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Automatic Servo Tuning

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Presentation Outline

1. Introduction

- Presentation area and goals
- Definition of some terms
- Optimization objectives: *Robustness*, *Trajectory tracking*, *Disturbance resistance*.

2. Servo Tuning Overview

- Frequency domain analysis
- Elements of speed and position control loops
- Methods for control loop optimization

3. Auto Tuning and AST

- Use cases for machine tool builder and end customer
- Siemens software for auto-tuning

4. Wrap-up

- Review some key points to remember
- Question and answer session

Part 1.

Introduction

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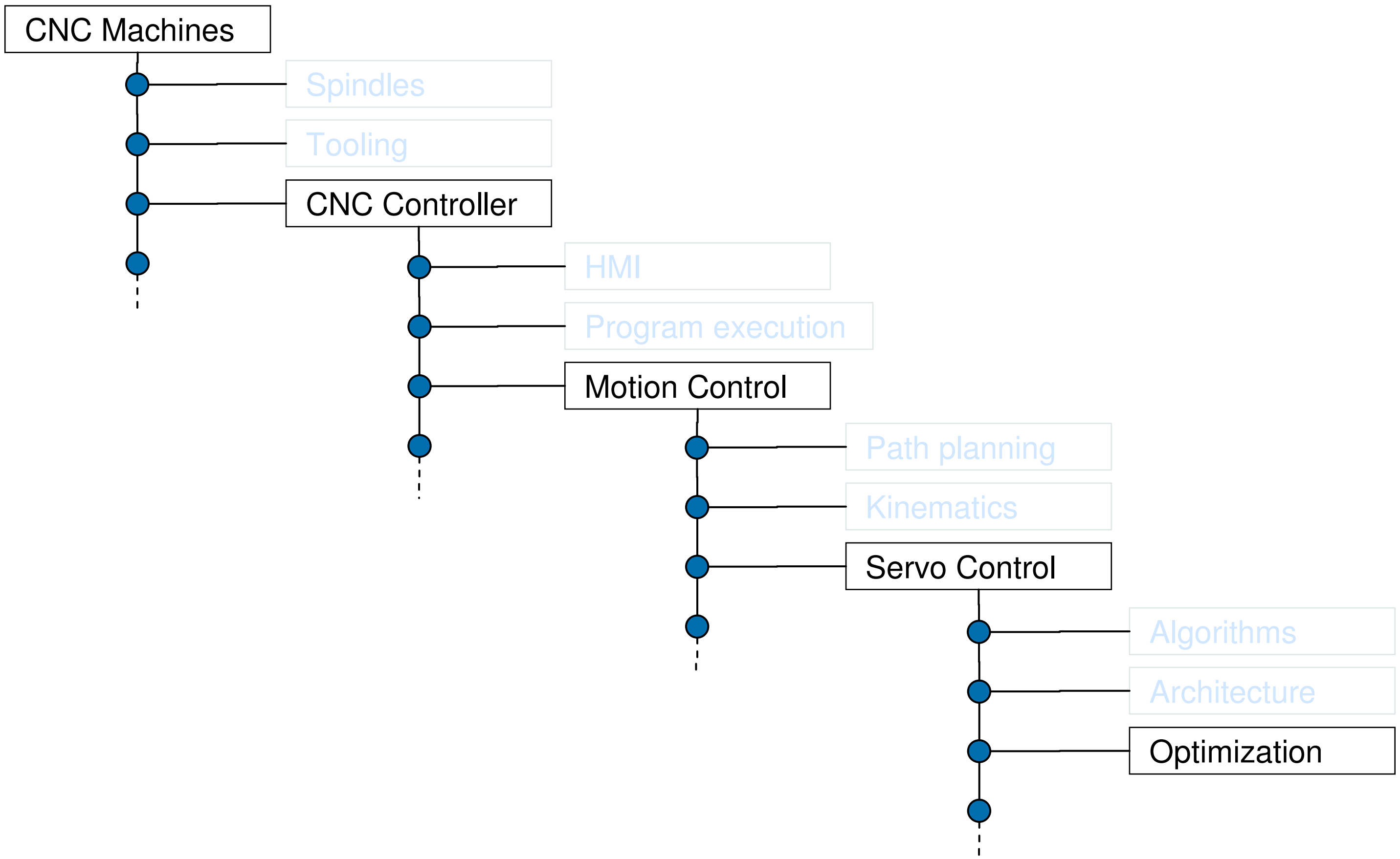
Quick orientation for this topic of discussion



Questions addressed by this presentation

What is “Servo Optimization”?

