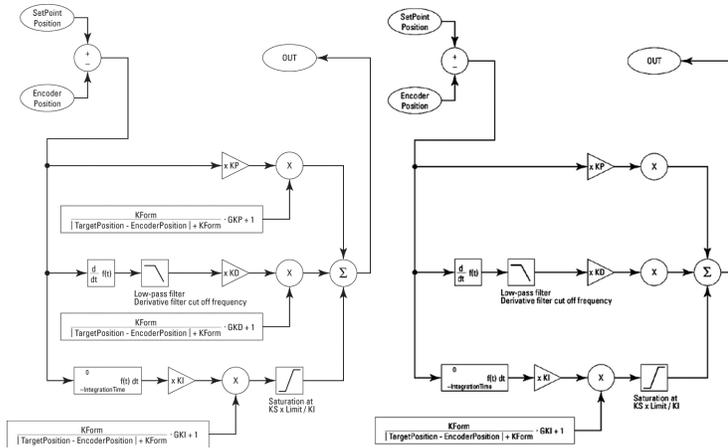


Basic Guidelines for Tuning With The XPS Motion Controller

1.0 Concept of the DC Servo

The XPS positions the stage by optimizing error response, accuracy, and stability by scaling measured position error by the correctors Proportional, Integral, and Derivative (Kp, Ki, Kd). The XPS responds to measured position error (Setpoint - Encoder) is indicated in Section 14.1.2.1 of the XPS user manual:



The Kform term in the left diagram is set to zero for standard stages. The Kform with variable gains is a tool for changing the PID parameters during the motion and reserved for larger assemblies and special stages. Standard DC Servo stages can have position certainty and stability set by the simplified diagram on the right. The diagram on the right can be written in the form below which provides an analogy for understanding the relationship between the corrector parameters Kp, Ki, and Kd.

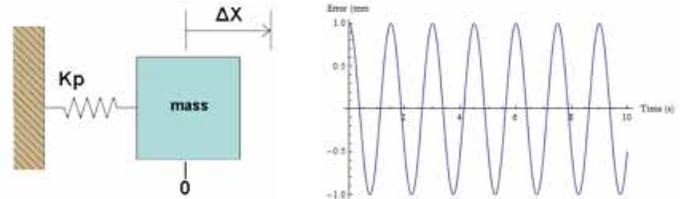
$$Output = K_p \cdot e(t) + K_d \cdot \frac{de(t)}{dt} + K_i \cdot \int e(t) dt$$

The relationship between Output and the terms Kp and Kd can be considered as a damped harmonic oscillator like a spring mass system or an LRC circuit. The Ki term is an integral of the error over time, hence it applies gain to the collection of error over time: the Ki term is the gain for steady state error. Similarly, it can be seen that the Kd term multiplied by the derivative in time applies gain for fast changes like a damper would. Finally, Kp applies gain for the instantaneous error in time and can be seen to speed the adjustment of error in the system by applying an immediate response. In the detailed description of the simple harmonic oscillator, the behavior of each corrector (Kp, Ki, Kd) becomes apparent.

1.1 Simple Harmonic Oscillator

In a simple spring mass system analogy, Hooke's constant is to the stretch in the spring as Kp is to error in position of the DC Servo. If the mass is set on a

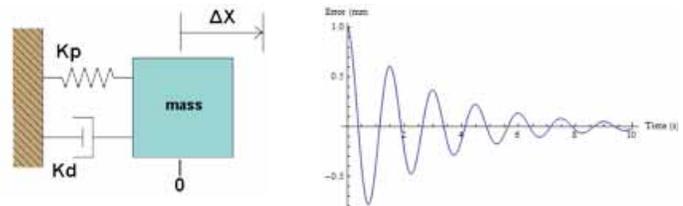
frictionless surface at a rest position and a perturbation is applied by pulling the spring and if the Kp (Hooke's) value were zero, then the mass would not move to correct for the perturbation. With an appreciable Kp>0, the spring responds and is put into oscillation.



Similarly, if the DC Servo were a perfectly frictionless system, then Kp would send the system immediately into oscillation as it corrects for position. Like a spring, the value of Kp results in the speed of response to the error: like a stiffer spring, a higher Kp will cause the stage to return more quickly.

