Application note:
Motion Control Profile Parameterization

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This application note is meant to be a practical guideline for motion profiles parameterization of TRINAMIC ICs. In order to understand *where* to find the parameters mentioned, and how to set them, please refer the specific product documentation.

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2 Motion Control Basics

Motion control regulates position, velocity and acceleration of actuators like electric motors and its load. Although motion control profiles could be quite complex moving multiple axes, this contribution focus on different motion profiles for one axis carrying a load from one point to another. Pure motion control is mostly done by the ramp generator, the heart of the motion controller.

2.1 Understanding relevant motion parameters

As a first step, you should understand which parameters have a direct or indirect influence on the motion profile.

Parameter		Description	Dimensions	Calculations
Position	P	A definite characterized location of a point in space in relation to an arbitrary reference origin.		
Distance	s	The absolute difference of the positions of two points P_1 and P_2.	L (L = length)	$s = \|P_1 - P_2\|$
Velocity	v	The distance which is covered by a point for a certain time period Δt.	$L \cdot T^{-1}$ (T = time)	$v = \frac{\Delta s}{\Delta t}$ $v(t) = \lim_{\Delta t \to 0} \frac{\Delta s}{\Delta t} = \frac{\partial\, s(t)}{\partial\, t}$
Acceleration	a	The rate of change of velocity with time. An acceleration which is lower than 0 is also called deceleration d.	$L \cdot T^{-2}$	$a(t) = \frac{\partial\, v(t)}{\partial\, t} = \frac{\partial^2\, s(t)}{\partial\, t^2}$
Jerk	j	The rate of change of acceleration with time.	$L \cdot T^{-3}$	$j(t) = \frac{\partial\, a(t)}{\partial\, t} = \frac{\partial^2\, v(t)}{\partial\, t^2} = \frac{\partial^3\, s(t)}{\partial\, t^3}$

Table 1 Motion profile parameters

In some of our applications, the parameter ***bow*** appears, which is the same as a constant j(t). A bow value < ∞ is used to generate a soft transition for a load, leading to reduced system resonances to acceleration value changes. System resonances or overshoots act like an additional load on the motor, thus reducing the available useful portion of motor torque. Furthermore, the necessary time span to fade away system resonances could be diminished by lower bow values as well, thus giving the opportunity to start early with further actions if a whole system stop is required. As a result, so called S-shaped ramps for the velocity profile are generated.

2.2 Specific motion profiles

In the following, different motion profiles are introduced with its advantages and disadvantages.

2.2.1 Constant velocity

The simplest way to drive a load is to set a constant velocity to the electric motor if motion is required (the solid line in Figure 1). Due to the use of velocity commands only (*a* = ∞/0 and *bow* = ∞/0), motion control is easy, but also not precise due to the time finite behavior of systems and its load which have to accelerated to the required velocity. This results in fluctuating time delays t_a, t_d for acceleration which are dependent on system and load. Differences of the real world velocity of the system and load are displayed in Figure 1 with a dotted line. Due to the relationship between velocity and distance, precise positioning is not possible without further regulation.

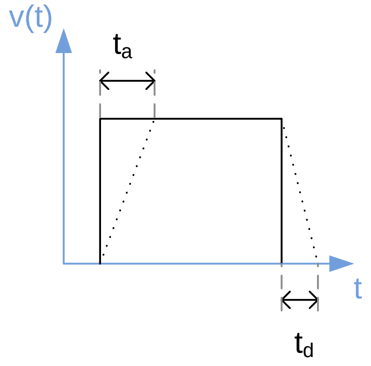

Figure 1 Constant velocity ramp (solid line) with real behavior of the system (dotted line)

2.2.2 Constant acceleration – Trapezoidal velocity ramp

To predict the acceleration rates t_a and t_d, a trapezoidal velocity ramp could created. Thereby, the velocity of the system will be increased and decreased linearly with a constant gradient which are the acceleration value a_{MAX} and the deceleration value d_{MAX} to the maximum velocity v_{MAX} (Figure 2). Hence, t_a, t_d and the distance s could be calculated precisely:

$$s = v_{MAX} \cdot \left(t_{RAMP} - \frac{t_a}{2} - \frac{t_d}{2}\right) \quad (1)$$

$$t_a = \frac{v_{MAX}}{a} \ \forall \ a > 0 \quad (2)$$

$$t_d = \frac{v_{MAX}}{d} \ \forall \ d > 0 \quad (3)$$

System resonances will still occur, but for many systems it could be neglected.

