ADS11

The ADS11 test repeated ADS10 with the degraded operation loading (400 kgf), still in the + direction. No lookup table was used. It is also worth noting that for this test the initial home position was off by 56 μm, which is a surprisingly large variation in the homing reference.

The error plot is shown in Figure 32, and shows comparable results to ADS10. The average step size for this test was 61.042 μm for an average commanded motor step of 5000.1 counts. This corresponds to 12.21 nm/motor-step.

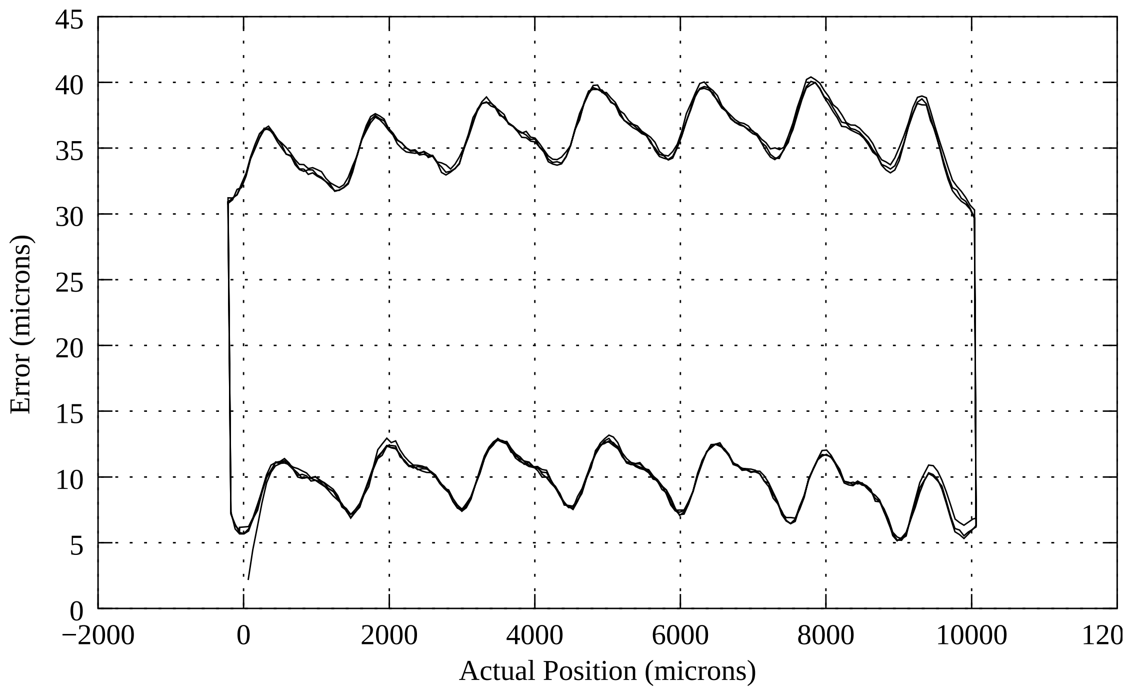

Figure 32: Error vs Actual Position, ADS11

A.2.12 Filename: ADS12

This is a repeat of the ADS11 test but using a lookup table based on ADS7. The peak current observed for the actuator during this test was 1.6 A. From the error plot is shown in Figure 33, it is obvious that the lookup table correction has not been applied correctly. Rather, the results are comparable to ADS11. The average step size for this test was 90.05 μm for an average commanded motor step of 7375.0 counts. This corresponds to 12.21 nm/motor-step.