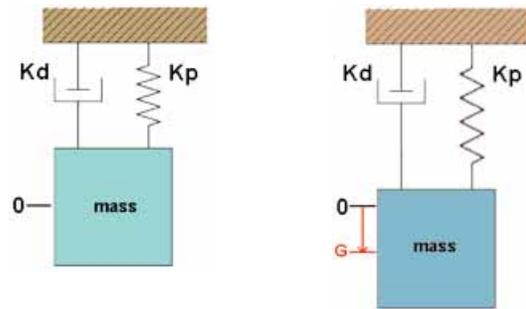
1.2 Damped Harmonic Oscillator

A real stage system, however, always has some friction or an electronic dampening term. The spring mass system shows that the magnitude of the error (periodic overshoot) is diminished by Kd. For a DC Servo, the Kp and Kd terms are sufficient to cause the stage to respond to an error and to settle the oscillations.

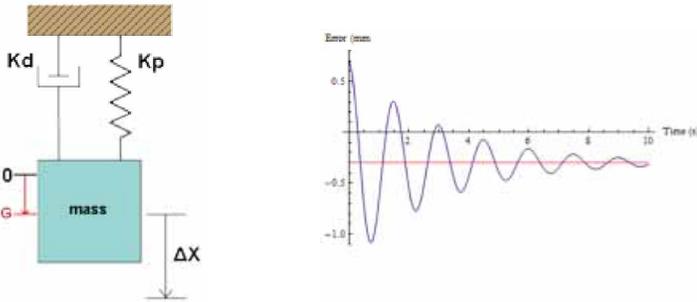


1.3 Following Error

In the spring system above the rest position and the target position are the same, X=0. Consider a situation where the rest position after responding to the error (Kp) and dampening the error (Kd) is displaced from the target position. This scenario can be illustrated by putting the spring mass system into the gravity field where gravity G applies a force away from the target position.



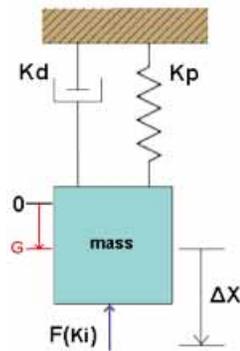
Basic Guidelines for Tuning With The XPS Motion Controller



In the image above, before any stretch is applied to the spring, the rest position is set to G instead of the target of X=0. Hence, after the spring is stretched and Kp responds and Kd dampens, the final position will have an error. This error is seen as position Error = -0.3mm in the image below: this error is the following error where Kp and Kd have no affect on it.

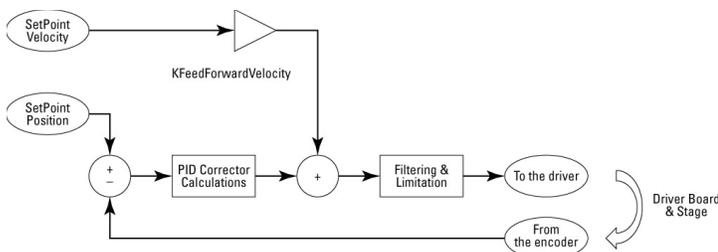
No matter how quickly (Kp) or how well damped (Kd) the following error exists. Following error requires a closer look into the harmonic oscillator analogy since Kp and Kd to not affect following error.

In the spring mass system, the displacement error G can be corrected by a pneumatic cylinder or some other force that brings the position back to X=0 from the following error position X=G. The correction of following error requires a second step: the system response and oscillations are first optimized then the following error is corrected with Ki. The corrector force Ki can impart an oscillation to the system when its value is too high. Hence, the Ki term is applied cautiously and to a system that is well behaved.



2.0 Speed Control Loop

From the above example of the spring mass system, the analogy is a good representation for stages that are controlled by force/torque, also known as PIDFFAcceleration corrector. In following flowchart, a system can be controlled by speed where the PID parameters objective is to make the actual motor speed match the ideal motor speed. In the below image provides a representation of a PID loop with a speed input.



In a speed control loop, Kd parameter is redundant and normally avoided, but at higher values from Kp & Ki, Kd can help improve the “tightness” of the transient response. The lack of derivative action in a speed control loop may make the system steadier in the steady state as the derivative action is more sensitive to higher frequency terms in the input. Kp, proportional gain, can drive the cut-off frequency of the closed loop. And integral gain, Ki, has the capability to overcome perturbations of physical or mechanical imperfections and to limit static error.