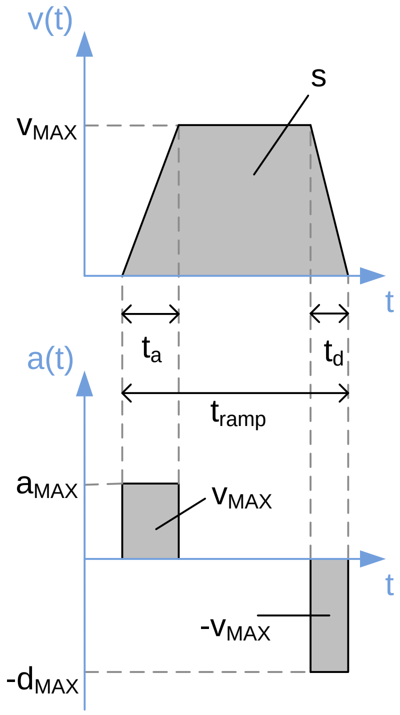

Figure 2 Trapezoidal velocity ramp with corresponding acceleration curve (similar to the motion profile of TMC457 with bow_max = 0)

2.2.3 S-shaped velocity ramps for minimum system resonances

In some cases, system resonances should avoided as much as possible. Therefore, a gradual modification of the acceleration parameter *a* has to be provided. By taking the bow parameter into account, overshoot problems could be eliminated and hence, mechanical vibrations could be reduced to a minimum. Disadvantages are a higher complexity for velocity and positioning calculation and a slower positioning due to lower acceleration value than the maximum possible acceleration. Figure 3 depicts the velocity, acceleration and bow ramps for a constant change (*bow*) of *a*. These S-shaped ramps provide a precise and smooth motion profile which is fast as possible due to the lowest acceleration values at the start and end of the ramp and the maximum acceleration between.

