Tutorial about the regulation for electric servo drives

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Chapter 1 - General - Theoretical Aspects

1.1 - Definition

The regulation of industrial processes includes all the material and technical means for maintaining a physical quantity to be adjusted equal to a desired value, called a setpoint. In general, regulation is the set of techniques used to maintain the constancy of a function.

1.2 - Regulation terms - example of the PID regulator

A Proportional Integral Derivative (PID) controller is a control device for performing closed-loop control of an industrial system. It is the most used regulator in the industry and it can control a large majority of processes.

The PID allows 3 simultaneous actions on the setpoint / measure error:

- **Proportional** action: the error is multiplied by a gain $G$

- **Integral** action: the error is integrated over a time interval $s$ and divided by a gain $Ti$

- **Derivative** action: the error is derived following a time $t$, then multiplied by a gain $Td$

There are several possible architectures to combine the 3 effects (series, parallel or mixed); below, the parallel architecture:
1.2.1 - PID setting

The setting of a PID must define the coefficients $G$, $T_d$ and $T_i$ in order to obtain an adequate response of the process and the regulation. The goal is to be robust, fast, accurate and limit overshoot. Robustness is probably the most important parameter to find. This requires:

- choose settings to limit the possible overshoot of the set variable and to allow it to return within a reasonable time to its set value,
- obtain a high stability: a system is robust if the regulation still works even if the model changes a little, the regulator must be able to ensure its task to adapt to behavioral hazards (mechanical backlash, variable friction, elasticity, etc.),
- look for the best possible dynamics: the speed of the regulator depends on the rise time and the steady state settling time.

The accuracy criterion is based on the static error (natural manifestation of a drift between the value of the output signal to be adjusted and the set value assigned to it).

Below, the typical response of a stable process:
The PID parameters influence the system response as follows:

**G**: When G increases, the rise time is shorter but the overshoot is greater. The settling time varies little and the static error is improved.

**Ti**: When \(1/Ti\) increases, the rise time is shorter but there is a larger overshoot. The settling time at steady state is longer, but in this case a zero static error is ensured. The higher the value of this parameter, the slower the system response.

**Td**: When \(Td\) increases, the rise time changes little but the overshoot decreases. The settling time at steady state is better. No influence on the static error. If this parameter is too high, it stabilizes the system by slowing it down but in a second time the regulator anticipates a lot and a system with high dead time quickly becomes unstable.

For these three parameters, the setting beyond a too high level will cause a growing oscillation leading to instability of the system.

The analysis of the system with a PID is very simple but its realization can be difficult because there is no single method to solve this problem. One must find compromises, the ideal regulator does not exist. In general one sets a specification to be respected on the robustness, the overshoot and steady state settling time.

In practice, professionals often use the successive approach method, which responds to a rigorous procedure: one first adjust the P action only to have an overshoot of 10 to 15% and the derivative action so as to "plane" at best the previous overshoot, finally adjust if necessary the integral action by setting a final overshoot between 5 and 10%.

### 1.3 – Smart regulators

#### 1.3.1 – Predictive control

**Predictive control** (or **compensation** or **anticipatory correction**) is an advanced control technique of the automatic. Its purpose is to control complex industrial systems. The principle of this technique is to use a dynamic model of the process inside the controller in real time in order to anticipate the future behavior of the process.

Predictive control can be used to control complex systems with multiple inputs and outputs when the simple PID controller will not be effective. This technique is particularly interesting when the systems have significant delays, inverse responses and many disturbances.

#### 1.3.2 – RST regulator

The RST regulator is a control device for performing closed-loop control of an industrial system. It's a regulator commonly used in numerical control systems.

The initials RST comes from the name of the 3 polynomials to be determined in order to obtain an effective command. The synthesis of this type of corrector is done by placing poles. The resolution of the system implements a tracking polynomial, and a filtering polynomial.
1.3.3 – State observer

In automatic, a state observer is an extension of a model expressed as a state representation. When the state of a system is not measurable, an observer is built which allows to restore the state from a model of the dynamic system and measures of other variables.