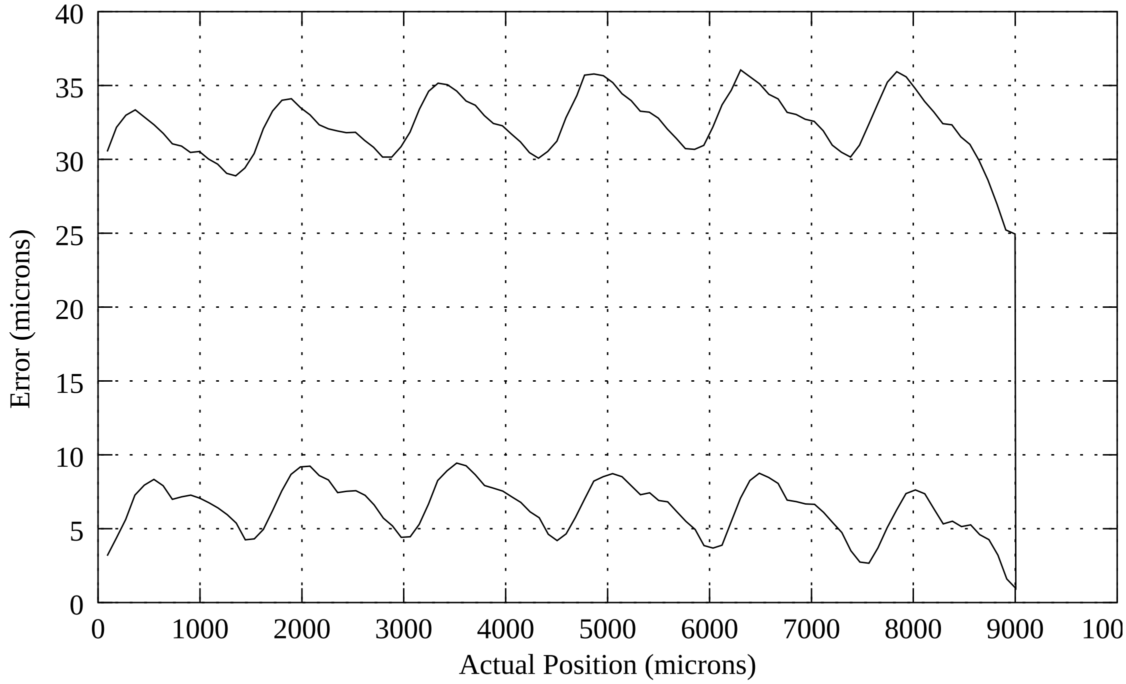

Figure 33: Error vs Actual Position, ADS12

A.2.13 Filename: ADS13

This is a repeat of the ADS10 test (operational load) over a larger number of cycles. Due to the problems with the lookup tables, none was employed for this test. From the error plot is shown in Figure 34, and shows the same behavior as earlier tests. The average step size for this test was 61.013 μm for an average commanded motor step of 5000.0 counts. This corresponds to 12.20 nm/motor-step.

