Servo Cylinder

Understanding Test Results

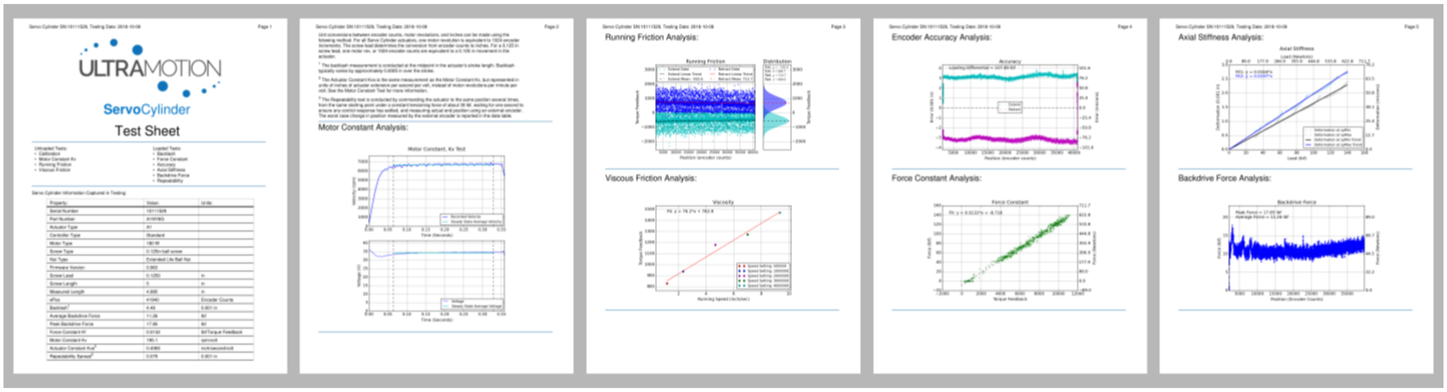


Figure 1: Servo Cylinder Test Sheet Thumbnails

Contents

Purpose:

Each Servo Cylinder equipped with an -N- or -P- controller undergoes thorough testing before being shipped to a customer. The CANopen Servo Cylinder controller does not go through this acceptance testing procedure. This document is intended to allow a user to fully understand the Servo Cylinder Test Sheet results, and how to apply these results to better understand your actuator. This report is organized into three main sections, the Testing Overview, which supplies general introductory information, the Test Sheet Cover Page section, which describes the information supplied on the first page of the Test Sheet, and the Test Procedures section, which gives a detailed description of all testing procedures and described how to read the results. For consistency, all testing examples in this guide are taken from one A1NY8G Servo Cylinder, which is referred to here as the "example actuator."

Testing Overview

About the Test Setup

Testing on Servo Cylinder actuators is conducted in a specialized fixture, which is equipped with a load force supplying actuator, an external optical strip encoder, and a load cell. All other measurements such as encoder position and torque feedback come from the built in drive electronics. Some tests require no outside loading or measurements. These unloaded tests are conducted in a decoupled state, and do not require the fixture.

Tests

Tests procedures that are performed on a Servo Cylinder actuator can be divided into two groups, tests that can be run with only the on board drive electronics, and tests that require external loads and measurements, which are supplied by a custom test fixture. These tests are respectively referred to as unloaded and loaded tests in this report, and on an actuator's test sheet. Table 1 lists unloaded test procedures, and Table 2 lists the loaded procedures. Detailed descriptions of each of these test procedures are supplied in the Test Procedures section of this document.

Table 1: Unloaded Test Procedures

Test Procedure:	**Description:**
Calibration	One time end stop calibration
4-20 mA Loopback Check	4-20 mA input/output verification. (Only conducted on compatible controllers)
Motor Constant Analysis	Determines motor constant Kv. Reported in the Test Sheet Data Table.
Running Friction Analysis	Measures low speed running friction over the full stroke length.
Viscous Friction Analysis	Determines actuator viscous constant.

Table 2: Loaded Test Procedures

Test Procedure:	**Description:**
Backlash Analysis	Measures zero load lead screw backlash. Reported in the data table.
Accuracy Analysis	Measures relative error over the entire stroke length of the actuator.
Axial Stiffness Analysis	Determines the actuator stiffness relationship.
Force Constant Analysis	Determines the relationship between internal torque and force output.
Backdrive Force Analysis	Measures the average and peak force required to backdrive the actuator. (Not conducted on self locking lead screw actuators)
Repeatability Analysis	Measures the actuator's precision in consistent, uniaxial loading.

Unit Conversions

Most units in the Test Sheet are reported in imperial units: in, 0.001in, lbf, and seconds. Units internal to the actuator, specifically encoder counts and Torque Feedback, are also used in the test results. Encoder counts are directly related to motor revolutions, with one motor revolution being equivalent to 1024 encoder counts. Motor revolutions, in turn are directly related to actuator extension by the screw lead. Actuator displacement can therefore be calculated in terms of encoder counts by the equation below.

$$Actuator\ Displacement = Encoder\ Counts * \left(\frac{screw\ lead}{1024}\right)$$

Using this equation an actuator with a 0.125” lead would show 0.125” of displacement for a commanded motion of 1024 counts.