The theory of the deterministic state observer was introduced in the sixties by Luenberger for linear systems. Kalman has also formulated an observer considering a stochastic linear system (stochastic calculus is the study of time-dependent random phenomena, as such it’s an extension of the theory of probability). For non-linear systems, observation remains a very active area of research, but the most common application is the use of Extended Kalman Filtering (EKF).

The Infranor-CNC FASTware® numerical axis controller uses the state observer.

1.3.4 – Regulation by anticipative action

In Motion Control, many current systems include controllers that have one or more anticipatory terms to compensate the following error during acceleration and the dry & viscous frictions.

The INFRANOR servo drives have anticipatory terms (KF1, KF2, KA).

The Infranor-CNC FASTware® axis controller incorporates modern digital control (RST structure by pole placement). Following errors that can prove to be very penalizing, for example in interpolation operations, are fully compensated by advanced anticipative control techniques. The optimization of the axes is done through a procedure of identification of the transfer function in order to create a model defining the dynamics of the system.
Chapter 2 – INFRANOR position / speed regulator

2.1 – CD1 series regulator structure

The INFRANOR CD1 servo drives feature a high-performance position and speed controller that incorporates the principles of PID and anticipative action control. A dynamic model of the position loop is generated by a computation model that is compared with the actual value of the error of the position loop, in order to better control the tracking error. Below, the structure of the drive position and speed controller. The current controller (vector control with PI controller) is not described in this document.

![CD1 regulator structure diagram]

2.2 – Signals definition

- **position reference**: reference from the internal or external trajectory generator
- **speed**: motor speed measuring signal (resolver, encoder)
- **position**: position measurement signal (motor sensor or external feedback)
- **Idc**: output signal of the speed loop (speed error), current setpoint

2.3 – Definition of key variables affecting the gain of regulators

Our servo drives include a cascade type control, from the generation of the trajectory to the current control in the motor.

The three control loops are as follows:
- current loop, cutoff frequency from 1000Hz to 45 ° phase margin
- speed loop, maximum bandwidth from 100Hz to 45 ° phase margin
- internal position loop (CD1-a in electrical axis or stepper, CD1-k, CD1-pm), sampling period of 0.5ms

The main variables influencing loop gains are:
- current loop: **motor inductance**, PWM, supply voltage, inverter current rating
- speed loop: **total inertia**, driveline stiffness, variator characteristics
- position loop: **system resolution**, axis dynamics
2.4 – Definition of the terms of the position / speed controller

The main parameters are calculated during the auto-tuning procedure. The values depend on the selected bandwidth and filter type. They can then be modified by the user. The value of the scale of the gains (scaling gain) is also calculated.

Proportionnal position gain (KP1) : defines the proportional gain of the controller which acts on the position error.

Feedforward speed 1 gain (KF1) : defines the feedforward speed amplitude corresponding to the speed input command. This term allows to reduce the following error during the motor acceleration and deceleration phases. Its value is set at 1 after the auto tuning procedure if minimum following error is required. It can then be modified by the user if required.

Feedforward speed 2 gain (KF2) : defines the feedforward speed amplitude corresponding to the viscous frictions. This term allows to reduce the viscous frictions effect during the motor acceleration and deceleration phases. The gain value is equal to the damping gain value + the viscous friction compensation term. After the auto tuning procedure, the feedforward speed 2 gain is set equal to the damping gain value if minimum following error is required. The viscous friction compensation term can be calculated by measuring the current / speed ratio at various motor speed values.

Feedforward acceleration (KA) : defines the feedforward acceleration amplitude corresponding to the acceleration input command. This term allows to reduce the following error during the motor acceleration and deceleration phases. Its value is calculated by the amplifier during the auto tuning procedure if minimum following error is required. It can then be modified by the user if required.