Why is servo optimization important for machine tools?

How is servo optimization accomplished?

In what ways is automating the process beneficial?

How does the Siemens controller automate servo tuning?

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What is an Axis Servo?

Axis Servo, *noun*: The combination of hardware and software components that controls the motion of a feed axis (or spindle) on a machine tool.

Hardware components

- Electric motor
- Sensors for position, velocity, current
- Power components (inverters, power supplies)
- Computer hardware (CPUs, memory, communications, etc.)

Software Components

- Current Control Loop
- Speed Control Loop
- Position Control Loop

What is meant by "Servo Optimization"?

Servo Optimization, *noun*: The process of determining optimal numeric values for parameters that configure the operation of control loops.

Parameters configured:

- Control loop structure selection
- Feedback control gains and time constants
- Digital filters to stabilize against mechanical resonance
- Feed forward models

Primary considerations for what is considered *optimal*

- **Robustness:** Immunity to performance reductions due to changes in environment.
- **Trajectory following:** Precision with which an axis can track a command profile of position versus time.
- **Disturbance Resistance:** The degree to which the axis position and velocity does not deviate in response to an externally applied force or torque.

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How these optimization objectives relate to machine tools

Trajectory following

- High speed machining complex surfaces (aerostructures, mold & die, …)
- Dynamic path accuracy / multi-axis coordination

Robustness

- Machine-to-machine variations during assembly.
- Replaced mechanical components that have variable dynamic characteristic.
- Changing inertia and vibration modes of work-piece.
- Changing machine dynamics according to axis position (self and cross-axis).
- Changes with age and temperature.

External disturbance forces

- Non-linear friction
- Cogging & torque ripple effects
- Machining / process forces
- Inertial reaction forces between axes

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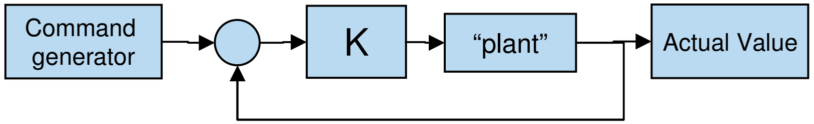
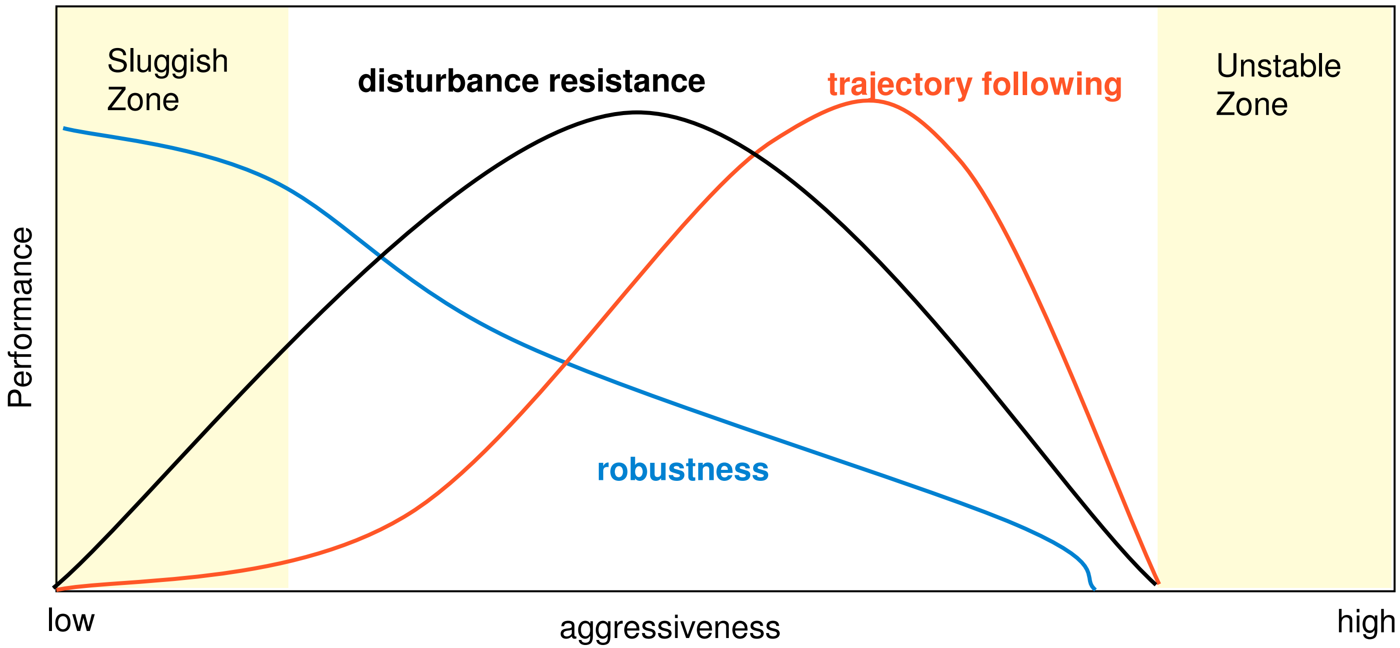
Tuning Aggressiveness and Optimization Objectives

