Application Note – Feedback Control Tuning with Motion Manager 6.3 or higher

Summary

To get the best performance out of your positioning system the feedback control parameters of the FAULHABER Motion Controller have to be adjusted to the application.

This application note describes the tuning of the feedback control parameters of the FAULHABER Motion Controllers via Motion Manager 6.3 or higher.

Concerning

The following products: **MC5010, MC5005, MC5004** and **MCS**

Content

Additional information and details have a green colored background.

An Overview of the next tuning steps is marked with a blue background color.

Motivation

This application note provides a step by step instruction how to tune the controllers in an efficient way, which reduces the commissioning time significantly compared to a trial and error approach.

First of all you should have a clear idea of your own tuning goals.

Controller Tuning can have different goals, for instance:

- Reaching the target position without overshoot
- Fast command response
- Good disturbance rejection
- Silent motor run
- …

The individual goals have to be weighted, as not all can be achieved with the same set of parameters. A system which is tuned for high dynamics will not necessarily run very silently at the same time.

Tuning goal of this application note

This application note focuses on the tuning goal of "fast command response with very little or no position overshoot". In addition the underlying velocity loop will be tuned to minimize disturbances, with a focus on positioning applications, like x-y stages, which would benefit from these criteria.

Motivation - Continued

The Feedback Control System

The Motion Controller mentioned above uses a cascaded feedback control structure, consisting of a subordinated current controller, a velocity controller and a superimposed position controller.

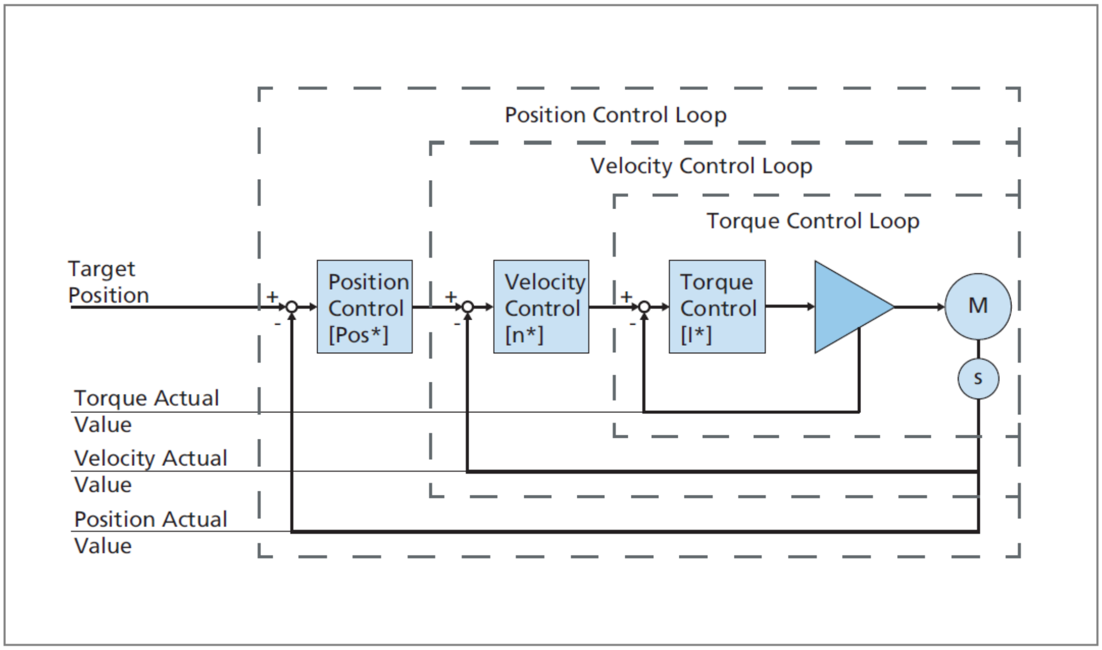


Figure 1: Control cascade

The position controller consists of a proportional controller with a parameter K_V. The velocity controller uses a PI-structure with a proportional gain K_p and a reset time T_N. The current controller uses a PI- controller as well. In addition feedforward values can be applied (not shown in figure 1). This results in an excellent command behavior and a minimal following error.

Background information: Comparison of PID-controller / Controller cascade

PID- Position controller, as well as in the drive business widely used cascaded controllers, show a very good control performance. One of the main differences is the naming of the single control parameters. For instance the proportional gain K_P of the velocity controller has the same effect as the Derivate term of a PID-Position Controller. Both amplify a velocity deviation, which increases the system damping to a certain point.

Motivation - Continued

When is it necessary to tune the controller?

- To achieve certain tuning goals
    - To get the best performance out of your positioning or velocity controlled system, achieving certain tuning goals, the feedback control parameters have to be adjusted to the application.

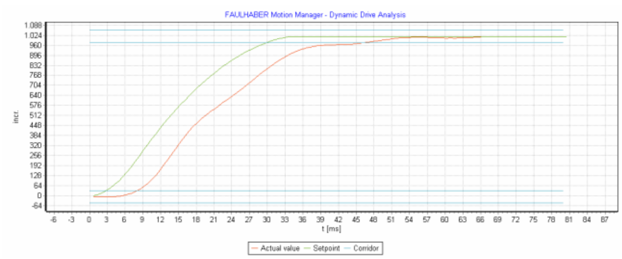


Figure 2: Dynamic Positioning with little overshoot

Prerequisites for Feedback Control Tuning

The Tuning methods introduced in this application note require the system to fulfill the following conditions:

- The system has to be complete, including the power supply
    - If there will be any significant system changes the feedback control tuning has to be repeated.

- The motor has to be set using the **motor selection wizard**

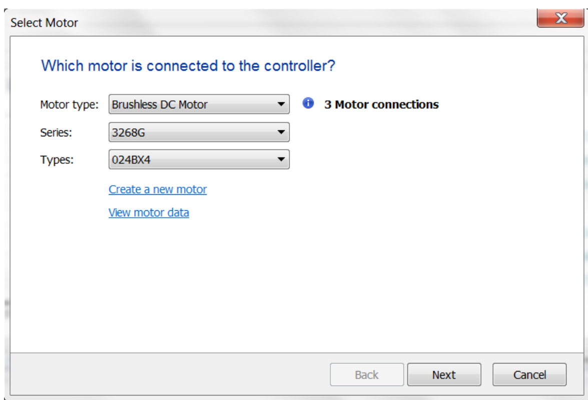


Figure 3: Wizard for motor selection

    - Here the current controller will be adjusted automatically based on the motor data. It is not meant to be tuned manually. Incorrect current controller settings will damage the motor or the power stage.
    - In addition the overvoltage threshold is set according to the voltage supplied to Umot (see page 25 for details).

Prerequisites for Feedback Control Tuning - Continued

- The load inertia reflected to the motor (= J_{Load}) has to be set using the **controller configuration wizard**

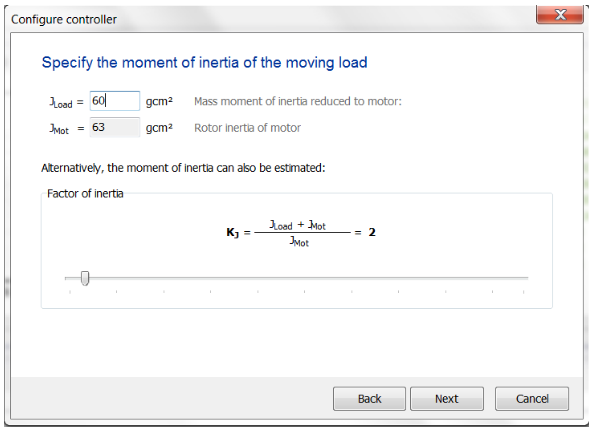


Figure 4: Wizard for controller configuration

  - The inertia factor $K_J = \frac{J_{Motor} + J_{Load}}{J_{Motor}}$ is essential for the basic parameter set of the velocity loop. The Motion Manager sets the time constant of the velocity feedback filter depending on K_J as well. Therefore the inertia factor K_J has to be chosen carefully, or if the automatic system identification wizard is used the result should be checked for plausibility. K_J should be provided with an accuracy of +/- 20%.