Proportional speed gain (KP2) : defines the proportional gain of the controller which acts on the speed error.

Integral speed gain (Ki) : defines the integral gain of the controller which acts on the speed error.

Damping gain (KC) : defines the proportional gain of the controller which acts only on the speed feedback.

Derivative gain (KD) : defines the derivative gain of the controller which acts on the speed error. This gain can't be determined by the auto-tuning procedure!

Derivative gain filter (FD) : defines the time constant of the first-order filter that acts on the derivative gain. This filter can't be determined by the auto-tuning procedure!

Speed error low-pass filter (Fev) : defines the cut-off frequency at -3dB of the 1st or 3rd order filter which acts on the current setpoint (Idc).

2.5 – Options of the auto-tuning procedure

The auto-tuning procedure identifies the characteristics of the motor and load and calculates the gains of the regulator. During the procedure, different choices are available to the user.

Time Interval for Speed Measurement (speed measurement filter) : the choice of the time interval for the speed measurement (0.5, 1 or 2ms) allows the resolution value of the speed measurement to be selected according to the resolution value of the position sensor:

Speed resolution (rpm) = 6000 / feedback resolution / time interval (ms)
The higher the value of the interval, the better the resolution, but also the gains of the servo loop are low due to a higher measurement time.

**Antiresonance filter**: the choice of the anti-resonance filter is necessary in case of loud noise in the motor due to the elasticity of coupling between the motor and the load, especially at standstill. This method is often applicable when driving a relatively large inertia via a belt.

**Max. stiffness filter**: the choice of the maximum stiffness filter makes it possible to obtain a maximum stiffness on the axis of the motor regarding to the disturbances of torque. However, this choice is only possible if there is no resonance induced by the elasticity of the driveline. **Don't use this filter with P-speed regulation only (case with Infranor-FASTware® CNC), the effective speed is halved compared to the speed setpoint!**

**Bandwidth**: the choice of the bandwidth of the speed loop defines the cutoff frequency value of the frequency response of the closed loop (Low = 50Hz, Medium = 75Hz, High = 100Hz).

**Minimum following error**: this choice makes it possible to obtain a precise following of the position reference value during the whole trajectory. In this case, all the anticipative gain values are calculated.

**Minimum position overshoot**: this choice makes it possible to obtain a positioning without any overtaking of the final position. In this case, all the anticipative gain values are set to 0 and the motor position is out of phase with the reference value of the position during the entire displacement.

**Chapter 3 – INFRANOR servo drive regulator setting**

**3.1 – PI speed loop setting example**

The controller most commonly used on a speed drive controller is the PI type. The influence of the inertia coupled to the motor acts proportionally on the value of the gains of the regulator. However, the correct setting of the speed loop can be difficult because quite a few problems can arise. Below, a non-exhaustive list:

- high inertia ratio load / motor inertia
- strong variation of this ratio (empty axis or with load)
- non-compensated vertical axis
- presence of elasticity (belt, elastic coupling, low rigidity of the chassis)
- presence of backlash (reducer or drive pinion backlash)
- high friction, high stress (screw nut too preloaded, screw reducer and crown without play)
- unfavorable natural mode (resonance frequency <100Hz)
- combination of these different factors

The following example will demonstrate the direct influence of the inertia coupled to the motor (single pulley) on the behavior of the regulator.

**Devices**: servo drive CD1-a 230/10.5, servo motor BS072A (rotor inertia 0.51x 10^-4Kgm²), pulley in aluminum, inertia de 2.77 x 10^-4Kgm².
3.1.1 – Adjustment with VDSetup software

Regulator type selection: PI, standard filter, high bandwidth

Parameters resulting from the autotuning, motor without load:
Response to a target index jump of 200 rpm, motor without load:

There is a speed overshoot quickly depreciated, the setting is correct.