The relative levels of **robustness**, **trajectory following**, and **disturbance resistance** are characterized according to the ***tuning aggressiveness***.

Tuning aggressiveness is roughly equated with the gain (K) of a feedback control loop.



Qualitative view of relationships between aggressiveness and tuning objectives.



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Some observations

- *The optimization objective is often different for every machine and every process.*
- *If performance is not required by the process, choose robustness.*
- *If the machine is subject to high external forces from factors like friction, then some tuning aggressiveness is needed to avoid surface blemishes.*
- *Model-based strategies like feedforward and friction compensation are by nature not highly robust to changes on the machine such as changing work-piece load.*
- *Higher quality machine construction often means consistent behavior and a natural robustness. This allows for higher aggressiveness and consequently higher performance.*
- *If robustness, tracking accuracy, and disturbance resistance could be quantified numerically an optimization objective could be formulated as a scaled sum of these quantities.*

Part 2.

Servo Tuning Overview

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Servo Tuning Overview

Summary of topics

- Explain frequency response analysis.
- How frequency response relates to optimization objectives.
- Speed control loop
- Position control loop
- Disturbance resistance
- Dynamic path accuracy

These factors are directly relevant to SINUMERIK’s Auto Tuning software.

Frequency Domain Analysis

Frequency domain analysis is used in servo theory because it is much **EASIER** than time domain analysis.

Example: combining a PT1 with a PT2 filter in frequency domain is a simple multiplication in time domain it is a difficult convolution integral