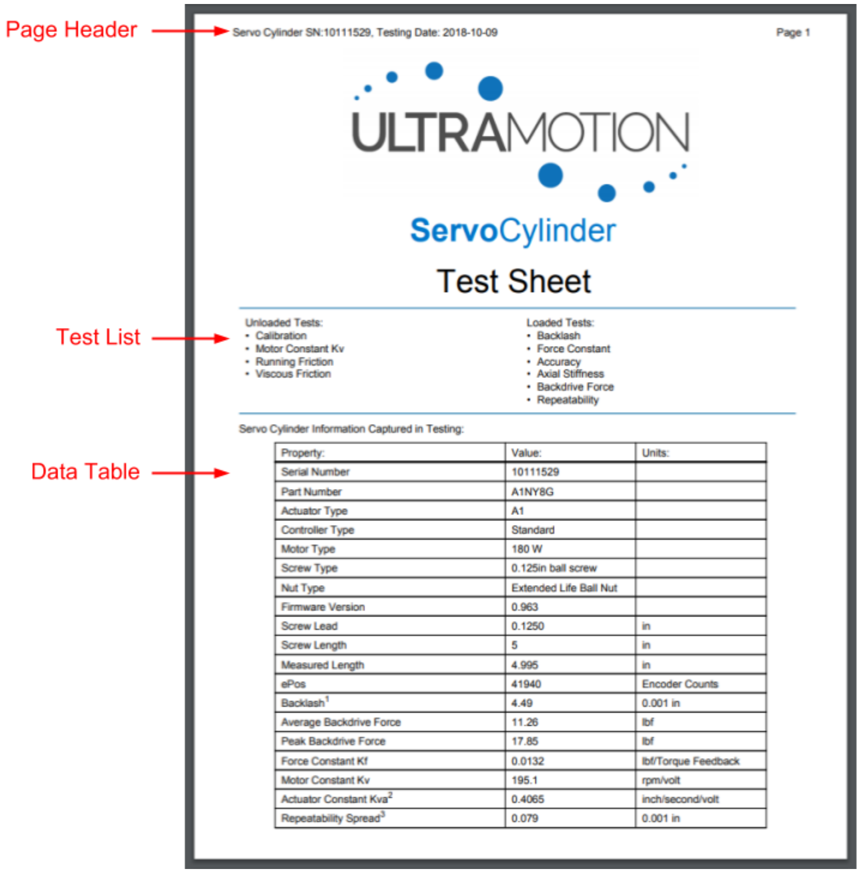
Torque Feedback is used throughout the Test Sheet to define the Servo Cylinder’s torque measurement. In the Servo Cylinder manual this is sometimes referred to as Motor Current (streaming variable 3). This measurement can be used as an approximation of motor current through the following relationship:

$$Phase\ Current_{peak}(Amps) = 0.000763 * Torque\ Feedback$$

The approximate force output of the actuator can be calculated using the force constant and offset determined in the Force Constant Analysis. See the Force Constant Analysis section for more details.

Test Sheet Cover Page

The cover page of the Test Sheet contains three important sections: the page header, the test list, and the actuator data table, as shown in Figure 2. The page header contains the actuator serial number and the testing date. The test list section outlines which unloaded and/or loaded tests were conducted. Finally, the data table provides full identifying information for the actuator as well as some important test results.



Servo Cylinder SN:10111529, Testing Date: 2018-10-09 Page 1

ULTRAMOTION

ServoCylinder

Test Sheet

Unloaded Tests:
- Calibration
- Motor Constant Kv
- Running Friction
- Viscous Friction

Loaded Tests:
- Backlash
- Force Constant
- Accuracy
- Axial Stiffness
- Backdrive Force
- Repeatability

Servo Cylinder Information Captured in Testing:

Property:	Value:	Units:
Serial Number	10111529	
Part Number	A1NY8G	
Actuator Type	A1	
Controller Type	Standard	
Motor Type	180 W	
Screw Type	0.125in ball screw	
Nut Type	Extended Life Ball Nut	
Firmware Version	0.963	
Screw Lead	0.1250	in
Screw Length	5	in
Measured Length	4.995	in
ePos	41940	Encoder Counts
Backlash[1]	4.49	0.001 in
Average Backdrive Force	11.26	lbf
Peak Backdrive Force	17.85	lbf
Force Constant Kf	0.0132	lbf/Torque Feedback
Motor Constant Kv	195.1	rpm/volt
Actuator Constant Kva[2]	0.4065	inch/second/volt
Repeatability Spread[3]	0.079	0.001 in

Figure 2: Servo Cylinder Test Sheet Cover Page, with header, test list, and data table.

Page Header:

The header on every page of the test results contains the serial number of the test unit, the testing date, and the page number of the testing data. This can be used to match results if pages become separated. See Figure 2, to identify the header.