Inertia coupled on the motor (5.43 x that of the motor), same parameters:

There is a strong increase in the speed stabilization time, so the gain is too soft. A new setting is necessary. The theoretical gain that must be obtained with the autotuning function should increase proportionally with the inertia, in this case 5.43 x the value obtained motor without load + this value (gain P motor without load = 36.69, or 36.69 + (5.43 x 36.69) = 235.91).
Parameters resulting from the autotuning, motor with load:

The gain obtained is in accordance with the theoretical calculation, a pure inertia rigidly coupled to the motor will act proportionally on the gains of the regulator.

Response to a target step of 200 rpm, motor with load:

Similar behavior is found with the motor without load but with a lower residual ripple smoothed by the additional inertia.

Note: it’s important to check the current (Idc and/or Iq) during the adjustment, it must never be at the maximum of the drive rating or the Imax limitation to ensure the correct operation of the regulation.
3.2 – Position / speed loop setting example

Two types of self-tuning will be addressed:
- setting of parameters to obtain the shortest overshoot during positioning, which leads to a great following error,
- setting of parameters to obtain the shortest following error, which may involve an overshoot during positioning.

The autotuning with minimum overshoot will be adequate for applications where the difference between the reference and the actual position during the different phases of the movement is not important, for example on the majority of independent pick & place robotic axes but where a great positioning softness is required. The different anticipative terms will not be calculated.

The autotuning with minimal following error will calculate and activate the different anticipative terms. This mode will be used for applications where a short following error between the reference from the trajectory generator and the actual position of the axis is required. Depending on the driveline and the dynamics, an overshoot may appear during positioning. Depending on the type of position measurement (directly by the motor sensor or second feedback on the load), it will be necessary to act on the different parameters of the controller.

With this example, we will simply use the motor and pulley of the previous manipulation. Only one feedback (the resolver of the motor) is used. The drive is a CD1-pm 230/10.5 positioner. The position profile is of type S (bicubic interpolation) with a smoother translation than with the trapezoid type profile.

3.2.1 – Adjustment with VDSetup software – shortest overshoot

Regulator type selection: Position, Standard Filter, High Bandwidth
Parameters resulting from the autotuning, motor without load:

Analysis of the trajectory:

There is a clear difference between the reference in red and the measurement in blue. The position error is relatively important during all phases of the translation. There is however no overshoot of the final position.
Parameters resulting from the autotuning, motor with load:

There is only an increase in the gain parameters of the speed loop of an order close to the increase of the driven inertia.

Analysis of the trajectory:

Similar behavior is found with the motor without load.
3.2.2 – Adjustment with VDSetup software – shortest following error

Regulator type selection: Position, Standard Filter, High Bandwidth

Parameters resulting from the autotuning, motor without load:
Analysis of the trajectory:

The reference and the measure coincide. There is a slight overshoot of the final position. The position error is very weak during the whole movement.

Parameters resulting from the autotuning, motor with load:

There is an increase in the speed loop gain parameters and a slight decrease in the anticipative gain acceleration amplitude corresponding to the acceleration setpoint.
Analysis of the trajectory:

Similar behavior is found with the motor without load.

3.3 – Elasticity of the driveline and appropriate dynamics

Current applications are increasingly using strong dynamics, particularly in the field of high precision production machines. However, to achieve these goals, drivelines as well as machine frames must be very rigid in order to "push up" the different natural modes present. The low frequencies of high amplitude are the most penalizing because they generate strong disturbances in the control of the axes. In order to avoid "hook" these frequencies, it's advisable to limit as much as possible the disturbances induced by the characteristics of the drives (motor cogging torque, sensor accuracy, etc.). It's also necessary to adapt the dynamics (acceleration and response of the axes) according to the mechanical response of the used driveline. If the stability requires a decrease of dynamics and that it incompatible with the specifications, it will then be necessary to review the concept.

Important point to never forget: in a driveline, it's almost always the smallest driven diameter that will have the lowest torsional stiffness. If a ball screw with a diameter of 20mm is driven with a motor shaft with a diameter of 11mm, it's the latter which will represent the most sensitive element in torsion, so the most elastic and most likely to generate instabilities.