  - In addition the Motion Manager calculates appropriate profile parameters based on the inertia of the system.

- **Position limits** have to be activated

  - Before feedback control tuning, position limits (e.g. software limits or limit switches) have to be activated, if the application is limited in its range of movement.

  - An example on how to set Software Limits is found on page 24

- The **Load inertia** should be **constant** - see page 23

- The **mechanical setup** should be sufficiently **stiff** - see page 23

Feedback Control Tuning – the Tool

The Tool offers support to tune the velocity controller and the position controller. In a cascaded control structure the inner loop always has to be tuned first, then the outer loop. This means even position-based systems must first have their velocity loop tuned. The performance of the system highly depends on a well-tuned velocity controller.

Recording - Velocity-View

The performance of a drive system is evaluated on the basis of a step response.

The Tuning Tool offers the possibility to command a velocity value via the box Setpoint. The button “One Step Response” starts the movement and triggers the recording. The parameter K_P can be tuned with a slide control.

Setpoint

Often 1000 rpm (related to the motor) is a suitable set point. Make sure the checkbox “Move to current position” is activated, so the system will move back, after recording a step response.

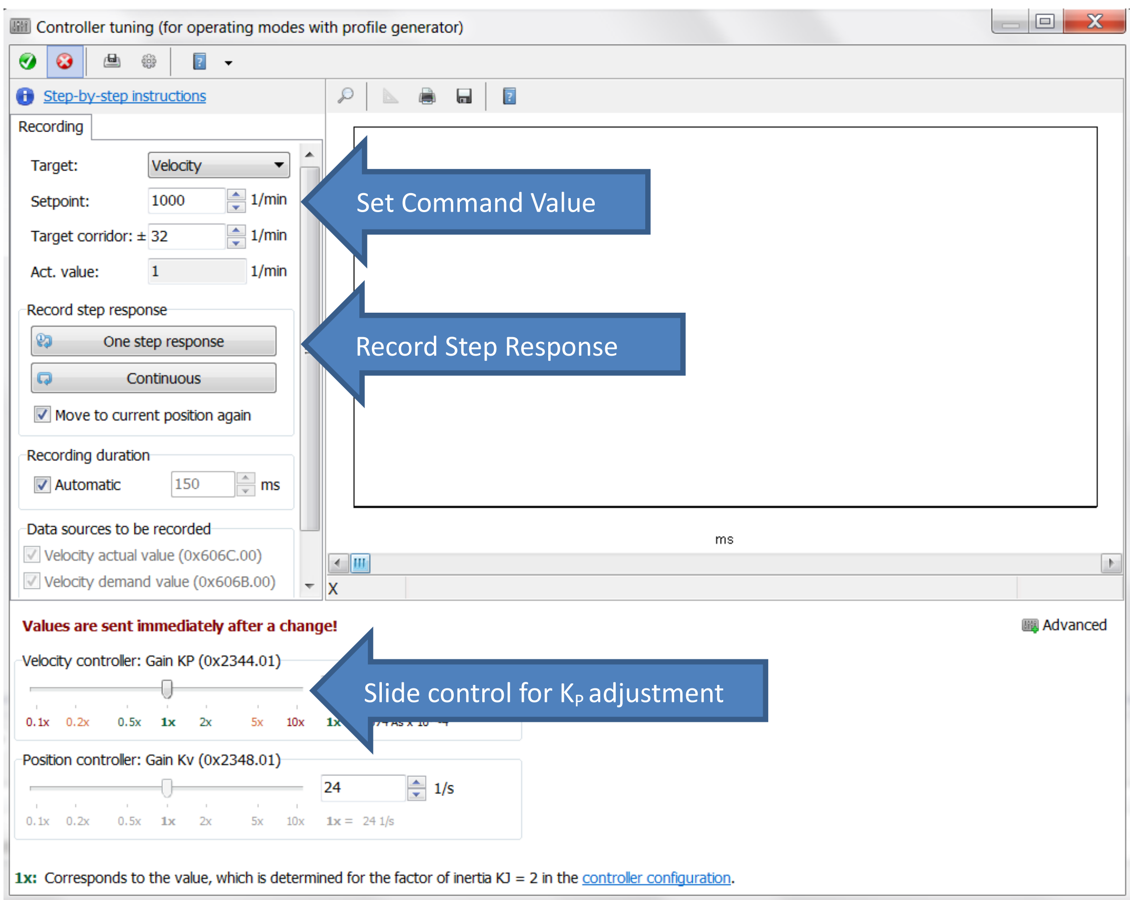


Figure 5: Feedback Control-Tuning – the Tool – Velocity-View

Feedback Control Tuning – the Tool – Continued

Recording - Position-View

K_V, the position control parameter, can be tuned with a slide control.

Setpoint

The set point is stated in increments and operates relative to the actual position. During the first tuning steps short distances like ¼ motor revolution should be chosen.

You may choose to have the motor return to the starting point after each move.

	Analog Hall Sensors	Incremental-Encoder with 512 Pulses	AES-4096
1 Motor-Revolution**	4096 Increments	2048 Increments*	4096 Increments

* Due to four edge / quadrature evaluation one motor revolution equals four times the number of pulses