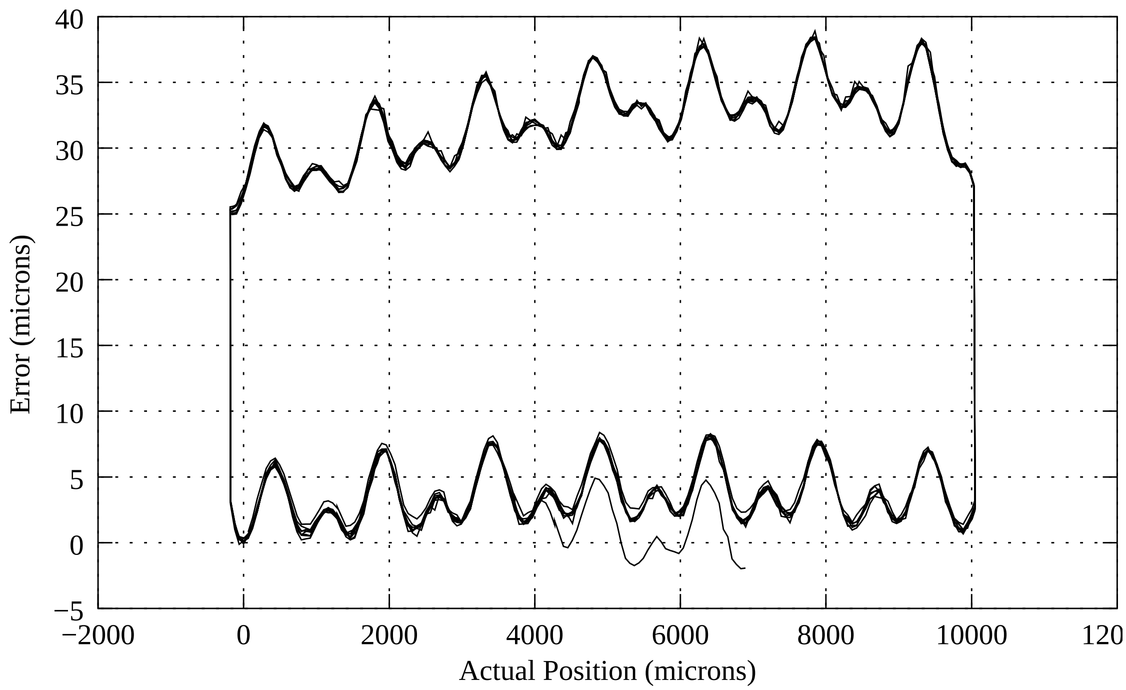

Figure 34: Error vs Actual Position, ADS13

A.2.14 Filename: ADS14

This was a short stroke (1 mm) test under the same loading conditions as ADS13, using a lookup table generated from that same test. While the error plot (Figure 35) looks much smoother, there were only 20 points in the test, and the table failed to compensate for the input backlash. The average step size for this test was 100.17 μm for an average commanded motor step of 8235.0 counts. This corresponds to 12.16 nm/motor-step. While this is different than previous values, this is likely due to the small number of samples.

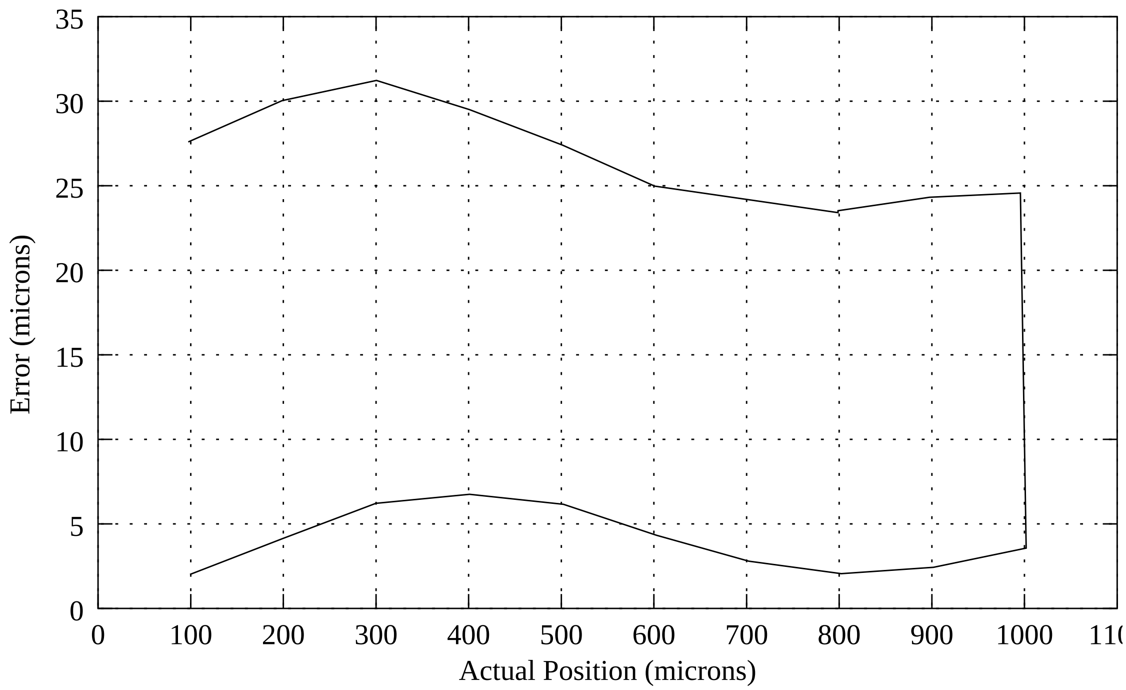

Figure 35: Error vs Actual Position, ADS14

A.2.15 Filename: ADS15

This was a long stroke (10 mm) repetition of ADS14. Unfortunately, the error plot shows the same behavior as the uncompensated tests (Figure 36). The average step size for this test was 99.997 μm for an average commanded motor step of 8193.2 counts. This corresponds to 12.20 nm/motor-step.

