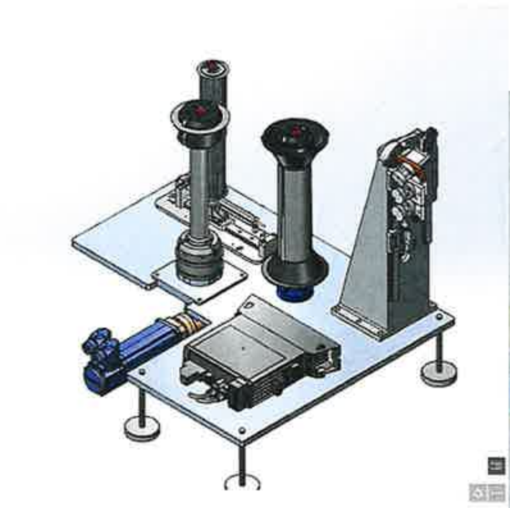
Bosch servo driven spool research

Abstract

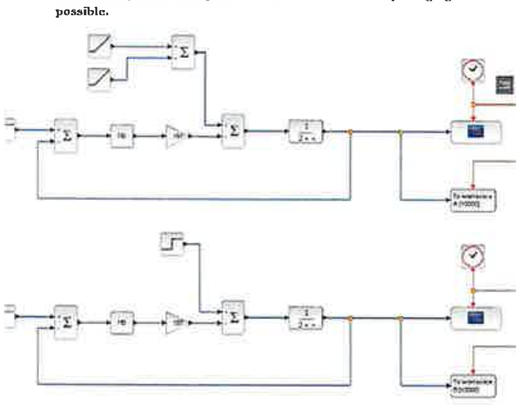
This document outlines the progress of the servo driven spool research process. This MSO Sway document serves as an executive summary detailing the primary results but not extensive calculations. A detailed report is kept internally for confidentiality purposes.



Test apparatus

The main features of the apparatus for testing is a main plate for mounting the take up, dancer assembly and 1/4" business end originally taken from 2 tow assembly. Drives are also mounted on the main plate via simple bolt holes. The model is shown following for reference.

The main feature is a sub-plate that allows different motors, brakes or gear box assemblies to be swapped out. In the first phase, we are interested in exploring different servo spooled options. **The primary goal is to achieve acceptable spool tension performance with the smallest packaging possible.**



Classical control and motor sizing

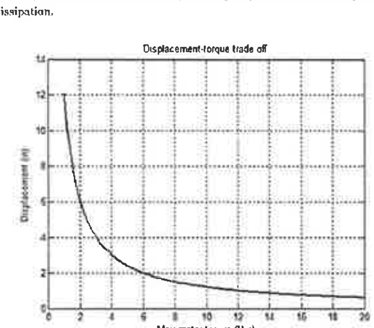
Most servo motor controllers have the functionality to send velocity commands directly. Such higher level commands pass through other processes in order to improve smoothness of operation.

In the scenario given, an integral process is controlled by the velocity input of the servo spool. Since the payout velocity is seen as an input disturbance, rejection must be done via integral action if only classical control is used.

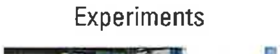
As requested from my supervisors, proportional control is to be proven first before more complex controllers are considered. It has also been shown that PI control is sufficient for maintaining tension. However, safety features such as anti-windup must be implemented as well in order to reduce overshoot and reduce safety hazards.

The important takeaway is that controller design allows us to push the limits of the motor. Thus, understanding how to select controller constants based on the system parameters, like peak torque, and equivalent inertia is extremely important. Poor selection of constants can result in high motor wear or oversized motors.

This requires further research since peak torque operation is limited by heat dissipation.