Test List:

Information on which tests were conducted can be found below the Ultra Motion logo, as shown in Figure 2. Most actuators receive full loaded and unloaded testing, which includes all of the tests listed in Table 1 and Table 2, except for the 4-20 mA loopback check, and the backdrive test. The 4-20 mA loopback test will only be conducted on actuators with Industrial version controllers. The backdrive analysis is conducted on all ball screw actuators, but cannot be performed for self locking lead screw actuators. Note that some actuators with custom modifications are incompatible with our testing fixture, and may receive only unloaded testing which is sufficient to identify any serious defects.

Data Table:

The data table, shown in Figure 2, contains self-explanatory information fully defining the actuator type, as well as important performance information captured in testing. Table 3 describes identifying and performance information reported in the Test Sheet data table, and provides sample values for the example actuator.

Table 3: Data Table Properties

Property Name	**Sample Value:**	**Description**
Serial Number	xxxxxxxx	Unique Ultra Motion Serial Number
Part Number	A2NZ9C	Servo Cylinder Part Number, encoding model information
Actuator Type	A2	Defines actuator series, (A1: unsealed, A2: sealed, AU: underwater)
Controller Type	Standard	Servo Cylinder controller type (Standard, Industrial, CAN)
Motor Type	100 W	Defines motor wattage (100W or 180W)
Screw Type	0.125in ball screw	Defines screw variation, indicating lead and ball screw vs. acme screw
Nut Type	Standard Ball Nut	Defines ball nut version, or acme nut material
Firmware Version	0.963	Indicates the actuator firmware version
Screw Lead	0.125in	Nominal screw lead
Screw Length	5.75	Nominal stroke length
Measured Length	5.747	Calculated based on end-stop displacement measurement
ePos	48106	Extended end-stop position (retracted end-stop is defined as position 1024)
Backlash	2.78×10^{-3}in	Zero load backlash measured at stroke midpoint. See the Backlash Analysis section for details.
Average Backdrive Force	18.07 lbf	The average load measured during backlash testing. See the Backdrive Force Analysis section for more details.
Peak Backdrive Force	24.66 lbf	The maximum load measured during backlash testing. See the Backdrive Force Analysis section for more details.
Force Constant Kf	0.0126 lbf/Torque	The actuator's dynamic force constant, in units of lbf/Torque Feedback. For details see the Force Constant Analysis section.
Motor Constant Kv	200.1 rpm/Volt	Maximum motor speed in rpm / supply voltage. See the Motor Constant Analysis section for details.
Actuator Constant Kva	0.4168 in/sec/Volt	Maximum actuator speed in in/s / supply voltage. See the Motor Constant Analysis section for details.
Repeatability Spread	0.059×10^{-3}in	The maximum observed displacement between rest positions as the actuator is commanded to the same position several times, under consistent uniaxial loading. See the Repeatability Analysis section for details.

Test Procedures

Motor Constant Analysis

The actuator's motor constant is measured by commanding the actuator to run at its maximum possible torque/speed while moving between the spMin and spMax positions and recording position, time, and supply voltage, in a completely unloaded state. This data is processed to reveal the motor constant Kv = steady state speed (rpm)/ steady state supply voltage (Volts). We also calculate the actuator constant as Kva = steady state speed (in/s)/ steady state supply voltage (Volts). Figure 3 shows the data from this test as it appears in the main body of the report for the example actuator. The calculated motor constant and actuator constant can be found in the data table. In this case the motor constant, as shown in Table 3, is 200.1rpm/Volt, which is typical. Note that this test, and all other tests are conducted using a 36V Ultra Motion Power Supply.