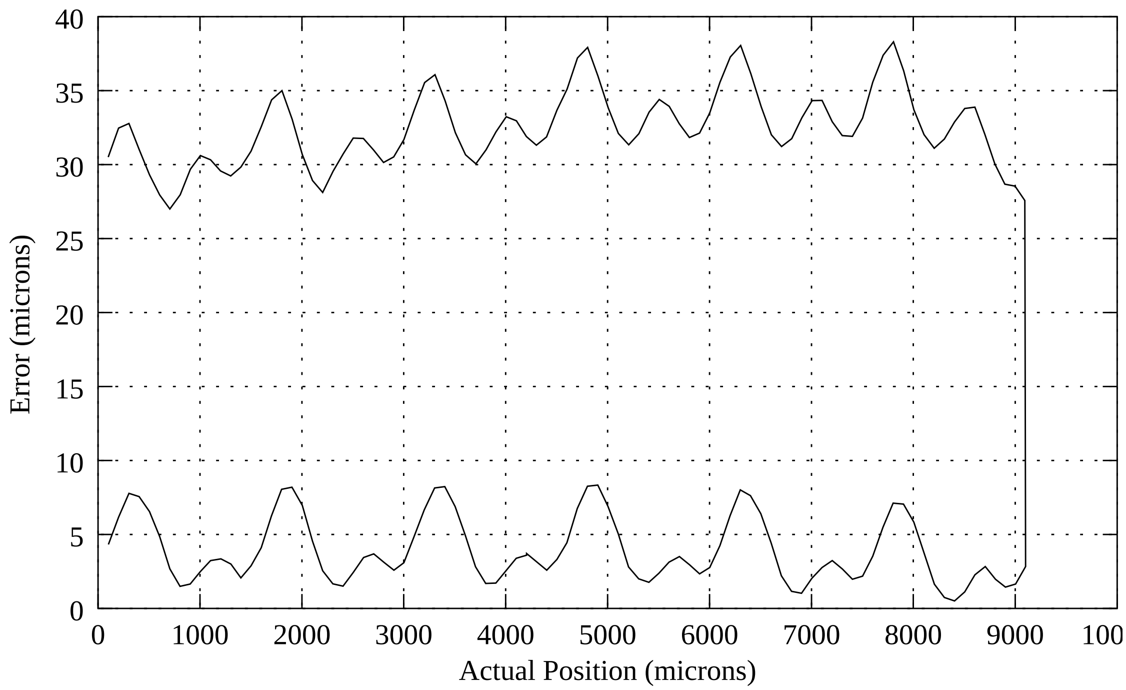

Figure 36: Error vs Actual Position, ADS15

A.2.16 Filename: ADS16

This test exactly repeated ADS15, and produced similar results (Figure 37). At a few places along the stroke, the actuator failed to take a commanded step, but always caught up by the next step. The average step size for this test was 99.983 μm for an average commanded motor step of 8193.3 counts. This corresponds to 12.20 nm/motor-step.