** If the factor group settings are still in delivery state

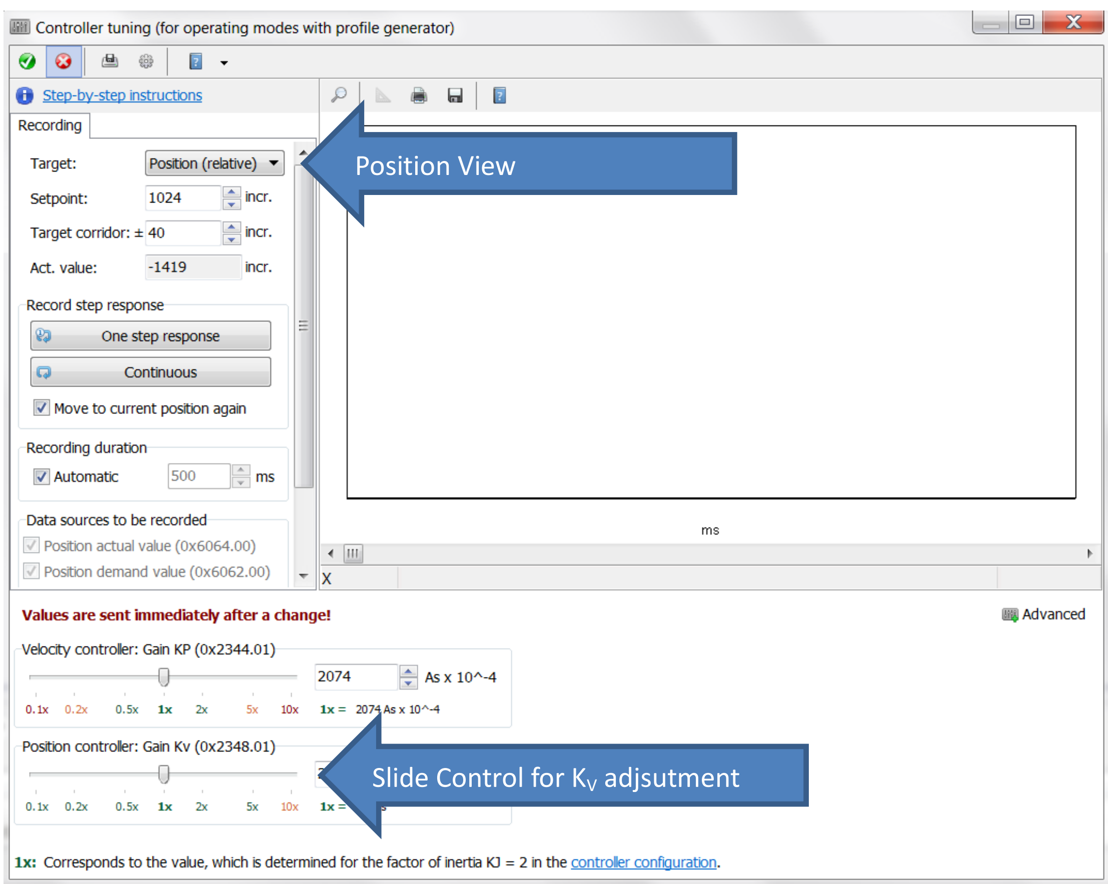


Figure 6: Feedback Control-Tuning – the Tool – Position-View

Feedback Control Tuning – the Tool – Continued

Analysis View

The Analysis View offers the possibility to switch between the different recorded step responses. In addition the parameter settings corresponding to the displayed step response are shown. The parameters can be loaded to the Motion Controller and saved "permanently".

This View is only available if at least one step response was recorded.

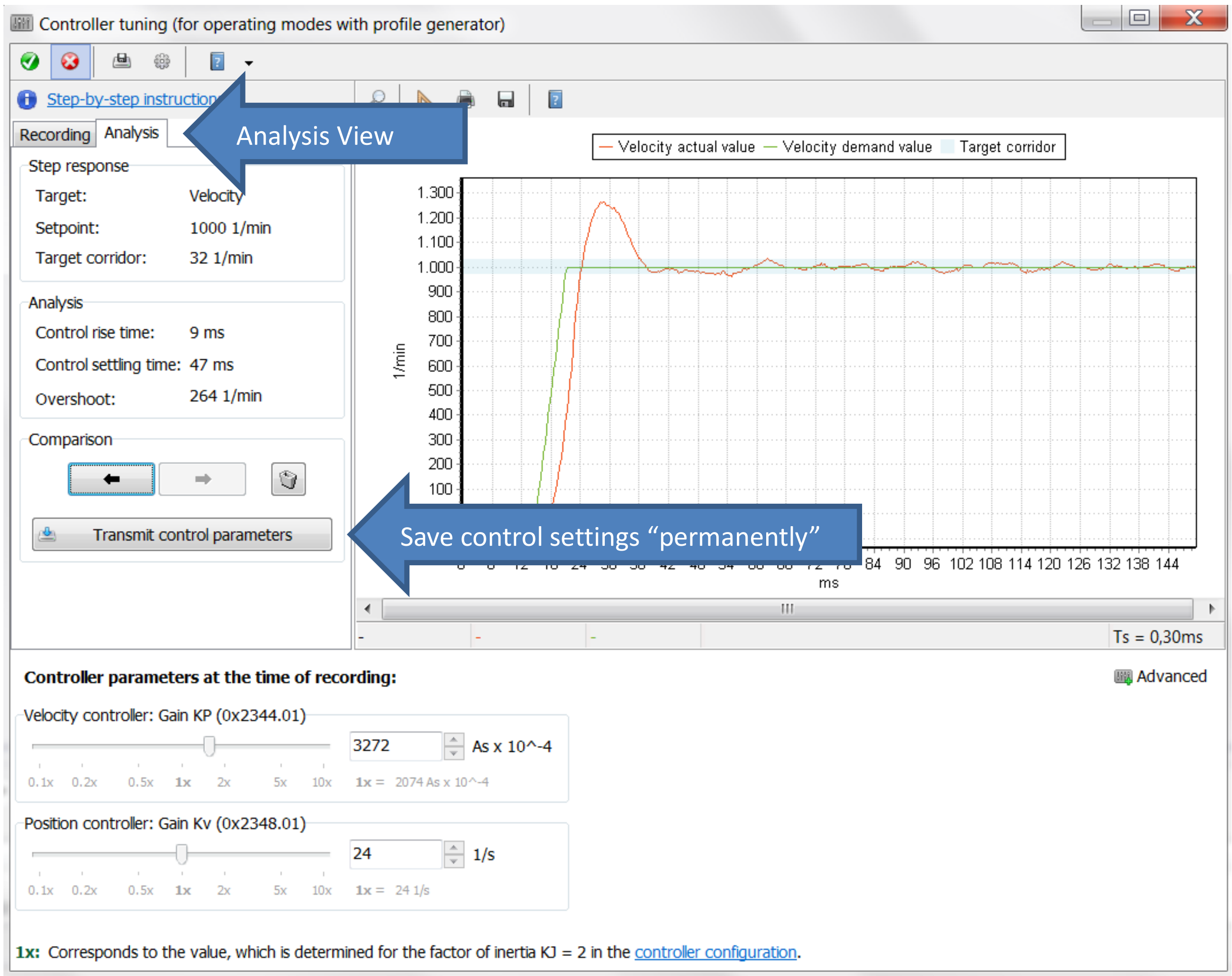


Figure 7: Feedback Control-Tuning – the Tool – Analysis-View

Feedback Control Tuning – the Tool – Continued

Recording Duration:

Initially “recording duration” is set to “automatic”. When this setting is active the motion manager will automatically estimate the time needed for the commanded move.

Velocity view
Be aware that the movement of the drive depends on the recording duration and the commanded velocity. This means a drive will move about 3 motor revolutions when a velocity of 1000 rpm is commanded and the recording duration is set to 150 ms.