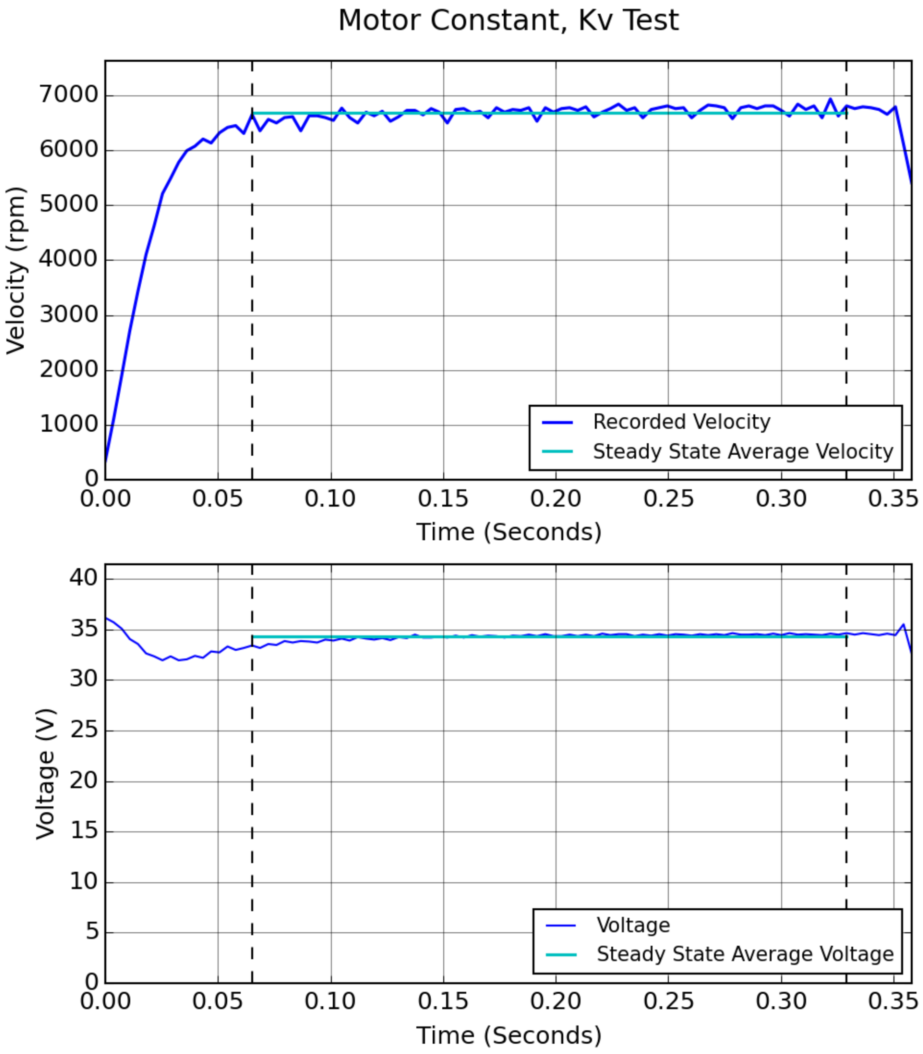


Figure 3: Motor Constant Test Data

Running Friction Analysis

During the running friction test, the actuator is given trapezoidal trajectory commands to slowly extend and retract between the spMin and spMax positions. The actuator speed is set to 50,000, and the actuator is configured to stream position and the motor torque required to maintain the constant speed trajectory. For constant speed motions, torque feedback (sometimes referred to as Motor Current/Streaming Variable 3) defines the torque required to overcome resistance to the defined motion. In an unloaded state, at a low speed, external forces and internal viscous forces are eliminated, enabling us to use the torque feedback measurement as a measurement of the internal friction of the actuator, as well as the base level of torque required to move the actuator. Torque feedback uses the same units as the actuator max torque setting. Most actuators require an average of 1,000 torque counts to overcome internal frictions. This data is displayed for both the extend and retract motions in the running friction plot in the main body of the Test Sheet. An example of this plot is shown in Figure 4. Looking at this example, we can see the average torque values, as well information on the spread of the data, which is a function of the stiffness of the PID control loop used to regulate position, as well as internal bind points or imperfections in the screw. This information is used by Ultra Motion to determine if an actuator meets shipping requirements. The data collected in this test is closely related to the backdrive force test, which is an external measurement of the force required to extend the actuator at low speed.

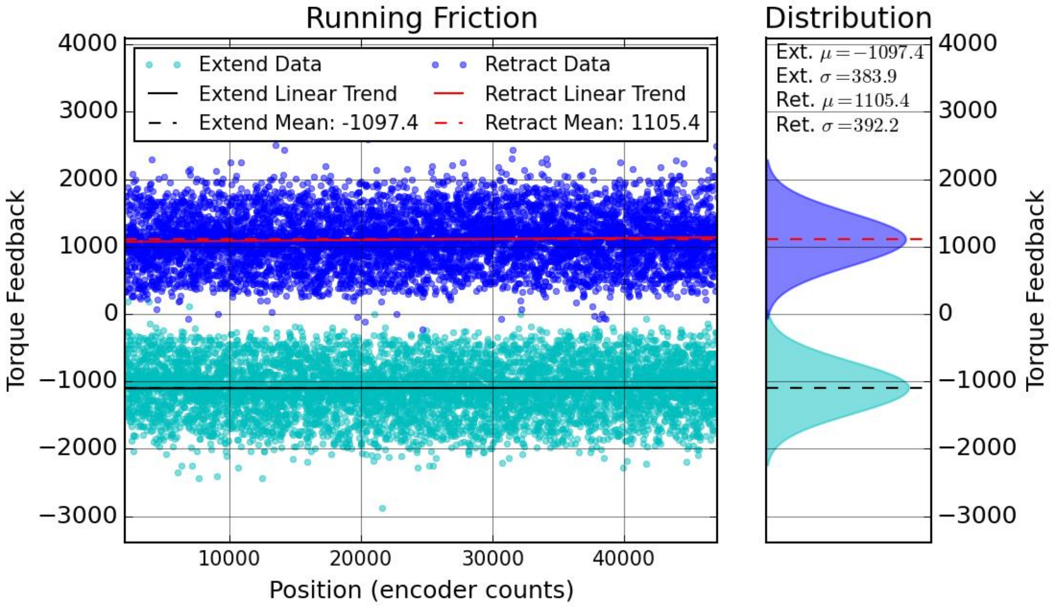
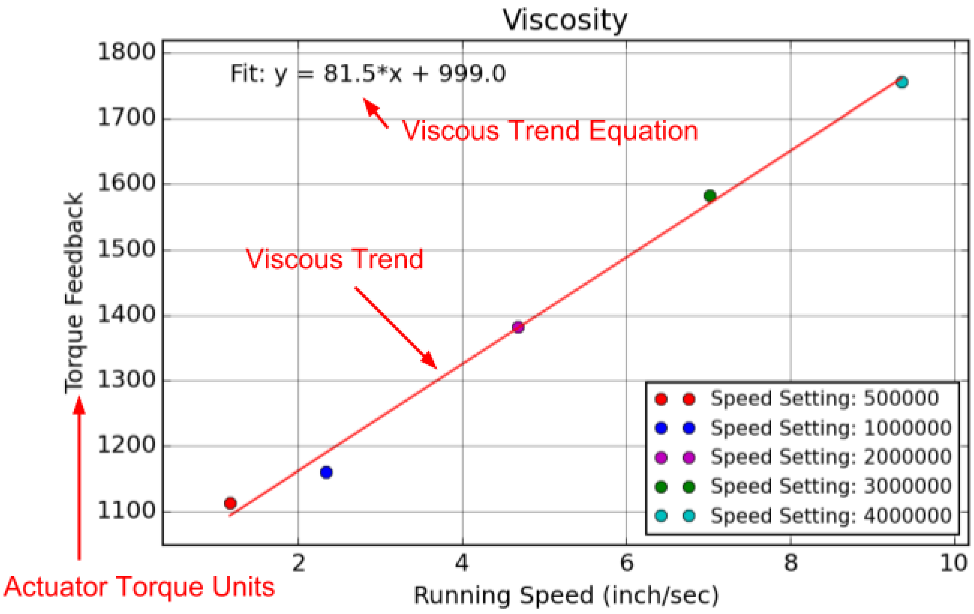