3.0 Summary of Correctors Kp, Ki, and Kd

The analysis of the Servo system starting from the corrector diagram in the XPS user manual section 14.1.2.1 are summarized below:

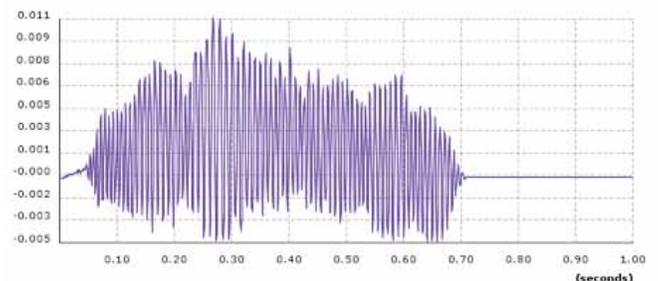
Parameter	Function	Value Set Too Low	Value Set Too High
Kp	Determines stiffness of servo loop	Servo loop too soft with high following errors	Servo loop too tight with oscillations
Ki	Reduces following errors during long moves and at stop	Stage does not reach or stay at the desired position	Oscillations at lower frequency and higher amplitude
Kd	Dampening factor used to reduce oscillations	Oscillations caused by other parameters being too high	Oscillations at higher frequency and audible noise from motor caused by large ripple in motor voltage

The table below shows the result of increasing each parameter on a DC servo:

Parameter's Effects	Kp	Ki	Kd
Overshoot	Kp Increases O.S.	Ki Increases O.S.	Kd Reduces O.S.
Rise Time	Kp Reduces R.T.	Ki Increases R.T.	Kd Increase R.T.
Following Error	Increasing Kp Reduces F.E. when Kp is very small	Ki Reduces F.E. robustly	Kd has NO EFFECT on F.E.

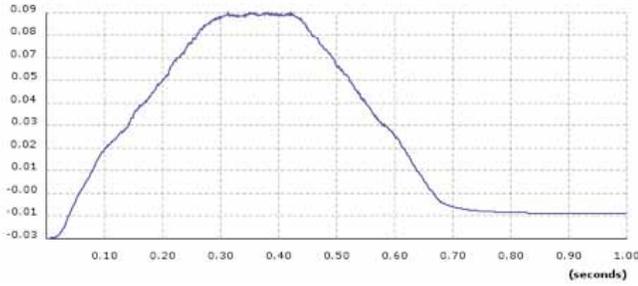
3.1 Relationship between Kp, Ki and Kd - PIDFFVelocity

In the following example, a demonstration of how the relationship between Kp, Ki and Kd by correcting a DC Servo waveform using the table above. This example is gathered with a velocity corrector loop stage (PIDFFVelocity), VP-25XA.

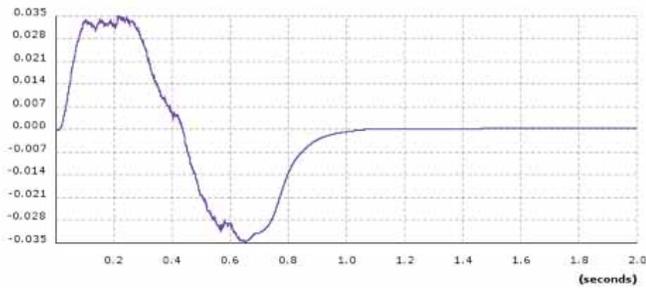


Basic Guidelines for Tuning With The XPS Motion Controller

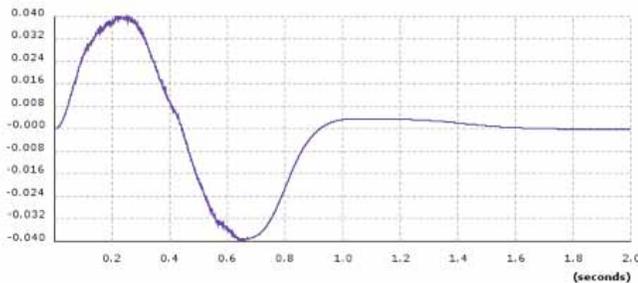
The waveform on the above image is the initial state where the value of K_p is high and K_i and K_d is low or set to zero. This is when the DC Servo is oscillating and may also have an error off of its target position. But notice with just K_p , the output response is increased and at the steady state has a low following error.