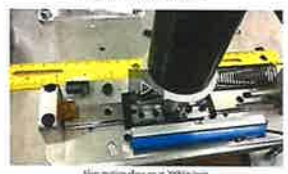


Experiments



First test with proportional control

First test with proportional-integral control



Diameter sensor

Currently, testing is being done in order to quantify whether a laser distance sensor, or ultrasonic sensor is more reliable and accurate. Controller gains will eventually be tuned based on diameter measurements, therefore it is pertinent that the sensor give reliable readings for good performance.

The experimental procedure is detailed below and repeated for both sensors to collect data.

1. Calibrate sensor
2. Load spool on test apparatus
3. Connect sensor to Bosch Indradrive (X32 Port)
4. Record sensor signal and position signal
5. Input step velocity command at 80,120,160,200RPM
6. Stop recording

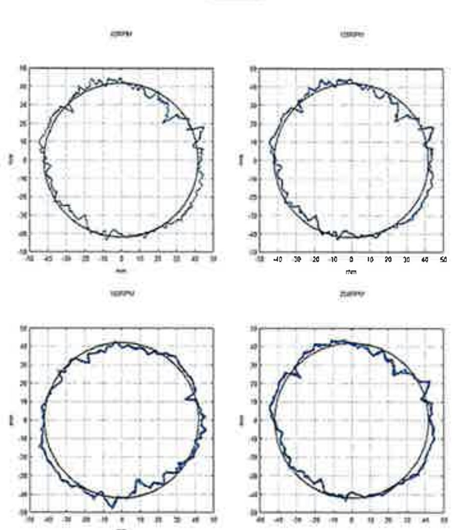
Precision Test

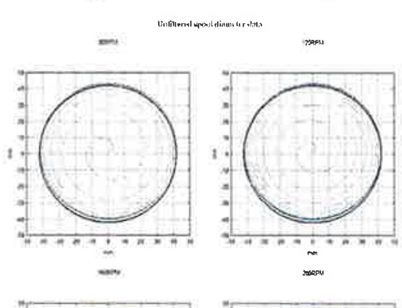
Laser Sensor (Balluff)

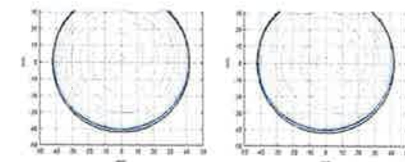
It was found that the black and yellow color difference between the carbon and the yellow backing can drastically affect the reading precision (+/- 15mm). However, since the cycle is repetitive, a first order filter can eliminate most of the fluctuation. The following comparison images show the effect of the filter.

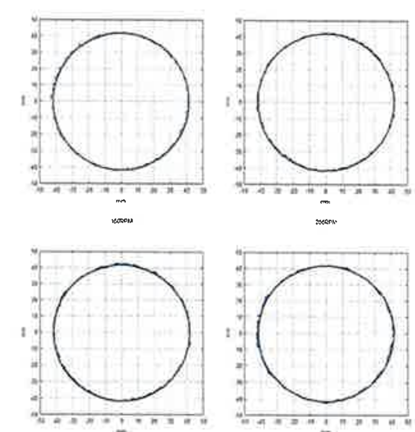
Thus, even though raw data is unreliable, a difference equation eliminates this problem almost completely. Notably, the digital filter must reach steady state initially, which takes about 4-5 time constants. This is the cause of the spiraling effect on filtered data.

Following the comparison picture is the data from using the cardboard spool which has uniform color, and regular surface bumps of ~0.5mm.