Frequency domain

$$\frac{a}{s+a} \cdot \frac{\omega^2}{s^2 + 2\zeta\omega s + \omega^2}$$

Time domain

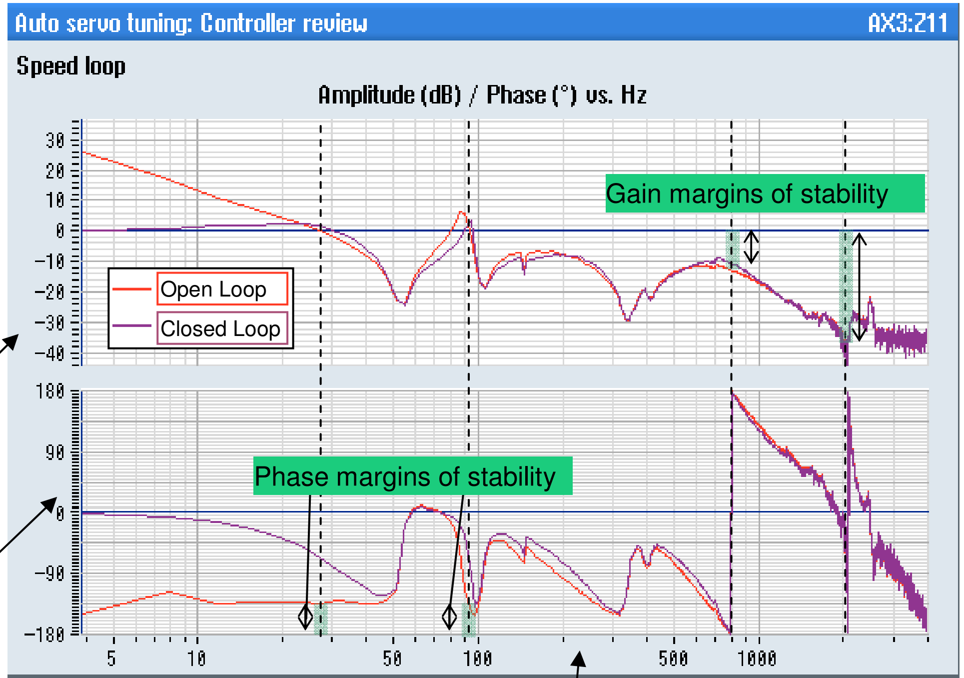
$$a\omega^2 \int_0^t \left(e^{-a(t-\tau)} \cdot e^{\zeta\omega\tau} \cdot \cos(-\omega\tau + \phi) \right) d\tau$$

Frequency domain analysis allows measurements of mechanics to be easily combined with models for controller components

- Filters, gains, and delays are easily converted from analytical formulations to frequency responses.
- Conversion from a frequency response to an analytical formulation is a modeling operation called system identification and can be difficult to automate – fortunately this is, for the most part, not needed for tuning the standard servo parameters.

Anatomy of frequency response (Bode plot)

- Shows input-output behavior of a *dynamic system*.
- Represents the steady-state response of a linear system to a sinusoidal input.
- Linearity ensures that the output is always a sinusoid of the same frequency with a possibly different amplitude and phase shifted relative to the input signal.



Amplitude (dB)
(output_amplitude / input_amplitude)

Phase (deg) (output_angle – input_angle)

Frequency (Hertz) (log scale)

Some more facts about frequency response

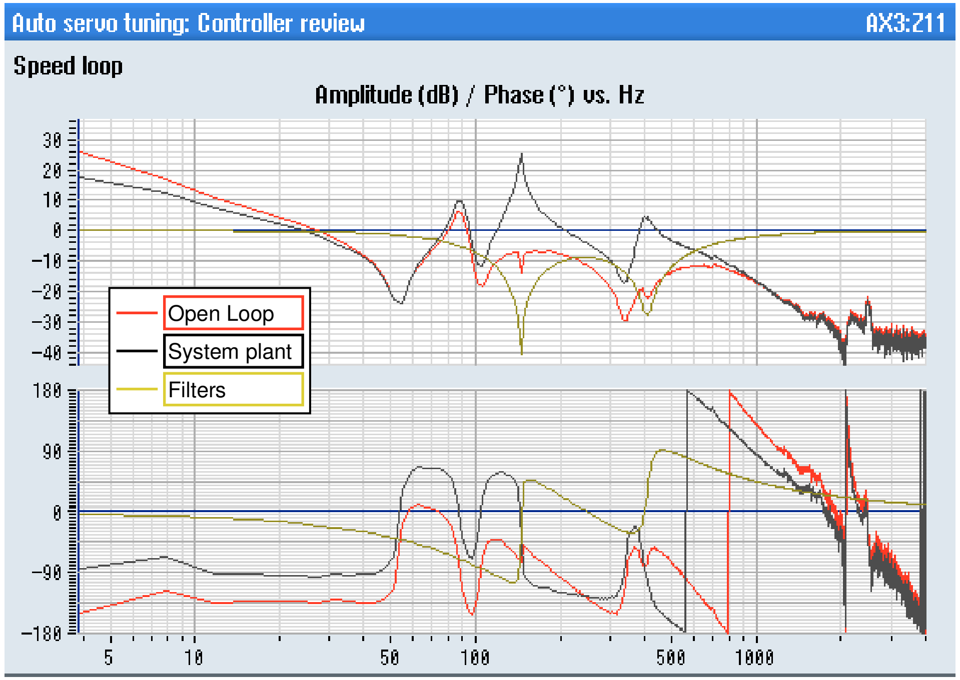
- Pertains only to linear time-invariant stable dynamic system LTI.
- Contains all the information necessary to represent every possible system behavior.
- A Bode Plot can directly indicate the stability of the system.
- Can be measured quickly by injecting excitation whose energy content is distributed over a wide range of frequencies.