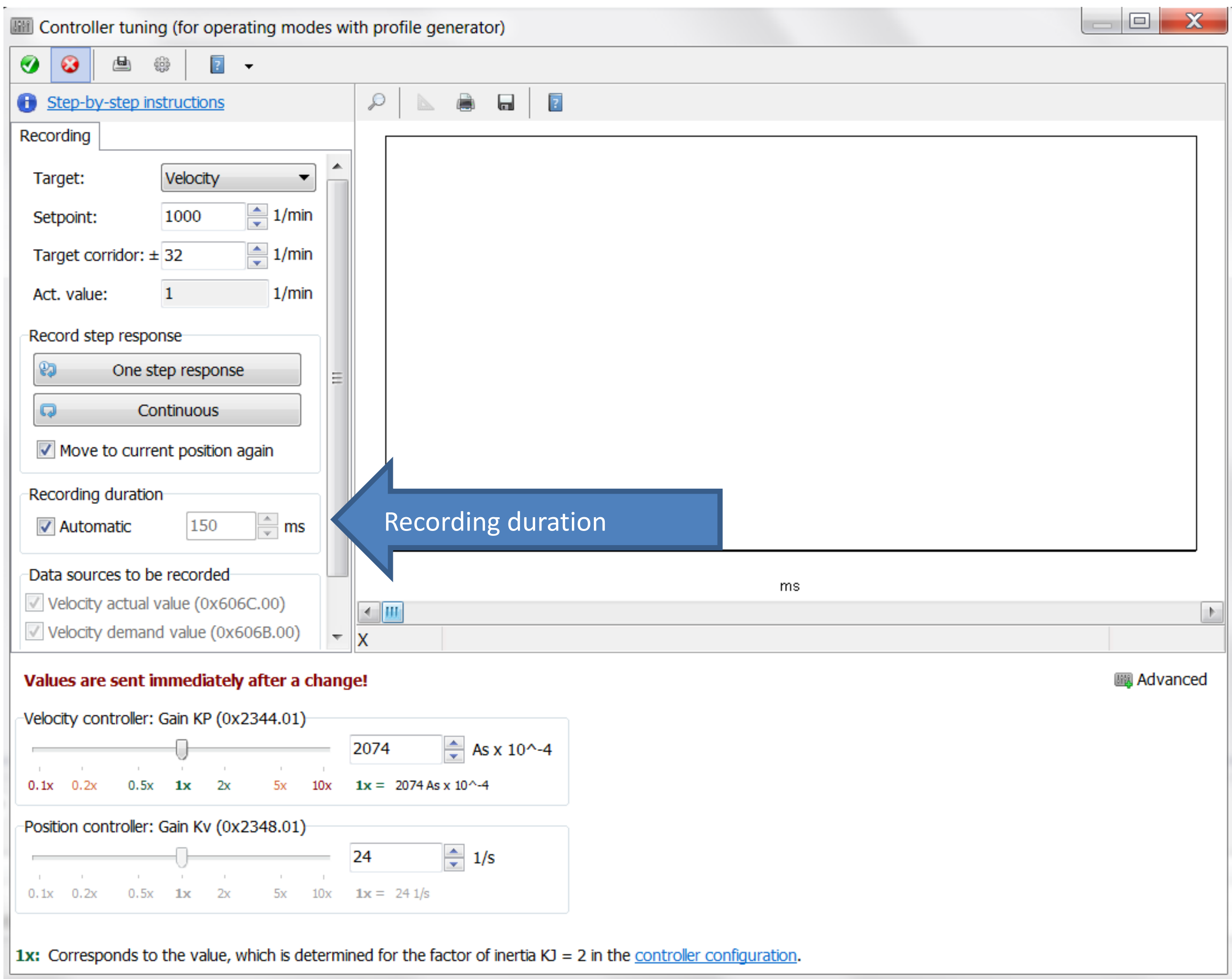


Figure 8: Feedback Control-Tuning – the Tool – Recording duration

Step by Step Instructions – Velocity Controller Tuning

Traditionally the performance of a feedback control system is determined by the evaluation of step responses.

For the velocity controller the goal is a good disturbance rejection. The Set-up wizards already set the reset time T_N – which usually does not have to be adjusted further. The proportional gain K_P is available for fine tuning.

A setting which contributes to the goal "good disturbance rejection" always produces a high overshoot of the velocity, if the command value changes rapidly. The overshoot will typically be about 40%.

Figure 9 shows the step response of a well-tuned velocity controlled system. The system should be well-damped, which means the second overshoot (see figure 9 – red rectangle) should be quite small and the system should settle afterwards. This goal is achieved by increasing the proportional gain K_P.

The position controller will also highly benefit from the damping introduce here, because it allows higher dynamics.

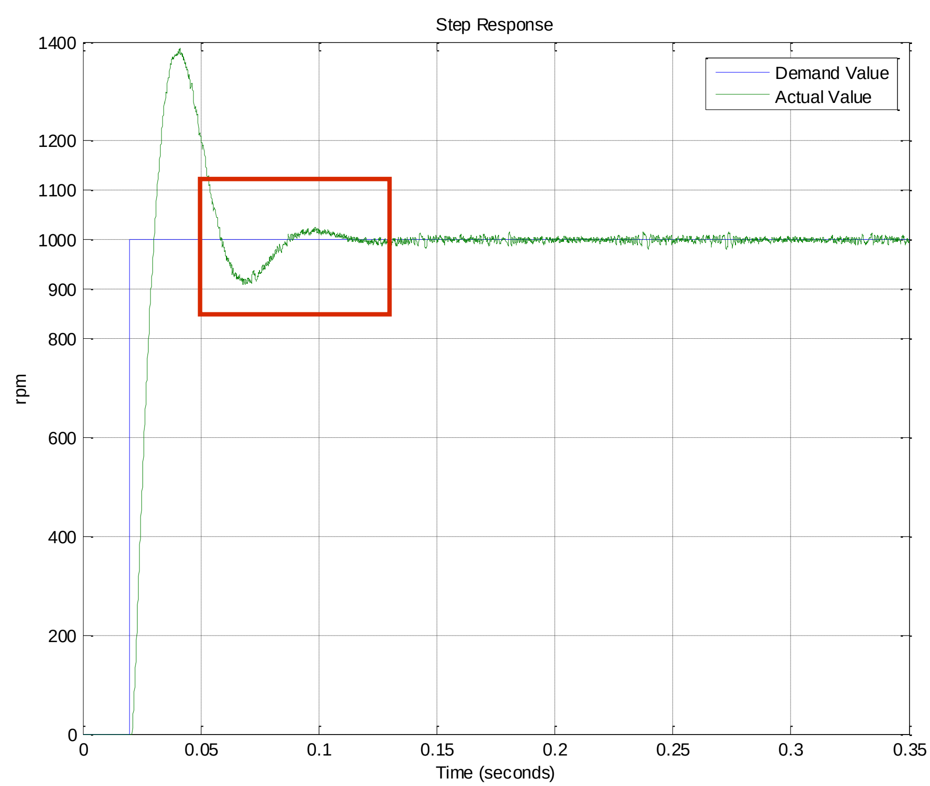


Figure 9: Ideally tuned velocity step response - simulated (MATLAB®/SIMULINK®)

Step by Step Instructions – Velocity Controller Tuning – Continued

Velocity Controller - Tuning

Overview of Velocity Controller Tuning - Step by Step:

Tune K_P - based on the step response

Tune K_P - based on the step response

- Set the setpoint value to 1000 rpm
- Make sure the checkbox "move to current position again" is activated
- Make sure the "recording duration" is set to automatic
- Record step responses and gradually increase Kp using the slider until the system is well-damped (see figure 9 on page 11, evaluation of the second overshoot)

The following table shows expected reasonable ranges of the K_P-factor (1.5x, 3x..) based upon the feedback sensor type. The gain factor 1x is based on the value determined by the start-up wizards.

	Analog Hall Sensors	Optical Incremental-Encoder	Magnetic Incremental-Encoder
K_P	1.5x .. 3x	3x..5x	1.5x..5x

The higher the inertia factor K_J the smaller the possible gain factor (at the same time the absolute value of K_P increases with K_J).

Step by Step Instructions – Velocity Controller Tuning – Continued

Expected tuning results:

- The first overshoot will reach about 110..135% of the commanded value
- The first overshoot will be reduced (by approx. 50..250 rpm, compared to Kp = 1x)
- The second overshoot should be quite small (comparable to the remaining ripple) and the system should settle in the corridor afterwards as shown in figure 10.