The first approach is to reduce oscillations by reducing or eliminate K_p . Notice that the resulting following error at the rest position is further from zero. Now that the oscillations have been reduced, the steady state error is apparent and K_i may be increased to reduce the steady state error, resulting in the image below.



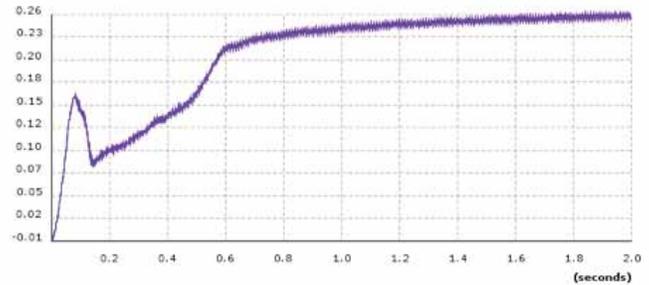
The following error plot above has no apparent steady state error but is oscillating during the transient response. Introducing K_d will reduce the high frequency oscillations resulting in the low frequency error shown in the below image. Notice as K_d increases to dampen and stabilize the transient response, but the settling time has increased a bit. For stages with a velocity corrector loop (PIDFFVelocity), K_d is not always needed and the above plot is suitable for most applications. A high K_d can add high frequency errors.



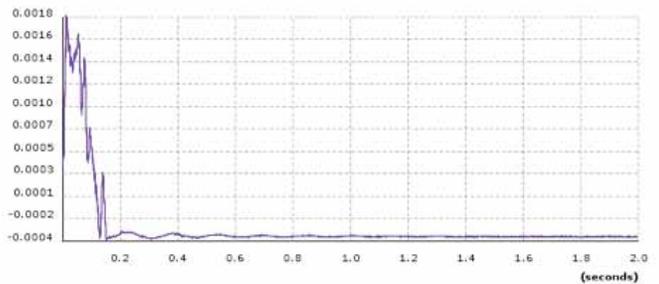
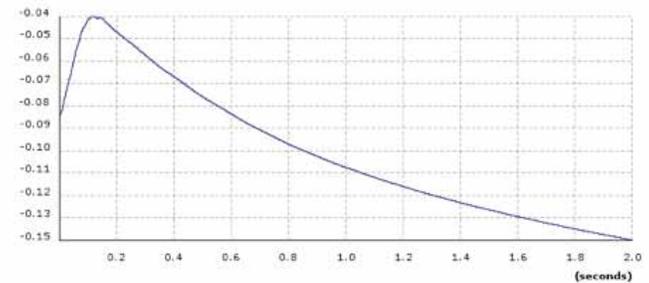
3.2 Relationship between K_p , K_i and K_d - PIDFFAcceleration

In the next example, a demonstration of how the relationship between K_p , K_i and K_d by correcting a DC Servo that is based off from an acceleration corrector loop (PIDFFAcceleration) using an XMS100 stage.

In an acceleration corrector loop, also known as a force/torque loop, the derivate term drives the cut-off frequency of the closed loop and must be adjusted first. The waveform on the below image is the initial state where the value of K_d is high and K_i and K_p is low or set to zero. This is when the DC Servo is oscillating and may also have an error off of its target position. Notice that the plot shows a high frequency.

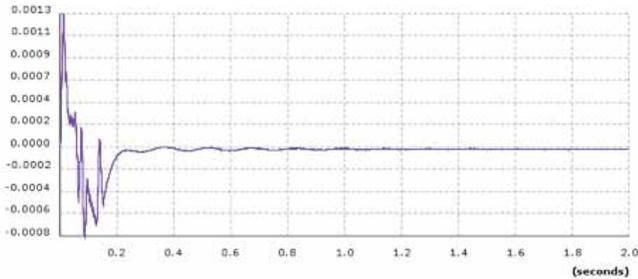


Lowering the value of K_d will reduce the high frequency and oscillation shown in the plot below. K_d will improve the transient response, but the steady state error is apparent and needs to be improved by increasing K_p .



Basic Guidelines for Tuning With The XPS Motion Controller

The following error plot above has a lower apparent steady state error and still oscillating during the transient response. Introducing Ki will limit the static errors and improve on settling time shown in the graph below.