Figure 4: Running Friction Plot Example

Viscous Friction Analysis

The viscous friction analysis is conducted by commanding trajectory moves with different speed settings, while recording position, time, and torque feedback. Data from the steady state portions of these movements is processed to give steady state average torque output, which is plotted against steady state speed in inches of actuator extension per second. The linear trend observed in the viscosity test plot (Figure 5), allows us to calculate the average torque required to operate the actuator at any running speed. See Figure 5 for a detailed explanation of test results.



Viscous Trend Equation

Viscous Trend

Actuator Torque Units

Figure 5: Viscosity Test Data Explanation. The actuator viscosity constant is measured in terms of internal torque feedback per running speed in inches per second, and is calculated based on several running speed data points. This data can be used to anticipate the affect that running speed will have on force output. On this actuator, as running speed approaches 10in/s running friction is nearly doubled over the low speed running friction observed in the running friction test (Figure 4). These results can also be used to estimate the physical speed of the actuator based on the trajectory speed setting, by matching the speed setting in the legend to the running speed indicated by each data point. Actuator viscosity is caused largely by viscous effects within the motor windings (iron losses), and viscous effects of the grease lubrication. If the viscous constant is very high, this can be an indication that the motor has been damaged.

4-20 mA Loopback Check

The 4-20 mA loopback test is conducted only on Servo Cylinder actuators that have an Industrial -P- controller, which features a 4-20 mA input signal, as well as a 4-20 mA output. In this test, the 4-20 mA output is connected to the input, to confirm that the output signal is within the expected tolerance.

Backlash Analysis

The backlash analysis measures the zero-load lead screw backlash, which is not captured by the Phase Index encoder, at the stroke midpoint. This is accomplished by commanding the actuator to its midpoint, loading the actuator in compression to ensure that the backlash is fully actuated, and then slowly unloading to a zero-load state with the actuator against one side of the backlash. This procedure is then repeated in tension so that the actuator is up against the opposite side of its backlash. The change in position during this procedure is measured with an external optical strip encoder with a resolution of 0.00002”, and is reported in the data table on the first page of the report. Backlash typically varies by up to 0.0005” over the full stroke. It is important to note that the effective backlash observed in use is also affected by changes in loading, which cause elastic deformation. See the accuracy analysis for more details about how this can affect performance.