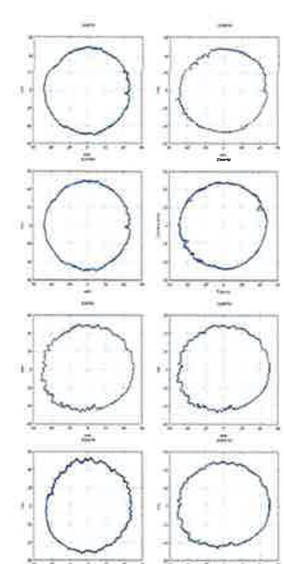






Laser (Leuze)

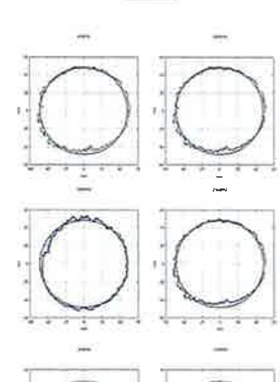
This laser performed very well relative to the Balluff laser in terms of precision with a maximum deviation of +/-7mm. This is about half that of the Balluff sensor. The standard deviation between one revolution of measurement is approximately 0.2m. The following picture is a comparison of the two, with the Leuze sensor on the left and the Balluff sensor on the right.

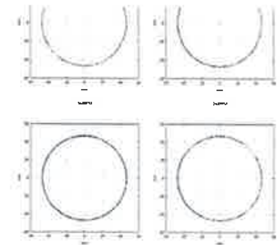


Ultrasonic sensor

Notably, the ultrasonic sensor was used in isolation from other ultrasonic sensors. There is cross sensitivity between such devices which corrupts readings. Thankfully the sensor does have modes of operation that allow multiple sensors to be used in a small vicinity. However, such functionality was not tested.

During testing at times a current spike was recorded, the cause is known, but likely due to the protoboard used to convert current to voltage via a resistor.

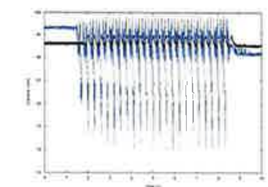




Accuracy Test

Using two spools of known diameter, both sensors were calibrated.

At 200RPM, the time domain diameter signals are shown. **In blue is the laser sensor, and in black is the ultrasonic sensor.** Notably there was wobble that did result in noticeable (~1mm) changes in radius, thus, the rotation does create real changes in distance and the sinusoidal nature of the signal is not due to cross sensitivity.



Diameter signal measurements over time

Result

Overall the ultrasonic sensor outperformed both laser sensors. However, the difficulty in implementation may prevent us from using it. Thus, the Leuze laser sensor will be used as a fallback. Following is a table showing the performance of the different sensors when measuring a **95.4mm** spool.

Sensor	95% CI (mm)	Min/Max (mm)
BOD000N	(94.4, 96.3)	(79.7, 105.0)
ODSL8	(95.0, 95.7)	(87.4, 99.2)
S0043	(95.2, 95.52)	(93.9, 96.5)

Animatics Testing

Abstract

After preliminary testing with the Bosch system, motor sizing calculations were verified so that different systems could be tested. The most promising seemed to be the Animatics integrated motor, drive and controller. This document outlines the tests and the performance of the system

Animatics motor mount

A new mounting plate and adapter elements have been designed. The new design uses a rigid shaft coupling in order to maintain the alignment between the spool and the gearbox output. Previously alignment was an issue and re-tightening the system was very cumbersome.

Servo packaging options

Currently, sourcing different motor options on the market is being done in order to obtain the smallest packaging possible that can drive the system without the dancer bottoming out.

Notably although many companies do offer reasonably small servo motors, the reducer takes up about the same amount of space. Harmonic Drives has expressed interest in working with EI in order to develop a thin gearbox (which they have done already in the past). This is for future testing after verification that the current motor selections are all viable options.

Harmonic Drive has also extended us high quantity unit pricing for gearboxes for testing purposes in order to establish good will for future business.

Moog Animatics Testing

Even though I understood the size difference from the CAD models, holding the Animatics motor in the palm of my hand was something else. It was amazingly small and light, although there are definitely a few drawbacks mainly from the software. Furthermore, real testing must be done in order to validate the motor's performance, as often spec sheets do not give a good indication of real world performance.