4.0 Basic XPS PIDFF Architecture

Corrector loops PIDFFVelocity, PIDFF Acceleration and PIDFFDualVoltage all use the same architecture as the PID corrector that is detailed above. PIPosition is a simplified version of this loop that is used to provide closed loop positioning via encoder feedback to stepper motor positioners.

PIPosition	Used when a constant voltage applied to the driver board results in a constant position of the positioner (stepper motor, piezo...)
PIDFFDualVoltage	Used when a constant voltage applied to the driver board results in a constant voltage applied to the motor (DC motor and driver board with direct PWM command)
PIDFFVelocity	Used when a constant voltage applied to the driver board results in a constant velocity of the positioner (DC motor and driver board with velocity loop)
PIDFFAcceleration	Used when a constant voltage applied to the driver board results in a constant acceleration of the positioner (DC motor and driver board with current loop)

5.0 Setup XPS For Tuning

5.1 Administrator Rights for PID Tuning

Access the XPS using Internet Explorer and login in with Administrator rights.



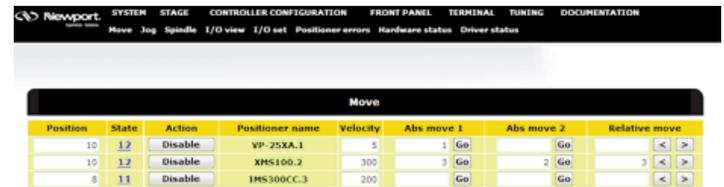
The XPS boots to the System menu. If you are coming from another menu like Front Panel then select the System menu. Within System, select the Auto configuration submenu.

5.2 Select Stage to Tune

Go to the Front Panel and either Move or Jog screen to identify the Positioner name to tune. This exercise will tune XMS100.2 Initialize and Enable the stage. In the window below:

- VP-25XA.1 has been initialized and enabled.
- XMS100.2 has been initialized and Enabled
- IMS300CC.3 has been initialized and enabled.

Note: Pressing the disable button will disable the stages.



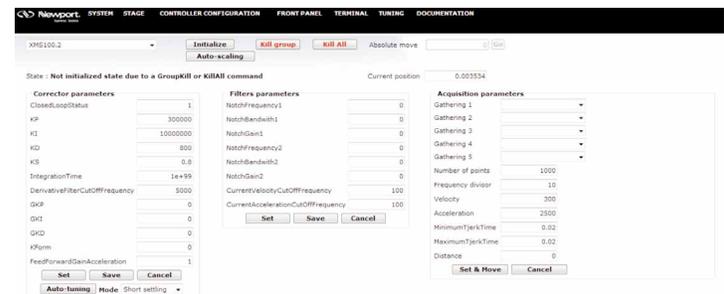
Within the System \ Auto configuration page, confirm the plug number is the physical stage to tune.



6.0 Optimize PID Parameters

6.1 Summary of XPS TUNING Application

Go to the TUNING page and select the stage from the drop down in the upper left. XMS100.2 has been selected. Notice that the State indicates the stage is in the ready state and that parameters have been loaded.



Basic Guidelines for Tuning With The XPS Motion Controller

When opening the XPS TUNING page, parameters like the above image will be populated with the last saved values. The Corrector Parameters are the parameters that the tuning exercise will adjust to optimize the motion as defined in the Acquisition Parameters. The center filter parameters are determined by the stage design or system test and these will not be adjusted during general PID tuning.

6.1.1 Corrector Parameters

- ClosedLoopStatus: 1 for Closed Loop and 0 for Open Loop
- KP: PID servo loop proportional gain, K_p . The servo loop multiplies the current following error by the value of K_p to react immediately to following errors: K_p is the instantaneous corrector. An increase in K_p results in a larger correction to following error for faster response. For moves with small following errors, a larger K_p is required to overcome static friction. Small moves generally require higher K_p values than larger moves since the following error is small. Small moves have an appreciable static friction which requires the instantaneous K_p to overcome.
- KI, PID servo loop integral gain, K_i . K_i corrects for the steady state error: following error at constant velocity or stopped. The effect of K_i is inversely proportional to the oscillation (error) frequency. A caveat is that at zero frequency, the K_i term can become infinite so it is essential to limit K_i which introduces the K_s term.
 - o K_s , PID servo loop integration limit for K_i . The integral term K_i becomes unbounded as frequency approaches zero so K_s sets the upper limit to K_i to prevent oscillations. K_s is typically set to 0.5 where it has span of 0 to 1 where smaller values indicate a lower total K_i contribution.