Accuracy Analysis

The accuracy analysis compares the Servo Cylinder’s reported position to an external position measurement conducted with an optical encoder with a resolution of 0.5 µm, and accuracy of 3 µm/m. This test is carried out by loading the actuator with approximately 55 lbf in compression, and commanding the actuator to slowly progress from its fully retracted to fully extended positions, while recording internal and external position, and loading. The loading direction is then reversed to 55 lbf in tension, and the actuator is commanded to return from its extended to fully retracted positions. The observed difference between the internal and external position feedback is calculated as error for this full movment and is dispalayed in the accuracy test plot (Figure 6), as relative error vs reported position. This plot shows a comprehensive summary of overall error, including, in order of importance, backlash, axial deformation, lead error, and Phase Index error along with localized loading variations. Backlash in this test is composed of the combination of the zero load backlash, measured in the backlash analysis, and the change in axial deformation casued by the the approximately 110 lbf loading differential in the shift between tension and compression. Axial deformation can be predicted based on the results of the axial stiffness analysis. The error introduced by axial deformation is emphasized in this test, to give the user accurate expectations for performance under varying loading conditions. Lead error is characterized by trends in the error extending over multiple motor revolutions, as displayed in Figure 6. Finally, the combination of phase index uncertainty and small variations due to inconsistencies in the loading, are characterized by small osicllations in error. The peak to peak error for this example is approximately 0.006”, meaning that under similar loading conditions we can expect relative error to be at worst 0.006”.

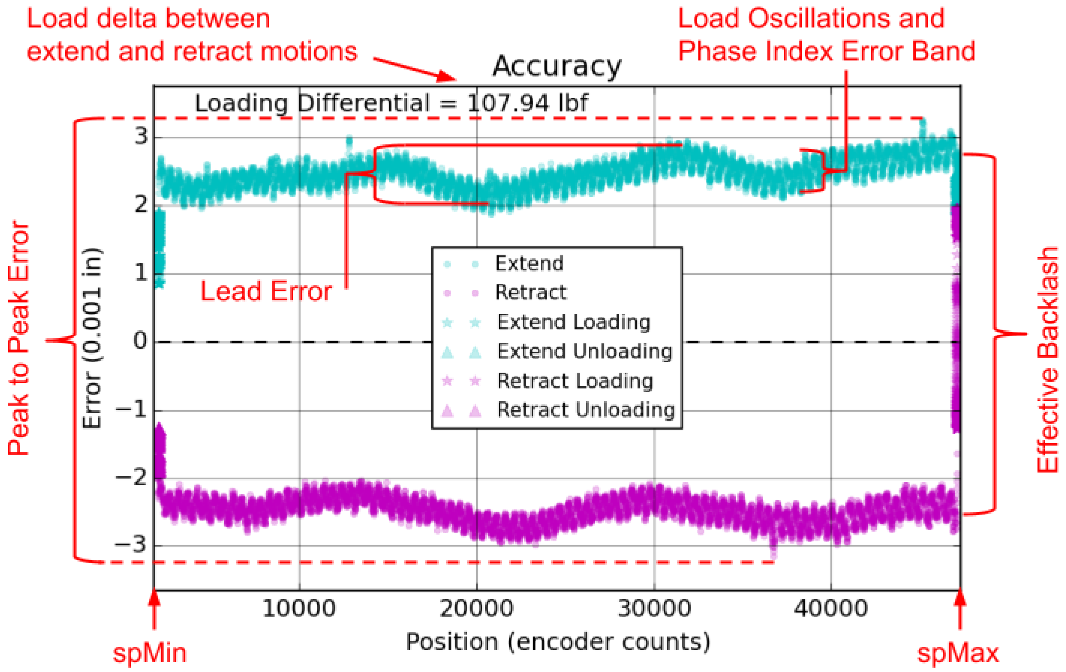


Figure 6: Accuracy Test Plot Explanation. The Accuracy plot shows overall worst case error measurements at the specified loading differential. In this plot we can see contributions to the overall error from several different sources including lead screw backlash, axial deformation, lead error, Phase Index error, and small oscillations resulting from uneven loading. Axial deformation and backlash are observed together as effective backlash. For this actuator the zero load backlash is 0.00278” (see Table 3), and the expected axial deformation is approximately 0.002”, based on the axial deformation analysis at 108 lbf (Figure 7), so the effective backlash should be approximately 0.00048”, which is consistent with the observed results.

Axial Stiffness Analysis

The axial stiffness analysis is conducted by commanding the actuator to maintain position at its spMin position, while the loading actuator applies a steadily increasing tensioning load. After a sufficient load has been reached, the loading actuator reduces load to zero, and the procedure is repeated at the extended spMax position. During each loading procedure internal and external position and load are recorded. Deformation is calculated as the relative motion recorded by the external optical strip encoder while the internal Phase Index encoder reports no change. Data from this analysis is displayed in the Axial Stiffness plot (Figure 7). The stiffness constants displayed in the upper left corner of the plot can be used to estimate axial deformation under different loading conditions, although it is important to note that the actuator mounting configuration affects axial stiffness. In the test fixture the actuator is mounted in a shaft clamp style mount, most similar to the Ultra Motion Adjustable Clamp mount. Stiffness will typically be lower at the fully extended position, because more of the lead screw is under tension. This effect is exaggerated for longer stroke length actuators. To calculate expected deformation, for instance under the loading delta of 108 lbf indicated in the accuracy test, we can take an average of the two different fit equations, which should be approximately equivalent to the deformation at the stroke midpoint:

$$Deformation = \left(\frac{0.0174 \times 10^{-3}\,\frac{in}{lbf} + 0.0208 \times 10^{-3}\,\frac{in}{lbf}}{2}\right) * 108lbf = 0.0021in$$