Main drawbacks

1. Software has very few features and even basic functionality must be coded using SmartMotor Interface (SMI) language
2. The software has no builtin data recording, this must be communicated via RS232 to Serial (which is slow but probably sufficient for testing)
3. No built in system identification of torque loop tuning (we must tune the system blind)

Main advantages

1. Since all software is written in house only necessary commands will be used
2. Data transfer can be highly optimized
3. Formulas for this application are extremely simple, learning UI is not necessary
4. 7 Fully configurable I/O to take analog or digital
5. Daisy chain-able (up to 100 motors)

Remedies to drawbacks

1. Learning the basic commands through user manuals and support from Jordan Schwarz (Olympus controls applications engineer)
2. Already have implemented real time data printing however, the transfer rate must be optimized
3. Using the data collected, comparing command velocity and the control signals can allow for a rudimentary identification of the system

Position loop identification

Dan W. a senior applications engineer at Moog Animatics has replied to email indicating that the documentation around the PID loops by Animatics is proprietary. That is, the exact structure and implementation is not available. This is why documentation around the position control loop specifies a tuning method that is based on the Ziegler-Nichols method of empirical tuning.

Although it is very simple to perform Ziegler-Nichols manually, doing this for 16 motors on each head and ensuring that performance is reasonable for different spool diameters (which really means different inertia) is very cumbersome. This is why automatic tuning methods based on theory and verified by empirical tests method are of interest.

This section deals with the development of automated model based tuning methods to allow easy commission of the tension control system.

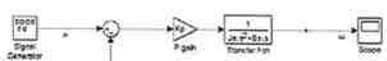
Ideally, the daisy chained system is wired, and one RS-232 communicates to a laptop via COM port and a test is run, tuning all 16 internal loops automatically. This is one of the standard modes of connection supported by SmartMotors and is shown in the diagram following.

Theoretical basis

Dan W. verified that the output of the controller accessible for tuning is a torque, thus the controller interacts with a second order system from Newton's law. Closing the loop then theoretically creates a second order system.

Note that in this model, the current control loop and PWM generators are ignored. This is because such systems are often of very high frequency (kHz order) which cannot even be measured via the current method which has a maximum of 500Hz sampling rate and are also irrelevant to the system which operates in the 0.1s response time range.

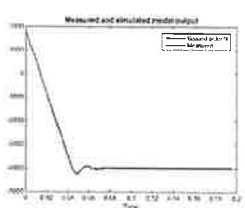
The simplified theoretical system is shown below. Note that the input to the system is in counts, and the output also in counts. Je and Be are scaled inertia and damping values respectively, which have unknown units.



Simplified theoretical system

Step test

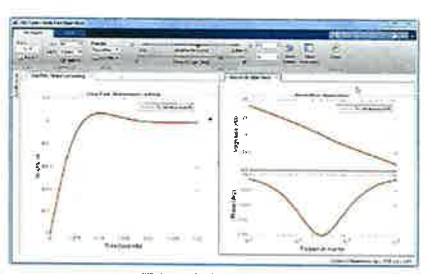
A step test with high gain from the model will reduce the steady state error due to friction and also reduce the damping ratio. It can also be thought of as increasing the bandwidth and decreasing the phase margin in a more general sense. A curve fit done in MATLAB was used to identify the system. Note that a true step cannot be done in practice since position cannot instantly change, thus a ramp to position was used. In the specific test following, the Kp value was set to 2000.



Model based tuning

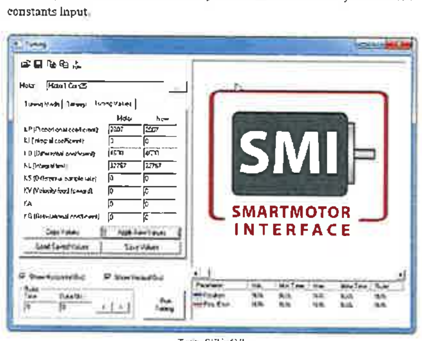
After the step test, a model of the plant has been made (Je and B constants identified). Now we can tune the PID in MATLAB with a few realistic constraints in mind. As a preliminary test, PD control is tested.