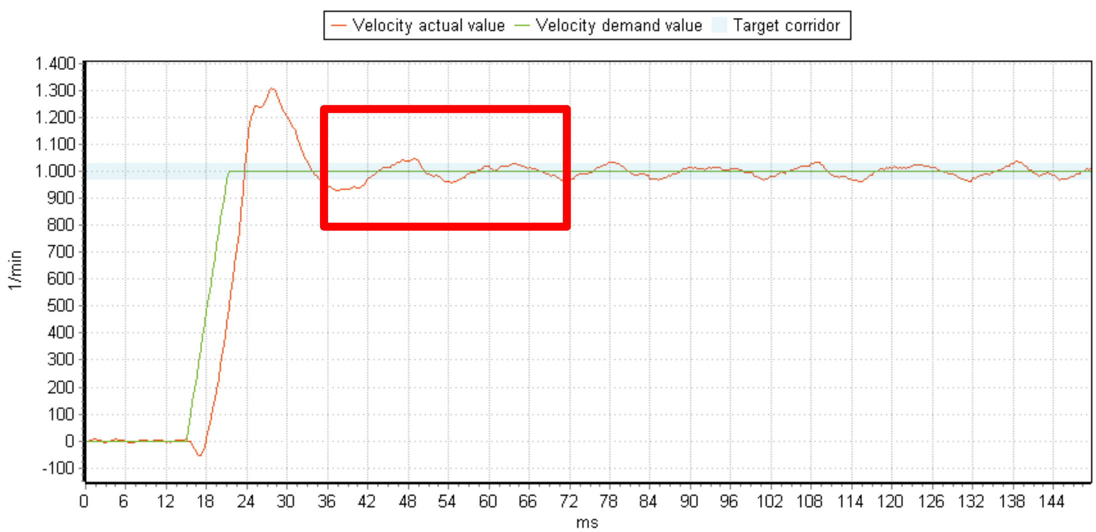


Figure 10: well-damped step response, 3268Bx4 with load disc of 60 gcm² (KJ=2), KP = 2x = 4148 As e-4

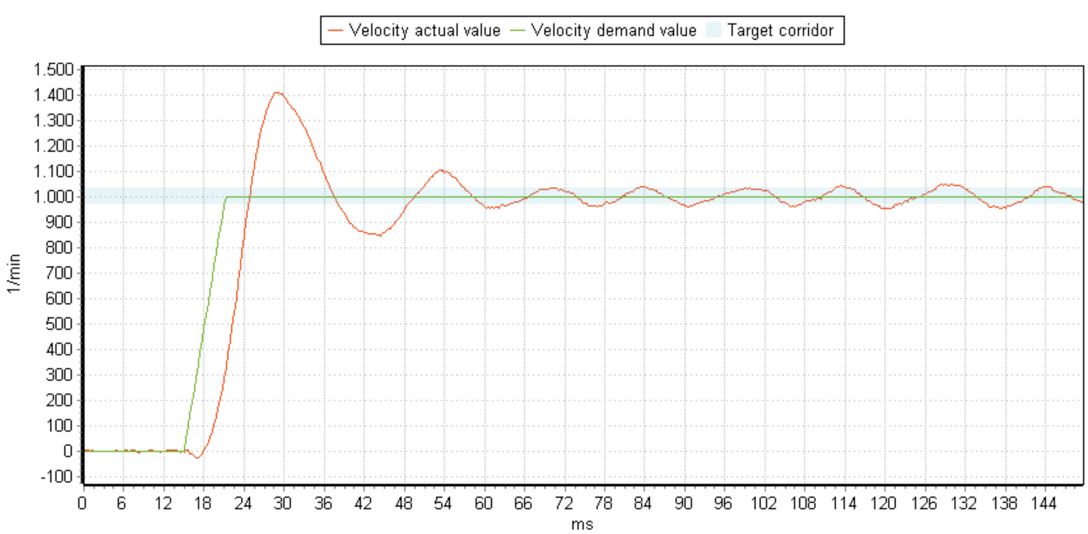


Figure 11: Moderate step response, 3268Bx4 with load disc of 60 gcm² (K_J=2); K_P = 1.4x = 2900 As e-4

Step by Step Instructions – Velocity Controller Tuning – Continued

Option: Supplement to velocity tuning for K_J >4, using analog hall sensors

Check the adjusted K_P value based on the stability limit

If an oscillating instability is not an issue for the system, this option can be used to check if the K_P value adjusted during velocity tuning is set in a safe distance from the stability limit.
Especially if the inertia factor K_J is large this approach can be helpful.

- Command a step response - now the feedback controller is active
- Increase K_P during **standstill** with the slide control until the clearly audible stability limit is reached. The value found with this approach be $K_{P\ critical}$
- Reduce K_P immediately
- The final K_P value should not exceed a range of 0.5..0.7 x $K_{P\ critical}$, if necessary reduce the K_P value which was found during velocity tuning

Step by Step Instructions – Position Controller Tuning

As the positon control loop encompasses the velocity control loop (as shown in figure 1), the positon control loop's performance ultimately depends upon the performance of the velocity control loop. In other words, the velocity control loop must be tuned before the position control loop, if not tuned yet, please go back to page 11.

The desired result of position controller tuning in this application note is a fast response with little to no positional overshoot. The section shows how to use K_v for tuning the Position Control Loop.

Position Controller Tuning

Overview of Position Controller Tuning - Step by Step:

Step 1: Adjust Max Motor Speed

Step 2: Tune K_V – based on the Step Response - commanding small distances

Step 3: Configure the following error as a quick stop source

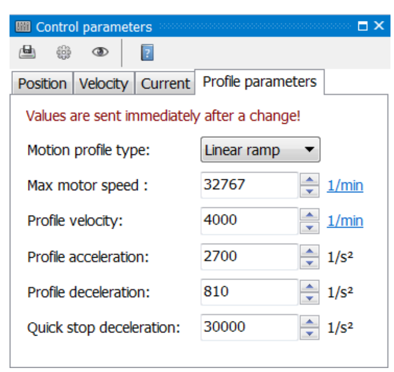
Step 4: Check the settings - commanding longer distances

Step 1: Adjust Max Motor Speed

<u>Max Motor Speed</u>

If the motor must not exceed a certain velocity in the application, the parameter Max Motor Speed should be set accordingly. This might be useful when using a gearbox for instance, since its appropriate input velocity is usually limited.

See configuration / control parameters / profile parameters



Step by Step Instructions – Position Controller Tuning – Continued

Step 2: Tune K_V – based on the Step Response - using small distances

- Set the setpoint value to ¼ motor revolution (see also page 8)
- Record step responses and gradually increase K_V until the desired dynamic is reached
- If the graph of the actual position shows slight oscillations, it is usually not useful to further increase K_V
- If the system shows some oscillation in the final position, K_V has to be reduced again
- Save the determined parameter K_V “permanently”

The following table shows expected reasonable ranges of the K_V-factor value (2x, 5x..) based upon the feedback sensor type. The gain factor 1x is based on the value determined by the start-up wizards.

	Analog Hall Sensors	Optical Incremental-Encoder	Magnetic Incremental-Encoder
K_V	2x .. 5x	5x..10x	2x..10x

Systems that function well on the higher end of the range of the K_P-factor (see page 12) will most likely function well on the higher end of the range of the K_V-factor.

Step by Step Instructions – Position Controller Tuning – Continued

Expected tuning result:

- Figure 13 shows a well-tuned system without overshoot
- The step response should show a constant following error in the range of 5..20 ms
-

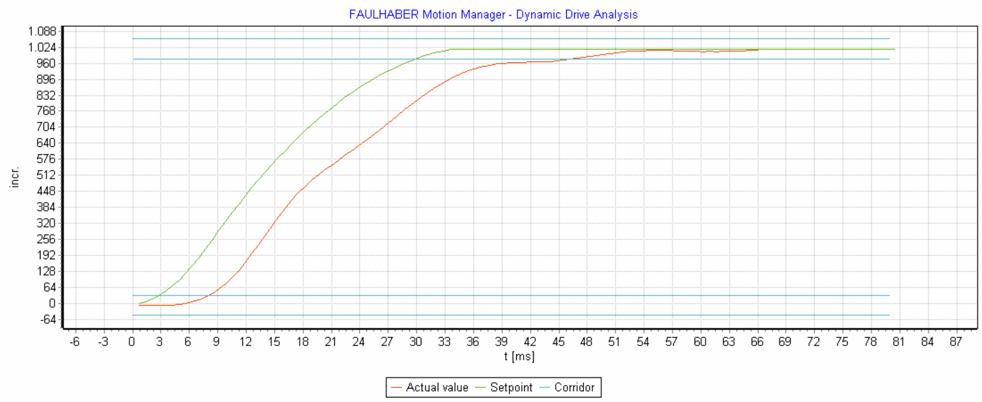


Figure 13: Dynamic positioning

Setpoint = ¼ Motor revolution; K_v =140; Rising time = Settling time =39 ms; K_J = 2;