Linear versus Nonlinear dynamic systems

Linear Time Invariant (LTI) dynamic system, *noun*: a system whose input output behavior is such that when an original input signal is modified by applying an amplitude scaling and time shift, a modified output signal occurs which is the original output signal scaled and time shifted by the same amount as the modified input.

- Linear systems are appropriately controlled by linear equations in the controller. Commissioning is much easier and may be automated.
- Machine tool axes are for the most part LTI systems.
- Non-linear systems are extremely difficult to analyze especially with regard to stability.
- Some examples of non-linearity.
  - Backlash
  - Cross-axis-dynamics: Pose dependent inertia, inertial reaction across axes. CNC machines are usually designed to minimize these effects (orthogonal axes instead of rotary joint chains)
  - Position dependent dynamics – Sometimes seen in machine tools with shifting of high-frequency vibration modes.
  - Eccentric crank mechanisms – not often seen in CNC machines
- In servo tuning special care is given to ensure that measurements are taken under conditions where the axis behaves as a LTI system.
- If possible, worst case operating point / mechanical configuration should be considered during tuning.

Use of filters to address mechanical resonance



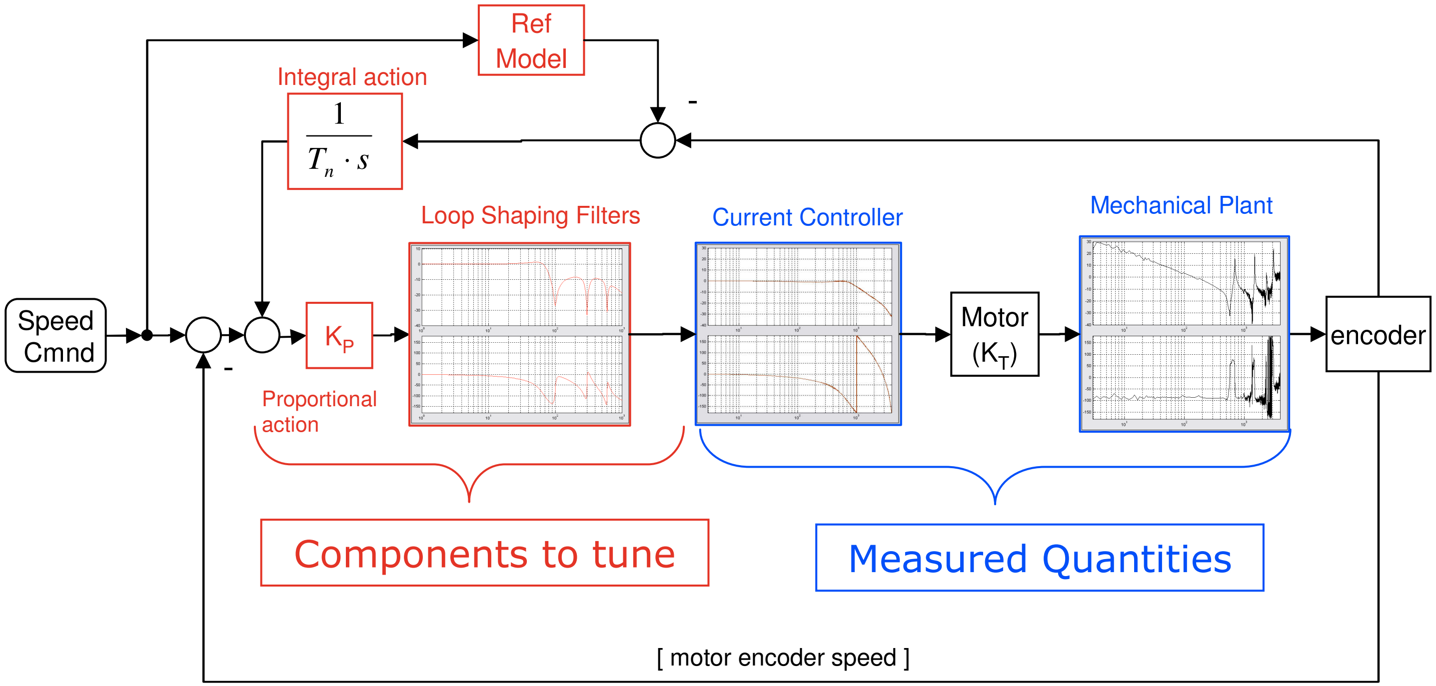