In frequency domain, it is very easy to tune the system, overall 70 degrees of phase margin corresponds with a very stable system, and the bandwidth is increased until the Kp is approximately 2000, since it was tested and stable at this point. Inside the MATLAB console, we can see that the step response is reasonable.



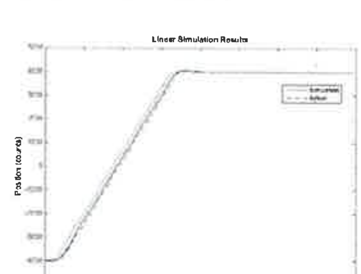
Experimental results

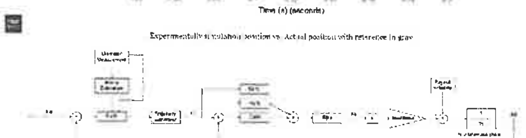
Using the SmartMotor Interface (SMI) the system can be experimentally tuned easily. This is a low time resolution tuning method built into the software. Following is the GUI used to tune the system with the theoretically determined constants input.



Experimentally, the simulation returned reasonably accurate results considering that a step identification was done. Thus, we can conclude that following identification via step input with high gain allows a reasonable estimation of the system for tuning purposes. Another interesting result of the theory is that the bandwidth and phase margin both increase as the inertia is decreased automatically based on the frequency response. **That is the system becomes more stable as the carbon is payed out.** Naturally, as the system loses mass, the performance can also be increased.

Further experimentation is necessary after mechanical components are made and the motor is installed in the test apparatus.





Fully tuned controllers

In preparation for testing, fully tuning the internal position control loop is important in order to get desirable performance. The PID loop inside the SmartMotor system is augmented by feed forward of velocity and acceleration via a constant gain. The desire then is to tune the following parameters:

- KP - Proportional Gain
- KI - Integral gain
- KD - Derivative gain
- KA - Acceleration feed-forward
- KV- Velocity feed-forward

Furthermore, the performance of this system must be evaluated as the inertia changes to ensure performance and safety.

The steps to tuning are outlined below:

1. Excite the system with a step input and find Kp such that a 20-30% overshoot occurs
2. Identify the system
3. Tune KD such that a 60-70 degree phase margin is obtained
4. Tuned KI such that the integral transition occurs at between 0.1 and 0.2 of the cross over frequency
5. Set KA = Je, KV = Be

This tuning method should allow for no large oscillations with less than 20% servo position overshoot, as well as steady state position, ramp, and acceleration tracking. However, since the Je constant will necessarily be changing as the spool unravels, the performance must be evaluated.

Analog Input

In order to test the analog input a potentiometer was connected to the 5V (PIN 12) and Signal ground (PIN 13) pins on the SmartMotor Breakout. The potentiometer leg was then connected to PIN 3 on the board and configured to be an analog input. This will be used to emulate proportional speed control without the dancer connected where rotating the potentiometer knob sets the speed.

Note that the dancer can have voltages up to 10V on the output and cannot run off the 5V on the breakout. This means that there will either need to be a DC-DC step up circuit or another connection to the high voltage. The motor itself is supplied with something like 48V maximum, meaning that in either case, a circuit will be necessary for step down or step up conversion.

So far the Balluff laser sensor will be tested, using a 5V to 24V step up will be able to power both the laser diameter sensor as well as the dancer displacement sensor.

Packaging size reduction

Dave Lax of Harmonic Drive had engineering work done to customize a standard 10:1 gear head (currently being used) to a shorter version. The shorter version, which has not been released would reduce the overall length of the gear head and motor assembly by 23%.

He has also suggested a 9:1 reducer, a standard part which is significantly smaller than the standard 10:1 reducer, with an overall length reduction of 33%. Following is the solid model comparing the current 10:1 reducer to the standard 9:1. Testing will be undertaken to see whether the 9:1 is a feasible option since significant packaging advantages as well as cost savings can be realized. This may require revisions to the control algorithm, and possibly even feed-forward.