3.3.1 – Estimation of the dynamics to apply

The easiest way to properly estimate the appropriate dynamics to adopt on a driveline is the following manipulation:
- open the position loop,
- choose the PI speed regulator,
- adapt the gains so that no instability appears at zero speed,
- apply small target steps, first without acceleration ramp and without saturation, then analyze the response of the axis: if strong disturbances are visible during acceleration, it will then gradually increase the acceleration time until the difference between the reference and the speed measurement becomes acceptable. The maximum acceleration to never exceed will be defined.
This manipulation should only be carried out when the safety conditions for people and equipment are guaranteed to avoid any risk of accident. In addition, it must be made sure beforehand that no blockage or excessive friction disturbs the procedure.

3.3.2 – Elastic driveline example

The manipulation carried out in the laboratory highlighted the adaptation of the dynamics to a characteristic of a relatively elastic driveline with a consequent inertia.

Manipulation layout:

![Manipulation Layout Image]

Used devices:

- servo motor BS072A,
- servo drive CD1-a 230/10.5
- standard toothed belt, trapezoidal tothing, pitch 5mm, width 10mm, total length 600mm,
- drive pulley attached to the motor shaft representing approximately 1 x the rotor inertia,
- driven pulley representing approximately 10 x the rotor inertia.

Settings:

- autotuning PI medium,
- maximal speed of 3000 rpm,
- tension standard de la courroie (on peut tourner le brin de 90 ° au milieu).
Measures:

1: target step of 400 t/min:

There are strong disturbances throughout the speed up phase until the overshoot. The "hooked" frequency is about 250 Hz:

2: setpoint of 400 rpm, ramp of 13.33 ms (so 0.1s from 0 to 3000 rpm):

The behavior is noticeably improved, but there is still a visible disturbance.

3: setpoint of 400 rpm, ramp of 26.66 ms (so 0.2s from 0 to 3000 rpm):

The behavior begins to become acceptable.
4: setpoint of 400 rpm, ramp of 40 ms (so 0.3s from 0 to 3000 rpm):

Here one can consider the behavior as acceptable for this application.

5: setpoint of 400 rpm, ramp of 66.66 ms (so 0.5s from 0 to 3000 rpm):

With such a ramp, the behavior is good with an overshoot practically damped in one oscillation.

3.3.3 - Analysis

The driveline of this example is far from the ideal case because the inertia coupled to the motor via the belt exceeds a ratio of 10, which is too important for a high-level application but on the other hand very common in many general handling applications. example.

However, it highlights the need to adapt the dynamics to the rigidity of the driveline if one want to guarantee the stability of the servocontrols.

In some cases of belt transmission where the inertia coupled to the motor is not too big, one can add a little derivative gain (KD) manually to improve stability when the axis is still . However, the use of a derivative gain generates a noise often perceptible: in this case, one will try to play with the derived gain filter (FD) to find the best compromise.
3.3.4 – Note concerning the choice of couplings

There are several types of mechanical couplings, some poorly suited to drives especially when one seeks a high stability of servo and a high dynamic behavior, while others more specific to servo drives.

It’s absolutely essential to avoid rigid twist couplings with helical slit in aluminum or stainless steel which have the peculiarity to generate oscillations resulting from their natural mode during translation of torque. These oscillations can cause the rupture of the coupling.

Bellows stainless steel couplings are widely used and are well suited to workouts as long as they are well dimensioned. Elastomeric couplings often give very good results, but with an elastomer of high hardness.

In conclusion

The adjustment of the regulation parameters does not depend only on theoretical notions. A reliable mathematical model remains important, but an empirical approach allows very often solving complex cases of regulation.

With each new application, the motion control technician will see his knowledge increase and this will enable him to apprehend any new application with maximum confidence in order to apply the most judicious choice of setting.

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Sources
- INFRANOR Group
- EPFL
- free encyclopedias

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