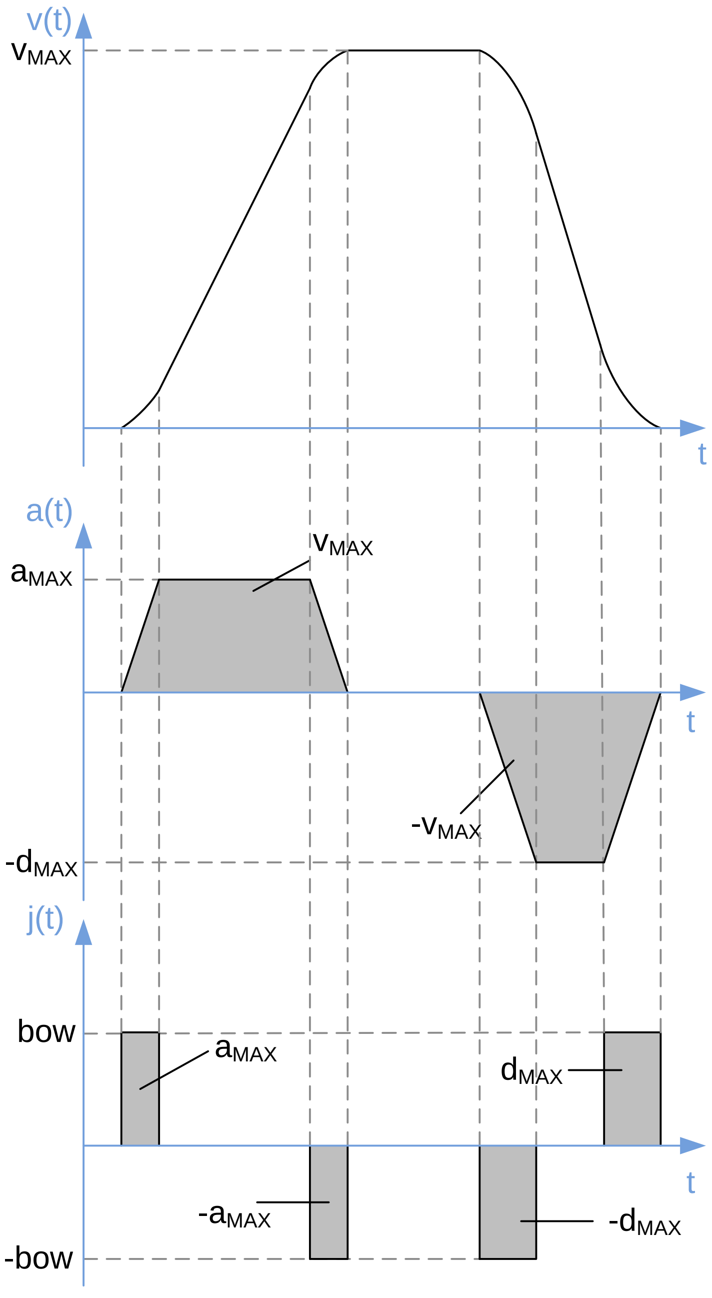

Figure 3 S-shaped velocity motion profile with linearly changed acceleration values and constant bow values (similar to the motion profile of TMC457 with bow_max > 0)

3 Trinamic Motion Controller – Examples

The motion profiles which are introduced in chapter 2 are implemented in Trinamic motion control integrated circuits. In the following, TMC429 and TMC457 and its motion profile parameters are introduced and explained.

3.1 TMC429 – Advanced trapezoidal velocity ramps

TMC429 is a miniaturized high performance stepper motor controller which controls up to three 2-phase stepper motors concurrently. The motor controller includes a motion controller which creates an trapezoidal velocity ramp.

The ramp mode *ramp_mode* has to be declared initially. Four modes are available. First, the default mode is the *RAMP_MODE* which provides positioning tasks. Second, the *SOFT_MODE* is similar to the previous mode except that velocity is reduced exponentially to reach the target position. This results in a soft, exponentially shaped velocity profile during deceleration phase which is similar to the S-shaped ramps (chapter 2.2.3) to reduce system vibrations at the target position. To drive stepper motors precisely with a constant velocity, the *VELOCITY_MODE* ramps the velocity to the requested value with user defined limits of velocity and acceleration. These limits are ignored in the *HOLD_MODE* which generates a motion profile from given velocities. That way the motion profile could be created completely by the connected microcontroller. To start positioning, the target position *x_target* have to be set differently to the current position *x_actual*. Both parameters may alter during positioning. The current velocity *v_actual* will be altered with a constant acceleration *a_max* to the user defined maximum velocity *v_max*. To finish positioning the current velocity will be reduced to 0 with a deceleration value which equals *a_max*. Exceptions to the pure trapezoidal velocity ramp (chapter 2.2.2) are explained in the following.

A minimum velocity value *v_min* could be set. If the current velocity is equal or smaller than this value during deceleration phase of the motion profile, the velocity could be stop abruptly if the target position is reached (see Figure 4 a), b)). This allows a faster positioning because the stepper motor is not slowed down this value until the *x_target* is reached. To ensure exact positioning, *v_min* should be greater than 1.

Due to the permanent calculation of *v_target* during positioning mode (*RAMP_MODE*, *SOFT_MODE*) deceleration phase could be started before maximum velocity is reached. As a result, a triangular motion profile is generated (see Figure 4 b)) fulfilling following equation which is a variation of (1):

$$s = v_{TARGET} \cdot \frac{t_a}{2} + (v_{TARGET} + v_{MIN}) \cdot \frac{t_d}{2} \qquad \forall \quad v_{TARGET} < v_{MAX} \tag{4}$$

Finally, an exponentially shaped velocity profile during deceleration could be achieved to reduce system resonances if the *SOFT_MODE* is chosen (see Figure 4 c)). This part is similar to a S-shaped velocity ramp.