New gearhead options

Previously, the new 9:1 reducer was introduced, which would likely require added complexity to the control scheme to make it would properly.

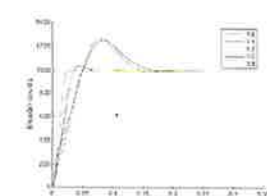
Speaking with Dave Lax gave insight on a new option that may be possible. If the Animatics motor shaft can be modified as the pinion, this would allow the 10:1 reducer to be used without mechanical coupling elements. Thus, the overall length would shrink to approximately 1/3 the original length, becoming even shorter than 9:1. This is likely a very expensive option, and it's costs and other factors will be weighed against the benefits.

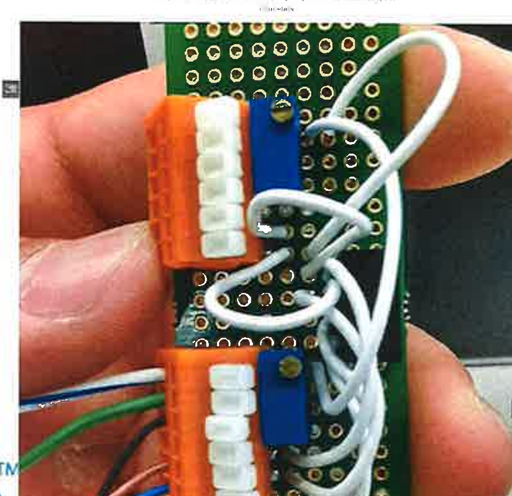
Experimentally validated torque loop stability

In theory, the PD controller which has input of position error, and output of torque should have increasing stability as the inertia decreases. This is due to the phase margin increasing as the open loop system shifts towards the high frequency range.

The main result is that practically speaking, the position response automatically increases bandwidth, and decreases overshoot. After initial tuning is done for larger spools, no adjustments need to be made unless performance must be pushed further at smaller diameters.

This was verified when a PD controller was tuned for a 7.63" diameter spool (KP = 500 KD = 2000) was used for 4 different smaller spools. **The trend is indeed verified that as the spool decreases diameter, the overshoot decreases, while the response speed increases.**





Dancer controlled speed test (Animatics)

A small circuit was made to power the sensors off the 5V supply within the motor. This allows the dancer sensor to be run off the motor. At this point, the dancer displacement data can be used to control the speed of the spool. Further testing is necessary to study the input circuit and ensure that the signal is in fact reliable.

Chris C. will soon provide a 3D printed distance sensor mount so that the analog voltage measuring dancer diameter can be added and studied.

Analog input biased

The analog input in most SM23165DT motors are hardwired to 5V. This causes problems in the sensor readings as there is additional signal from the VCC. A specific version SM23165DT-MTA1 does not have hardwired pull up resistors on the input, currently Olympus Controls is working on sourcing this version.

However, at this point, after dancer position calibration, tests can go ahead on the dancer position control response.

First payout test using full control loop

Using dancer and diameter sensors, the first implementation of a proportional control loop has been implemented successfully at low payout speeds. The torque control loop is pre-tuned and constant based on experiment while the higher level control loop takes in diameter measurements to calculate proportional gain.

On a side note, turning up the gain creates small oscillations in the spool. Filtering dancer data will be done in future tests. The next important test is the 4000in/s test at 0.5G acceleration. Notably the pull up resistor connected to the analog input must be desoldered in order for the sensor to work properly.

High speed tests

The first high speed test was conducted at 0.5G acceleration to 3000in/min. Noticeable overshoot on the deceleration is a problem, and debugging will be done. Currently it is hypothesized that the trajectory generator ramp is adversely affecting the system.