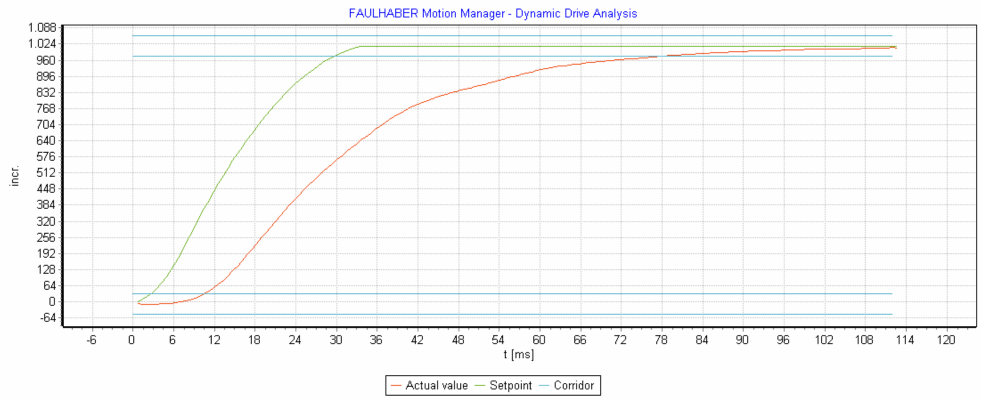


Figure 14: Not a dynamic positioning

Setpoint: ¼ motor revolution; K_v =56; Rising Time = Settling Time = 68 ms; K_J = 2;

Step by Step Instructions – Position Controller Tuning – Continued

Step 3: Configure the following error as a quick stop source

Before commanding longer distances it is highly recommended to configure the following error as a quick stop source. This prevents the system from instabilities.

This recommendation is based on the protection functions of the Motion controller which limit the available current, when

- the thermal models exceed a certain temperature (motor or power stage)
- an overvoltage is detected during braking

Especially if the inertia factor K_J > 3 a limitation of the current, may cause an instability.

In addition, if the Profile Velocity parameter is considerably too high, and a large distance is commanded, this can lead to instability as well.

Any instability can be prevented using the following error as a quick stop source.

See Drive Functions / Device Control for easy configuration of the error handling. There the following error can be configured as "Quick Stop" source.

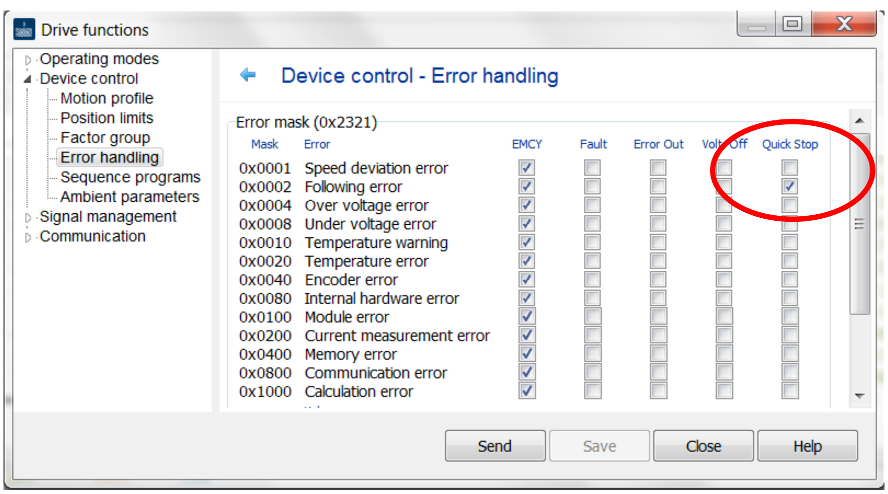


Figure 15: Drive Functions / Device Control / Error handling

Step by Step Instructions – Position Controller Tuning – Continued

Step 4: Check the settings - commanding longer distances

- Restart the Tuning Tool
- Set Setpoints relevant for the application (distance wise)
- Modify K_V, if necessary
- Modify the Profile Velocity (see “Advanced” settings), if necessary
- Save the determined parameters “permanently”

After following the steps 1..4, the position controller tuning is completed.

Appendix - Troubleshooting

a) Position course with slight tendency for oscillations

- Increase the Proportional gain K_P of the velocity controller by 5..10 %
  (Keep the stability limit in mind)
- Decrease the profile velocity value, see also g)
- Decrease the Proportional gain K_V of the position controller

b) Dynamics – Settling Time is too high, no oscillations

- Increase the Profile Acceleration and repeat step 4 of the position control tuning
- For longer distances: It might be possible to increase the Profile Velocity, see also g)
- See also f) Feedforward and d) further factors

c) Tuning rules do not seem to work

- Check if the correct motor was chosen in the motor selection wizard
- Check if the correct inertia factor K_J was set (see page 6)

d) Additional Factors influencing the dynamics

- A power supply capable of handling regenerated energy or a brake chopper can increase the dynamics
- Chose a mechanical setup with a small inertia factor $K_J = \frac{J_{Motor} + J_{Load}}{J_{Motor}}$; Ideally $K_J < 4$
- If $K_J > 4$ consider using a larger motor, or the use of a gearbox to reduce K_J, to get a higher stability margin or higher performance. The load inertia seen by the motor ($J_{Load\_Reflected}$) is reduced by the square of the reduction ratio using a gearbox → $J_{Load\_Reflected} = \frac{J_{Load}}{i^2}$

e) OverVoltage Error

- In order to ignore otherwise safe transient voltage spikes, it might be necessary to increase the Delay Time 0x235.05, see page 25

Appendix – Expert Tuning

f) Path Accuracy and Dynamics – Feedforward for Position Control

This approach shall increase the path accuracy by using **Velocity Feedforward** and may further reduce the settling time:

- First, the Step by Step Tuning starting on page 11, ending on page 19 has to be performed, especially the Following error has to be configured as quick stop source (see page 18).
- Only then the Velocity Feed Forward should be activated.

  In Position View the Velocity-Feed-Forward-Value should be set to 100 % (= 128)

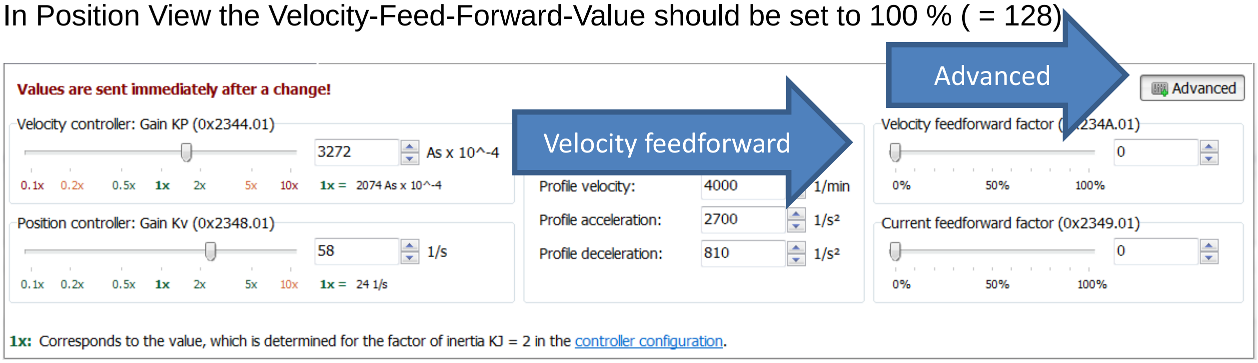


Figure 16: Control and Feedforward Parameters

As a result the following error will be reduced. The settling time might be reduced by 1 to 10 ms, depending on how well the system was tuned before.