- o Integration Time, sets the time range used in calculating the value of integral correction, K_i . A small value of Integration Time will limit the integral correction to the end section of the move: the small value for Integration Time reduces the overshoot at end of travel. The smaller Integration Time value, however, reduces the static error compensation.

- KD, derivative term. The derivative gain multiplies the difference between the previous and current following error by K_D and hence stabilizes the transient response. The K_D acts like a dampener and acts opposite to the integral term K_i : for K_D , the gain is directly proportional to the frequency of the following error, K_D corrects for higher frequency errors.

- o Derivative Cutoff Frequency: as the effect from K_D increases with frequency, the cutoff frequency acts as a low pass filter to prevent K_D from going unbounded due to noise.

- Variable Gains and K_{form} : G_P , G_I , G_D , K_{form}

- o The variable gains along with K_{form} benefit from tuning of demanding applications including very small moves and high loads. In these applications, the stage friction and inertia are dominant contributors to error which differs from the typical applications. Hence, the PID gain parameters are changed in these applications using the variable gains.

- o The use of variable gains will be addressed following the more general PID gain parameters.

- o For general PID tuning criteria G_P , G_I , G_D , and K_{form} are equal to zero.

- Feed Forward Velocity. Feed Forward Velocity settings are determined in the initial settings of the stage or for stages not in the XPS database use $V_{ff} = 1$.

6.1.2 Filter parameters

Notch filters remove a given frequency from being amplified. Motion systems with a known resonance frequency can apply the notch filters to remove the error corrector gain near the resonance frequencies. General tuning involves single stages or small assemblies where the resonance frequencies will be prevented by limits on K_D and K_I .

Basic Guidelines for Tuning With The XPS Motion Controller

- Set the Current Velocity Cutoff Frequency and the Current Acceleration Cutoff Frequency both to 100 for general tuning applications.

6.1.3 Acquisition Parameters

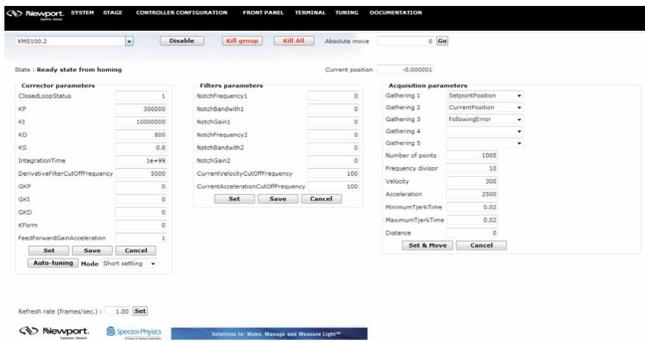


The acquisition Parameters define setup and the return of the tuning profile. Each of the Gathering parameters represent a datum to collect during the scan. For initial tuning, monitoring the Set Point versus Current Position is effective. Following error is the difference between Set point and Current Positions and is most helpful for initial tuning. After position tuning (i.e. Current Position versus Set Point) tuning for velocity regulation provides good results, especially with stages that include a tachometer.

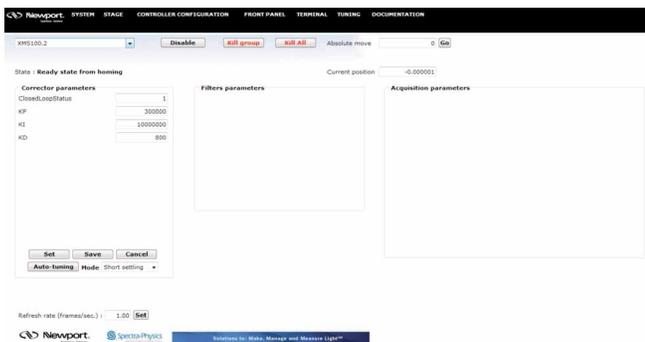
Define the distance to move and velocity to approximate the application. Keep in mind that higher acceleration values are more difficult to tune.