First high speed test at 3000in/min at 0.5G

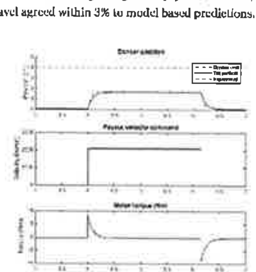
After setting the acceleration ramp high, velocity commands could effectively be sent without delay. The result is that the overshoot on the return is eliminated. Using the tuning techniques derived for the higher level controller, operation at 4000in/min was possible and stable. Currently, tests will be done to validate the stability at different diameters.

Update: Testing the 9:1 reducer with 5" diameter spools yields good stable results at 2000in/min and 4000in/min (0.5G). Picture below.

New servo assembly with 9:1 reducer attached

Simulation confirmation

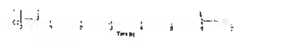
In order to confirm that stead state dancer displacement can be predicted to a reasonable accuracy an experimental was done with a 4.4 inch diameter spool at 2000in/min payout speed. Results are shown in the graph following. Note that the model neglected the complexities of the torque loop, which is likely the reason of variation near the beginning of the payout. However, in steady state the dancer travel agreed within 3% to model based predictions.



Large spool tests

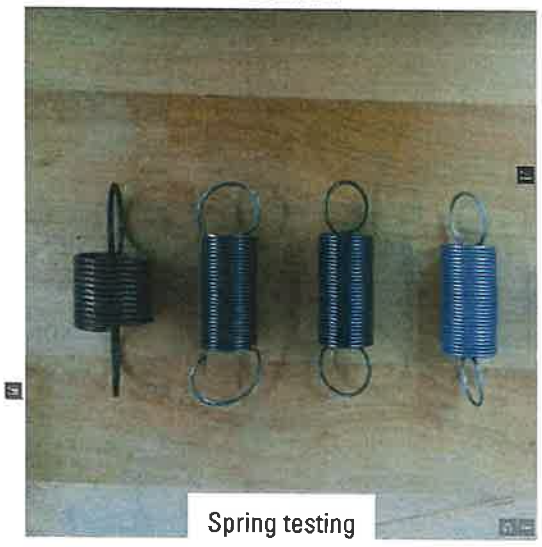
In theory 8.5" spools are the primary worry as they have extremely high inertia's relative to smaller spools. This is also observed as the torque loop and high level control loop both become less stable with the larger spool.

The test below is significant as it is a step test at 2000in/min with the largest spool that the system will face on current designs. Currently, 3000in/min with a 0.5G ramp has also been tested with success. It is hypothesized that the higher order oscillations in the dancer signal can be tuned out using integral action, however, this has yet to be tested.



Dancer displacement over time during payout

The final test to validate the feasibility of the servo spool is done. The 0.5G ramp to 4000in/min shows minor oscillation, and was purposely run near the max dancer displacement for better dynamic stability. In practice, there is approximately 1 inch more of dancer travel, allowing proportional control to work effectively alone and its less aggressive, more stable region.



Spring testing

In theory, when cascade control is implemented, the effect of the spring is minimal. As long as sufficient tension is maintained in the tow, the system behaves as a pulley system. The problem with heavier springs is that in deceleration the tension force opposes motor torque. This is especially problematic when proportional control is implemented with constant set point during high speed payouts as large dancer displacements will be present.

Thus, using the lightest spring possible is of interest for consistent symmetric performance in acceleration and deceleration during payout.

Currently, the spring constant in the 16 tow heads is approximately 4.6lb/in (Century 80962). This means during deceleration from 4000in/min, with the current tuning rules the opposing torque is approximately 3.36Nm during initial deceleration. This reduces the effective torque by 40% making the system perform poorly.

Of springs tested **Century 80826S** performed best. In the same scenario, the opposing torque is 0.64Nm, reducing effective torque by 8% initially. More importantly, no unexpected erratic behaviour was observed.