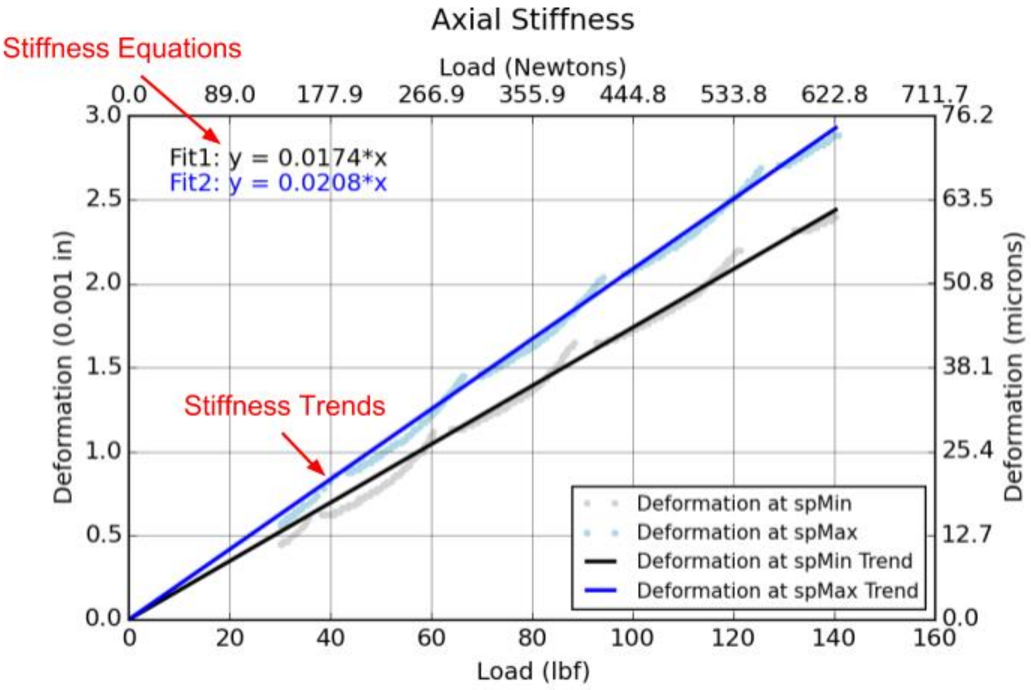


Figure 7: Axial Stiffness Plot Explanation. The axial stiffness trend is measured in tension at both the minimum and maximum extended positions. Typically these should be very similar, but with the fully extended position showing slightly less stiffness. Small peaks and breaks in the testing data are caused by the control system responding to increasing load, and can be ignored while analyzing mechanical deformation.

Force Constant Analysis

The force constant analysis is conducted by commanding the test actuator to slowly retract against the loading actuator, which supplies a steadily increasing load. Load cell measurements and internal torque output are recorded until a loading threshold is reached. The data collected is plotted in the Force Constant plot (Figure 8), along with a best fit line and the matching equation giving force output per applied motor torque. The force constant calculated in this test, along with the running friction and viscous friction measurements can be used to build a detailed force output model for the actuator:

$$Force = Kf * \left(Torque - Running\ Friction - (Viscous\ Constant * Running\ Speed)\right)$$

For the example actuator examined in this document, this equation would be:

$$Force = 0.0126 * (Torque - 1100 - (81.5 * Running\ Speed))$$

This relationship can be used to determine the torque that will be required to move against a resistive load. Users should note that the continuous torque limit for Servo Cylinder actuators is MT = 9000 for 100W motors and MT = 14,000 for 180W motors (assuming lab environments). As described in the Servo Cylinder manual, the torque limit of 9000 corresponds to approximately 100 lbf output for standard ballscrew actuators. The data shown in Figure 8 confirms this relationship. Setting the max torque over this limit should only done in cases where high force output will be momentary.