Velocity Feedforward might cause a tendency for small oscillations before settling. If this is the case and the tuning goal is to reach the commanded position without any overshoot, it might be helpful to consider current feedforward in addition - see page 22.

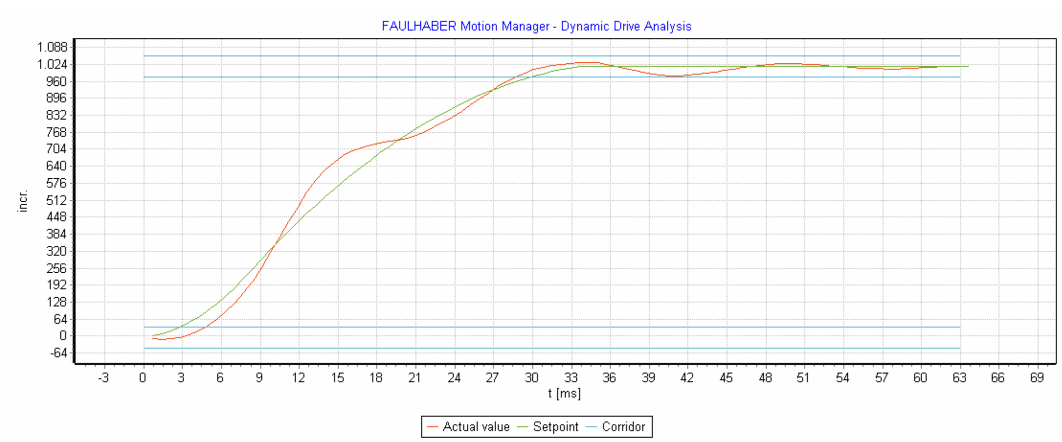


Figure 17: Positioning with Feedforward of Velocity

Appendix – Expert Tuning – Continued

- **Current Feedforward** can be used in addition to Velocity Feedforward. For Current Feedforward to be useful, the inertia factor K_J should be known within +/- 20%.
- In Position View the Current feedforward value should be set to 80..100% (= 102..128).

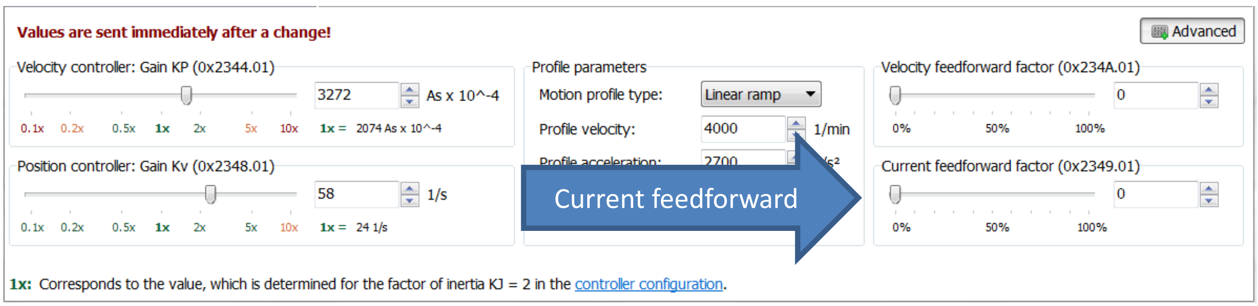


Figure 18: Control and Feedforward Parameters

With additional Current Feedforward the tendency for oscillations is likely to be considerably reduced compared to pure Velocity FeedForward. The Following Error is at is minimum.

The settling time might be slightly increased compared to pure Velocity FeedForward.

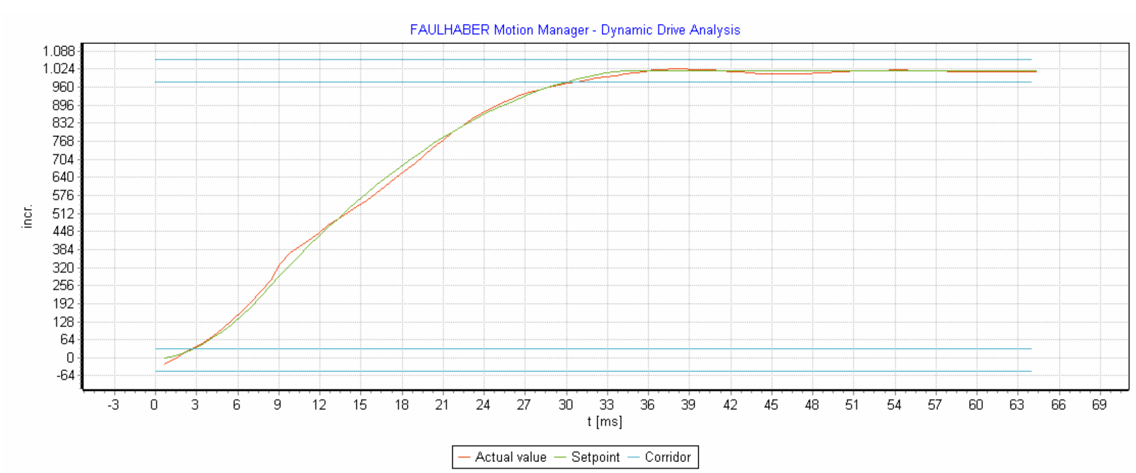


Figure 19: Positioning with Feedforward of Velocity and Current

Appendix – Expert Tuning – Continued

g) Profile Velocity in Detail

The parameter Profile Velocity acts as a limiter on the velocity command generated by the profile generator, chosen properly it helps to reduce the following error.

The longer the commanded distance, the larger is the maximum velocity which the profile generator calculates based on the distance and the acceleration and deceleration parameters.

The drive system may only follow this calculated profile, as long as the supply voltage is high enough to accelerate the inertia, while overcoming any friction and the Back-EMF-voltage at the same time.

The limiting profile velocity comes into play here. A properly chosen Profile Velocity parameter helps to avoid large overshoot or even instability of the system, because the drive system will be able to follow the commanded values. If the limitation applies, this results in a trapezoidal velocity profile.

See Advanced Settings / Profile parameters / Profile velocity

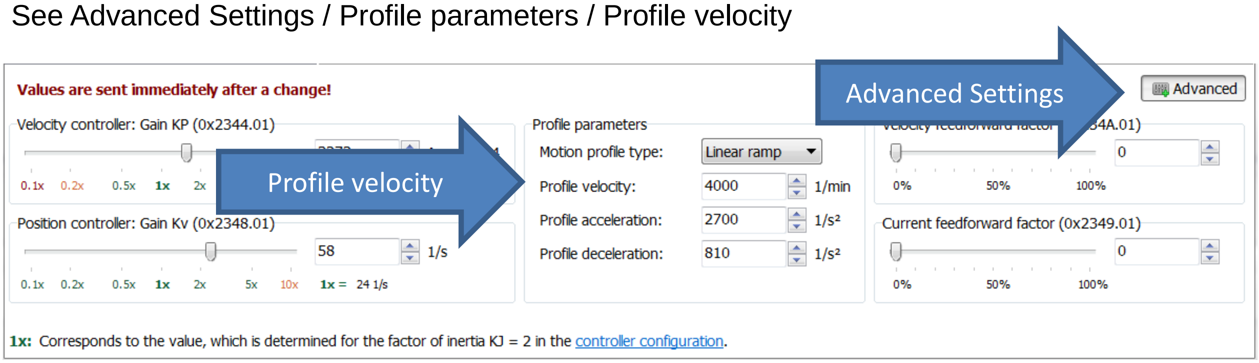


Figure 20: Profile Parameters

h) Constant versus Variable Load Inertia

If the load inertia changes significantly, the proportional gain K_P and possibly the velocity feedback filter have to be changed accordingly to keep the system stable.

i) Stiff / Elastic Mechanics

For systems with compliance, such as elasticity or high degree of backlash, the proportional gain K_P of the velocity control loop might have to be reduced. The tuning methods in the application note might not apply in these cases.