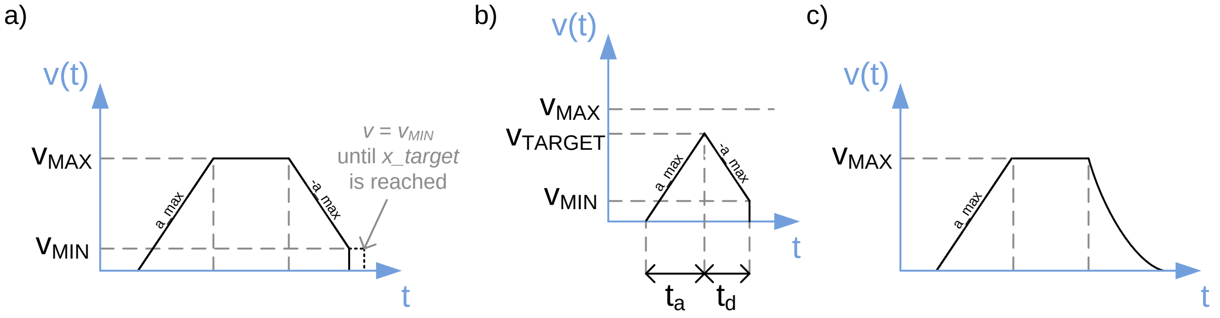

Figure 4 Velocity ramps of TMC429:
a) Trapezoidal ramp with minimum velocity v_min to finish positioning
b) Triangular ramp with minimum velocity v_min due to a small distance s
c) SOFT_MODE: Trapezoidal ramp with exponentially shaped velocity during deceleration phase

3.2 TMC457 – S-shaped velocity ramps

To provide 2-phase stepper and piezo motors with a precise, fast and jerk-free motion profile, the TMC457 is a very good choice. This motion controller provides besides a highly customizable S-shaped velocity ramp, trapezoidal ramps as well with the opportunity to alter all ramp parameters during motion. Three *ramp_mode*s are available: *positioning mode*, *velocity mode* and *hold mode*. These modes correspond to the modes *RAMP_MODE*, *VELOCITY_MODE* and *HOLD_MODE* of the TMC429. The *positioning mode* starts also by setting *x_target ≠ x_actual* and appropriate parameters for velocity, acceleration and bow. The deceleration parameter *d_max* could differ from the acceleration parameter *a_max*. If both parameters are equal, parameter *a_max_d_max* sets both to the same value. By setting the jerk parameter *bow_max* to an integer value which is larger than 0, a S-shaped velocity ramp – similar to the ramp depicted in Figure 3 – is calculated to reach precisely *x_target*. If *bow_max* = 0, a trapezoidal ramp is generated (Figure 2) which could be triangular if the maximum velocity *v_max* is not reached.
The parameter *v_target* has to be set appropriately to perform the other ramp modes. This specified velocity value is set immediately for the motor without considering any ramp parameter (*hold mode*) or a corresponding S-shaped or trapezoidal velocity ramp is created to reach this value with a motion profile depending on *bow_max*, *a_max* and *d_max* (*velocity mode*).

Bow parameter for TMC457 is given as logarithmic values. A double bow leads to half the time to reach a certain acceleration.

0	The ramp generator uses trapezoid ramps. This corresponds to an infinite bow value.
1 to 18	Bow for s-shaped ramps in logarithmic representation. A high bow value leads to a shorter bow phase. The bow_value is added with 1/1024 f_{CLK}[Hz] to acceleration *a_actual* up to the value set by *a_max* for acceleration resp. *d_max* for deceleration. bow_value = 2^(*bow_index-1)* *bow_index* = 1, 2, 3, …, 18 ⇔ bow_value = 1, 2, 4, …, 262144 *Attention on bow setting*: The resulting bow_value must not exceed A_MAX or D_MAX setting. Otherwise oscillations may result. Example: With bow=18, never set A_MAX to or below 262144.

Units of velocity, acceleration and bow for the TMC457

v_max	Maximum velocity for positioning mode	0 to $7FFF0000 for any a_max [µsteps / t]
v_target	Target velocity The sign determines the direction in velocity mode and hold mode.	± $7FFF0000 for any a_max [µsteps / t]
a_max	Acceleration, unsigned fixed point 16.8 representation	0 to $FFFFFD [µsteps / t^2]
d_max	Deceleration parameter, unsigned Fixed point 16.8 representation The effective deceleration with s-ramp enabled is 15/16 of *d_max*.	0 to $FFFFFD [µsteps / t^2]
d_stop	Deceleration for stop event, for security reason it is with bow = 0	[µsteps / t^2]
bow_max	S-Ramp configuration 0=linear ramp (trapezoid) *bow_index* = 1, 2, 3, …, 18 ⇔ bow_value = 1, 2, 4, …, 262144	bow_value [µsteps / t^3]

3.2.1 Conversion of the TMC457 units to real world units

The units of a TMC457 register content are written as register[457].