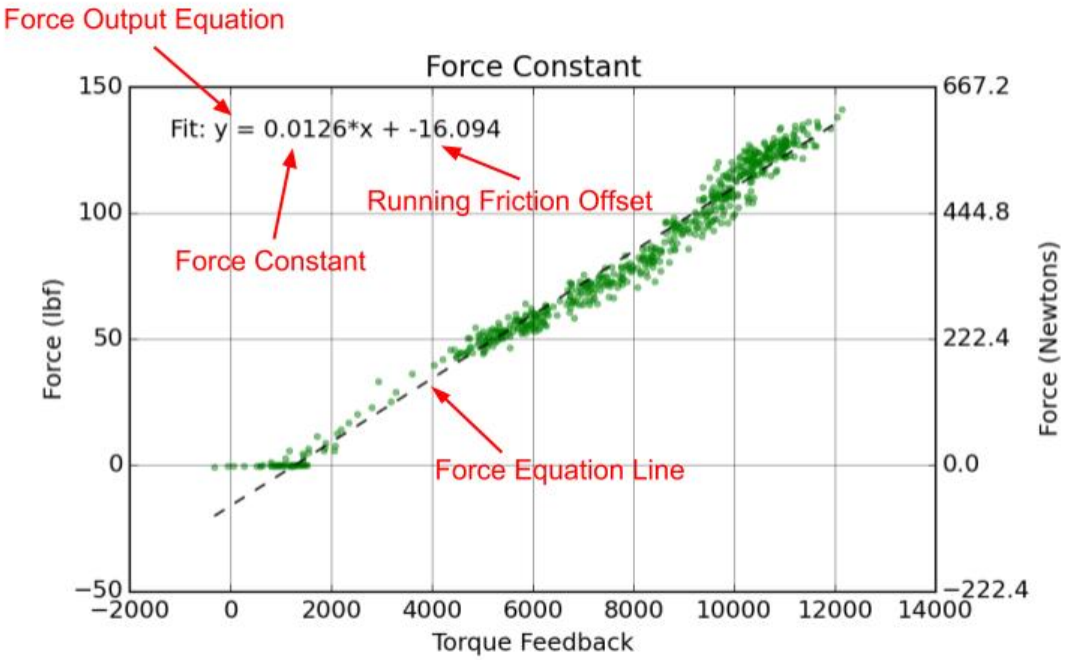


Figure 8: Force Output Plot Explanation. The force output analysis is conducted in tension, and captures the dynamic relationship between the torque reported by the actuator, and actual force output. Any time the actuator is moving it must overcome running friction, so we see no output force until the torque output goes above approximately 1000. This is consistent with the average running torque observed in the running friction test (Running Friction Analysis). Nonlinearities in the captured data result from varying efficiency in the lead screw and PID interactions between the loading actuator and the actuator being tested. Note that only a small portion of the actuator’s stroke is captured in this test.

Backdrive Force Analysis

The force required to backdrive the actuator is measured by "coasting" the test actuator at its retracted position, and commanding the loading actuator to steadily move from this position to the extended spMax position, while recording load cell readings and position. The results are displayed in the Backdrive Force plot (Figure 9). The average backdrive force is also reported in the data table.

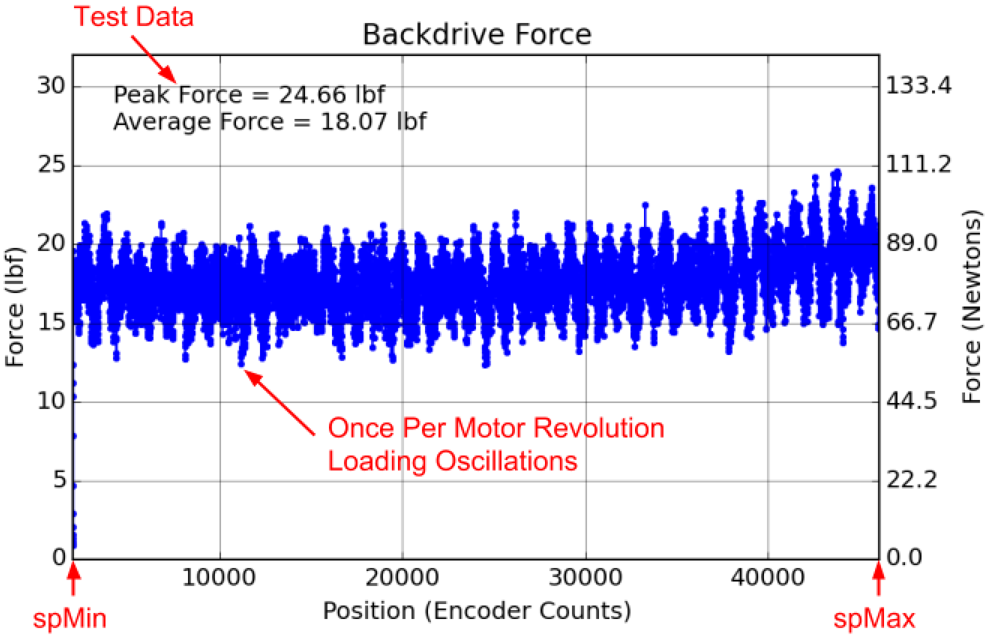


Figure 9: Backdrive Test Explanation. The average required backdrive force should be similar, but not necessarily identical, to the running friction offset observed in the force constant analysis (Figure 8), due to small differences in forward and backdriving efficiencies. Peak force can be used as a measure of the maximum force required to start movement. The noisy appearance of the data is caused by a combination of once per motor revolution friction oscillations, and small scale imperfections in the lead screw which are typical.

Repeatability Analysis

The repeatability analysis measures the actuator's ability to repeat a movement to the same position several times, under consistent uniaxial loading. In this procedure the actuator starts at the fully retracted position and then is commanded to an extended position, and back to the original retracted position, while the loading actuator provides a consistent tensioning force. This action is repeated several times while external position is recorded. The repeatability spread is taken to be the maximum difference in final position observed over all repetitions of this motion. The repeatability spread is reported in the Test Sheet data table.