Appendix – Software Position Limits

j) Adjustment of Software Position Limits

Before adjusting Software Position Limits it might be necessary to set the actual position to zero. This can be done via the Motion Cockpit Tool where you can find the Homing modes. Homing Mode 37 can be used to set the actual position to zero.

See Drive Function / Device Control for an access to the Position Limits. There the Software Positon Limits in increments can be adjusted.

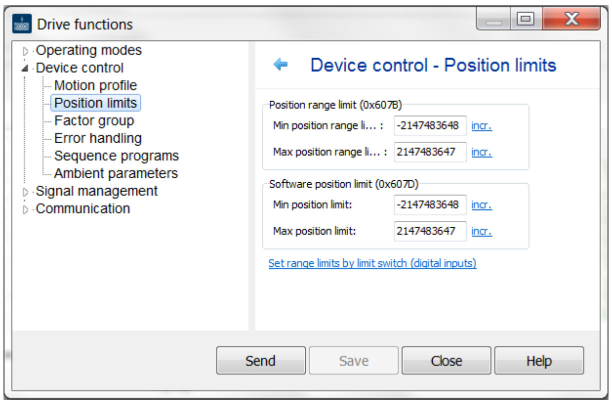


Figure 21: Drive Functions / Device Control / General

By default the software positon limits apply to modes of operation for positioning only.

If there are no limit switches in use, it is highly recommended to activate the software position limits for velocity controlled modes as well.

This is done by setting Bit 1 of object Operation Mode Options 0x233F to 1.

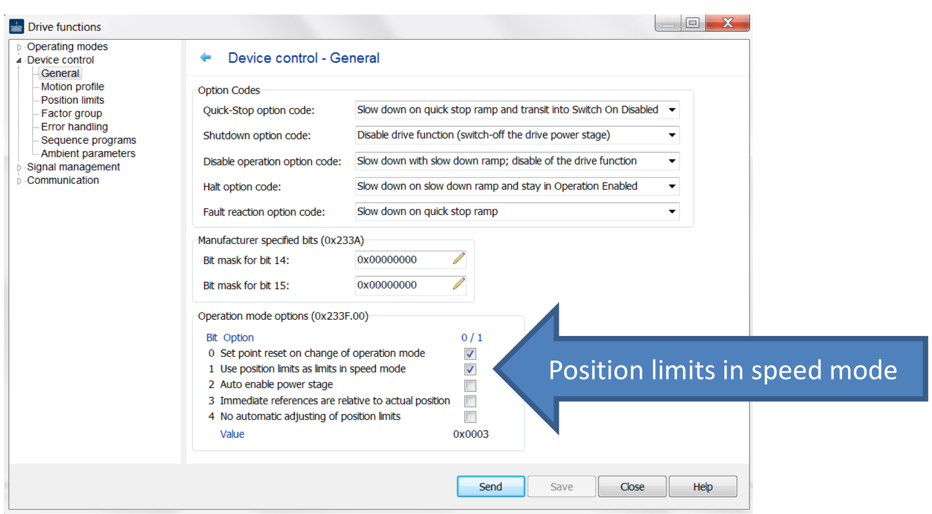


Figure 22: Drive Functions / Device Control / General

Appendix – OverVoltage Threshold

k) OverVoltage Threshold

During braking energy is fed back into the power supply. If the power supply is not capable of dealing with regenerative energy, the voltage will increase instead. The Motion Controller will take action to keep the voltage down. A certain voltage threshold triggers the “burning of energy” in the motor and/or the reduction of the current applied for braking.

For a 24V DC power supply with a tolerance of +/- 10%, the “Motor supply upper threshold” should be set around 27V to prevent unexpected shut-down or even damage of the power supply during braking. The motor selection wizard implicitly configures this threshold according to the supplied Umot voltage.

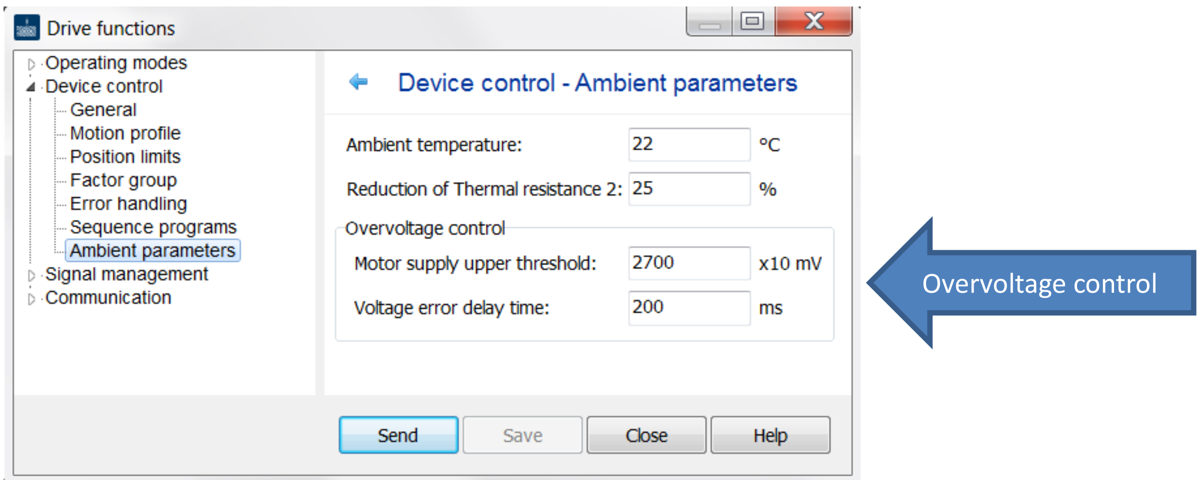


Figure 23: Drive Functions / Device Control / Ambient parameters

See Drive Functions / Device Control / Ambient parameters for an access to the over voltage threshold: „Motor Supply UpperThreshold“.

In addition the possibility to adjust a Delay Time (0x2325.05) is offered. If the Motor Supply Upper Threshold is exceeded for a time longer than this Delay Time the Motion controller will turn off the power stage and will set an over voltage error. When using high load inertia it is likely that the delay time has to be increased.

Appendix – Non-Profile Modes of Operation

I) Usage of Non-Profile Modes of Operation

- Cyclic Modes:

  By design cyclic modes depend on a stream of command values (and maybe additional feedforward values) from a Master PLC at regular intervals in the range of typically 1 to 10 ms. The control system can be tuned using the tuning tool, but afterwards the profile parameters have to be transferred to the Master PLC for the calculation of the command trajectory.

- Analog Modes:

  Analog Modes do not make use of the profile generator either. Instead command filters have to be used. If the Motion Manager Tool shall be used for control tuning, the maximum profile parameter values should be set and a command filter has to be activated.

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