Parameter vs. Units		
Parameter / Symbol	Unit	calculation / description / comment
f_{CLK}[Hz]	[Hz]	clock frequency of the TMC457 in [Hz]
s	[s]	second
US	microstep	
FS	fullstep	
velocity v[Hz]	microsteps / s	v[Hz] = v[457] * (2 * f_{CLK}[Hz] / 2^31)
acceleration a[Hz/s]	microsteps / s^2	a[Hz/s] = a[457] * f_{CLK}[Hz]^2 / (16*256) / 2^30
bow [Hz/s²]	microsteps / s^3	b[Hz/s²] = bow_value * f_{CLK}[Hz]^3 / (16*256) / 2^30 / 1024
micro step resolution USR (used U instead of µ for micro)	counts	micro step resolution in number of microsteps (i.e. the number of microsteps between two fullsteps)
v[FS] @ USR	US/s	v[FS/s] = v[US/2] / USR USR ⇔ microstep resolution
a[FS/^2] @ USR	US/s^2	a[FS/s^2] = a[US/s] / USR
ramp_steps[457] = rs	[457]	rs = 2 * (v[457])^2 / (a[457]) / 2^18 micro steps during linear acceleration ramp (if v_max is really reached during acceleration)

<u>General hint for selection of bow value:</u>
The ramp generator is the heart of the motion controller. It runs either ramp with linear velocity profile or ramp with s-shape velocity profile. The selection is done by the bow parameter. Setting bow to 0 selects linear velocity profile. Linear ramps perform the quickest motion, by using the maximum available acceleration at all times. But, since the acceleration becomes switched on and off abruptly, system resonances can occur. They appear like an additional load on the motor, thus reducing the available useful portion of motor torque. Further, system resonances need some time to fade away, and this can costs valuable system time, if a complete stand still is required, before other actions can start. With the S-shaped ramp, resonances can be reduced. However, it is advised to choose the bow parameter as high as possible, in order to optimize positioning time.

4 Motion Controller Registers vs. TMCL Parameters

On TMCM modules that are equipped with a TMC429 or TMC457 motion controller, most of the motion controller registers mentioned in this application note are directly mapped to TMCL parameters. On TMC429 based modules, these are mapped as follows:

Register	TMCL axis parameter
v_max	4 (maximum positioning speed)
v_target	2 (target velocity), ROL/ROR command parameter value
v_actual	3 (actual velocity)
x_target	0 (target position), MVP command parameter value
x_actual	1 (actual position)
a_max	5 (max. acceleration)

Selection of the mode (RAMP_MODE, VELOCITY_MODE) is done automatically by the ROL/ROR, MVP and MST commands.

The following table shows the parameter mapping on modules equipped with a TMC457 (currently these are only the TMCM-142 and PD-146 modules):

Register	TMCL axis parameter
v_max	4 (maximum positioning speed)
v_target	2 (target velocity), ROL/ROR command parameter value
a_max	16 (max. acceleration)
d_max	17 (max. deceleration)
d_stop	15 (stop deceleration)
bow_max	18 (max. bow)
X_target	0 (target position), MVP command parameter value
X_actual	1 (actual position)

Selection of the mode (RAMP_MODE, VELOCITY_MODE) is done automatically by the ROL/ROR, MVP and MST commands. TMCL parameter 5 sets both acceleration and deceleration to the same value. On TMC457 based modules it is also possible to select PPS units instead of internal units using the command SAP 255, 0, 1.

5 Revision history

5.1 Documentation revision

Version	Date	Author BD=Bernhard Dwersteg	Description
0.1	2012-JAN-16	HS	First version
0.2	2012-JAN-31	HS	First complete version
0.3	2014-JUN-24	BD	Added excerpts from TMC457 manual

Table 2: Documentation revisions