7.0 Enter Tuning Parameters

Start with the initial parameters for the stage and setting the Acquisition Parameters: Set Point, Current Position, and Following Error.



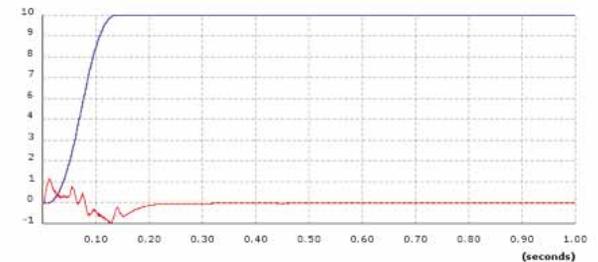
The values to optimize for the initial tuning are limited to those shown below:



When updating the PID parameters, select the "Set" button in the parameter box in order to update the values in the XPS memory. Then, set the acquisition parameters (Set, Current, and Error) and select the "Set & Move" button. The stage will execute the move and then a Java window will appear with the scan results. Please update the host computer's Java Runtime engine if the window does not appear or update.



In the chart above the ordinate (Y) axis is in the XPS units of mm whereas we expect the following error to be on the order of microns. Enter of gain of 1000 for the following error in order to have the following error plot display microns on the existing mm scale.

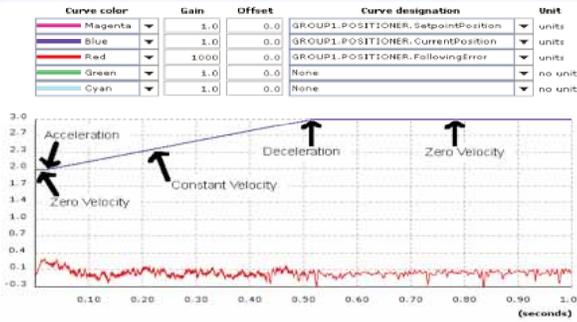


The plot above indicates a nearly ideal plot. The following error is zero as the stage comes to rest and there is no oscillation at the micron level. Any portion of the graph can be expanded by dragging a rectangle over the region of interest. To restore normal zoom then select the "Auto Range" button.

7.1 Detail of Motion Profile

The following plot indicates the regions of the motion profile. Negative following errors at the acceleration and deceleration phases indicate that Kp is too low and hence that the system is slow and loose. Higher values of Kp may cause overshoot on these acceleration and deceleration regions which can be reduced by reducing Kp. A high Kp without oscillation is a tight, fast system.

Basic Guidelines for Tuning With The XPS Motion Controller

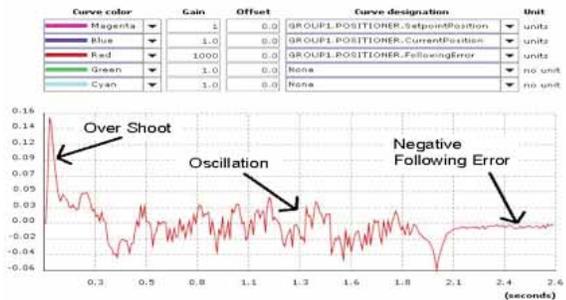


The two images below are indicative of typical motion profiles. The XPS controller uses a sophisticated S Gamma motion profile that provides better control of dynamic systems. It allows ideal control of the excitation spectrum that a move generates. Unlike a trapezoidal profile which has an instantaneous transition between circumstances of acceleration and no acceleration. The change in acceleration with time is known as Jerk. The Jerk is a time derivative of acceleration and the jerk time provides the time that it allows acceleration to reach its max.

The jerk time in a trapezoidal profile is infinite at its transition, while the S Gamma profile has a steady value that spreads the change of acceleration over a time period. Allowing the jerk to be high, there is a greater amount of energy that will present unnecessary vibrations in the system.



For the image above, the current position has an appreciable overshoot compared to the RMS noise further in the motion profile. Decreasing K_p will reduce the overshoot.



For the image above, a high value of K_p is contributing to overshoot. The oscillation occurs during the constant velocity phase where velocity regulation can be improved by selecting velocity in the acquisition parameters. When coming to rest, the stage exhibits a sharp negative transient error and then a small negative steady state error. For the steady state error, K_i can be increased. For this system, increasing K_i to reduce following errors would be in order and if no oscillations are exhibited in the steady state, then velocity regulation can be tuned by selecting the velocity terms from the acquisition parameters.