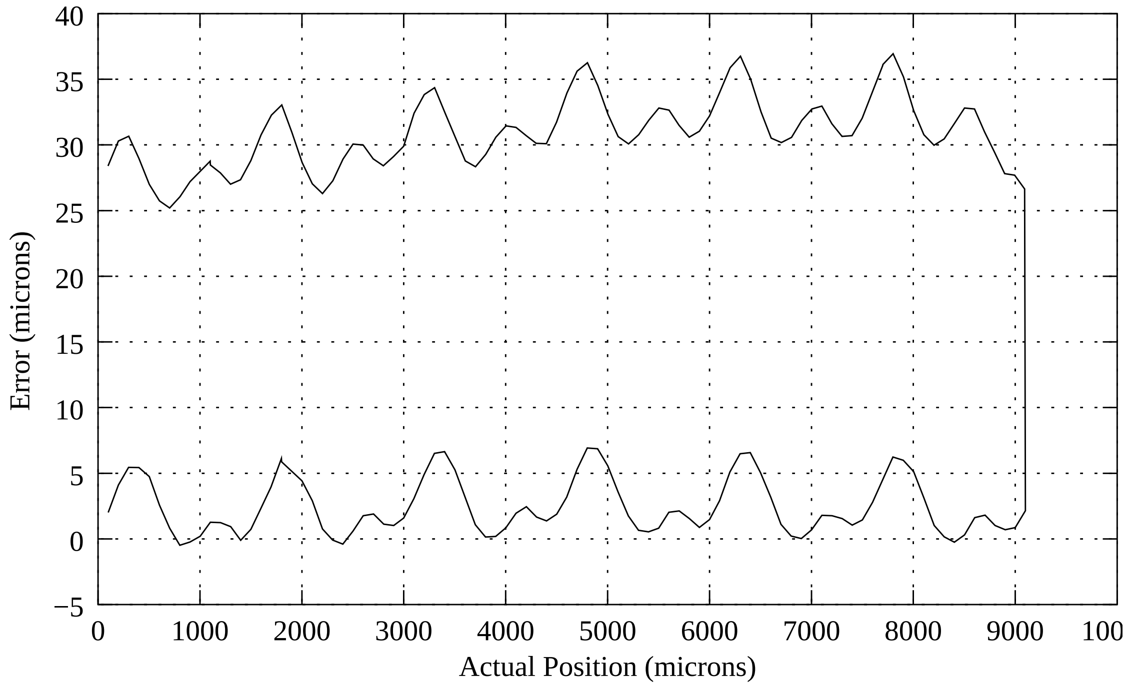

Figure 37: Error vs Actual Position, ADS16

A.2.17 Filename: ADS17

This test also exactly repeated ADS15, and produced similar results (Figure 38). As in ADS16, the actuator occasionally failed to take a commanded step, but always caught up by the next step. The average step size for this test was 99.948 μm for an average commanded motor step of 8190.4 counts. This corresponds to 12.20 nm/motor-step.

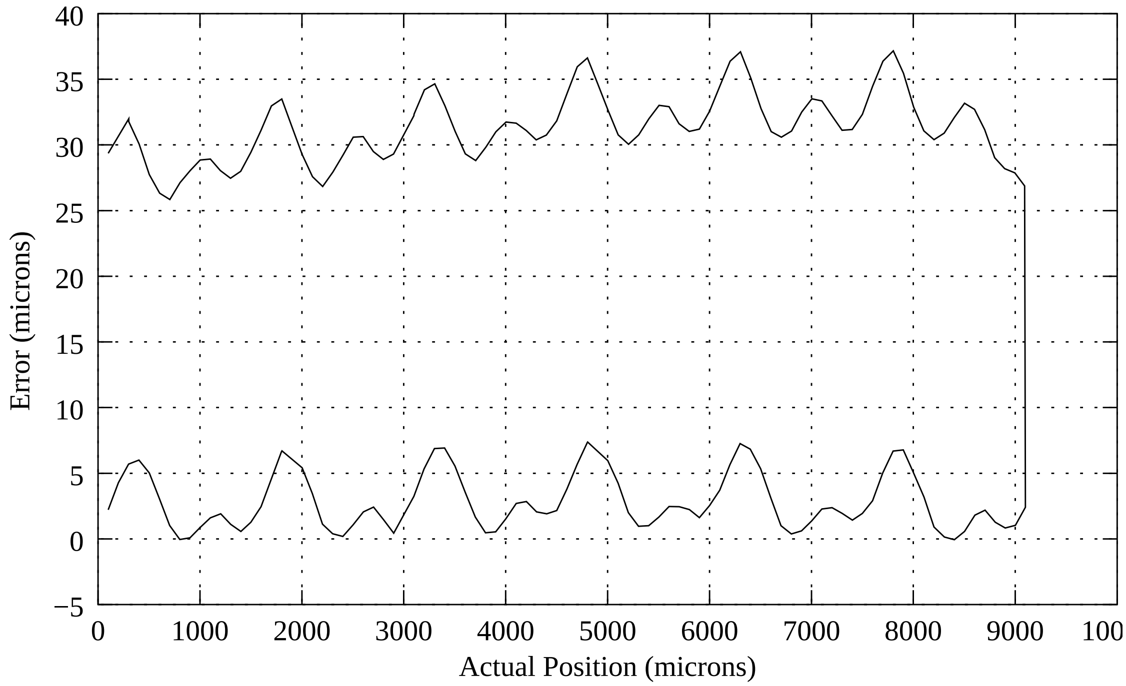

Figure 38: Error vs Actual Position, ADS17