7.2 Summary Guidelines

7.2.1 Stabilize an Existing System

To stabilize an existing system and reduce following error (FE), the following steps can be taken where the visualization of how K_p , K_i , and K_d functions is helpful in each step;

1. Reasons to Tune

- a. Achieve better motion performance: i.e. reduce following error.
- b. System is malfunctioning: oscillating or turning off due to large FE

2. Acceleration causes large velocity changes at start/stop which cause large FE and overshoot. Use smallest acceleration possible to reduce overshoot and makes tuning the PID filter easier.

3. In addition the causes of acceleration, jerk time as well can either reduce or allow for overshoot. When jerk time is increase, this will allow more rapid change in acceleration and the stronger vibration will be. The XPS allows for minimum and maximum jerk time that allows adjustments fo the system behavior to different motion step sizes.

4. Tuning for PIDFFVelocity:

PIDFFVelocity is a corrector output known as speed loop. The speed loop is when the positioner driver requires a speed input.

The following shows recommended for a speed loop.

- a. Verify the speed in open loop (adjustment done using Scaling Velocity)
- b. $K_{FeedForwardVelocity}$ value should be set to 1
- c. Close the loop, set K_p , increase it to minimize FE to the level until oscillations/vibrations start during motion, then decrease K_p slightly to cancel these oscillations.

Basic Guidelines for Tuning With The XPS Motion Controller

d. Set Ki, increase it to limit static errors and improve settling time until the appearance of overshoot or oscillation conditions. Then reduce Ki slightly to eliminate these oscillations.

e. Kd is generally not needed but it can help in certain cases to improve the response when the speed loop of the driver board is not efficient enough.

5. Tuning for PIDFFAcceleration:

PIDFFAcceleration is a corrector output known as force/torque loop. The force/torque loop is when the positioner driver requires a force/torque input. The following shows recommended for a force/torque loop.

a. Verify the AccelerationFeedForward in open loop (adjustment done using ScalingAcceleration; please refer to Scaling Acceleration Tech note)

b. KFeedForwardAcceleration should be set to 1

c. Close the loop, set Kd, increase it to minimize following errors until vibrations appears during motion. Derease Kd to eliminate oscillations

d. Set Kp, increase it to minimize following errors until the appearance of oscillations, decrease it to eliminate oscillations.

e. Set Ki, increase it to limit static errors and settling time until appearance of overshoot/oscillations

6. Tuning for PIDFFDualVoltage:

PIDFFDualVoltage is a corrector output that can be consider as a mix between the speed loop and force/torque loop. The following shows a recommended with association with a driver having a voltage input:

a. Adjust KFeedForwardVelocity in open loop to optimize the following of the speed at high speed.

b. Close the loop using the same value for KFeedForwardVelocity, set Kp, increase it to minimize following errors until oscillations/vibrations appears during motion, decrease Kp to eliminate oscillation.

c. Set Kd, increase until oscillations appears during motion and decrease it to eliminate oscillations.

d. Increase Ki to cancel static error and minimize settling time until appearance of overshoot/oscillations.

7.2.2 Setup Initial PID Parameters

In several cases, it is useful to determine new PID parameters. These cases may be for a new multi-axis system build or when the default parameters are unknown. For this method, use the behavior of the PID parameters provided in the introduction to gauge the steps:

1. Prior to setting PIDs, it is recommended to verify the proper Corrector Loop to determine the correct scaling and feed forward parameters.

2. Set Kp. Set Kp so that it responds to the error and minimizes the initial following error. Increase Kp until oscillations start and then decrease Kp just below the oscillation value. This establishes a good response to the error.

3. Set Ki. Setting Kp alone will leave a following error. Increase Ki so that the steady state following error improves to best case or until oscillations start. If oscillations start, reduce Ki to below the oscillation value.

4. Set Kd. In many systems, friction, hysteresis, and electronics of the stage provide enough damping that Kp and Ki can be used alone. Kp initiates the response and Ki corrects the following error, for stages that are not oscillating. If the stage is oscillating,8 then increase Kd to dampen the oscillations but do not go farther since in the DC Servo high values of Kd start high frequency oscillations.

5. Iterate. It is often necessary to incrementally increase Kp, Ki, and Kd as parameters affect each other.



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