Benefits of filters

- A notch filters tuned to a specific vibration frequency can eliminate the destabilizing effect of amplification of a mechanical resonance by a feedback loop.
- Can significantly raise potentially achieved loop gain

Trade offs

- Worthwhile/beneficial only for medium and high frequency resonance.
- At low frequencies phase is large enough that the closed loop controller alone dampens the resonance
- Filters introduce their own phase loss possibly limiting gain
- Robustness: for very lightly damped vibration modes precisely tuned filter fails if the frequency of vibration shifts

Tuning a speed control loop



Notes

- Kp is primary gain for speed control loop
- Loop shaping filters applied to current set point to address mechanical vibration modes
- Integral time Tn is inverse of integral gain: resists friction, gravity, & other disturbances
- Reference model eliminates overshoot otherwise caused by integrator

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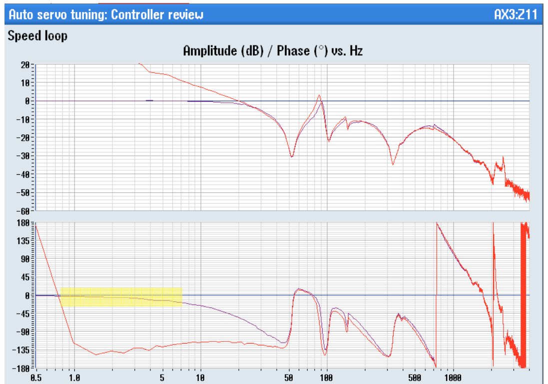
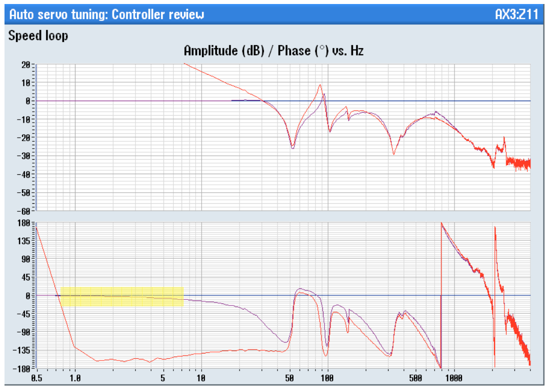
Example: Tuning a speed control loop

Results from AST with different *objectives* set by user

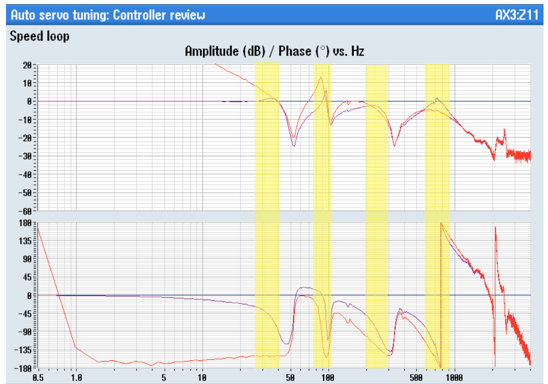
conservative	moderate	aggressive



- Most robust
- Weakest tracking response – seen in immediate onset of phase loss
- Phase roll off in speed loop will be limiting factor for Kv in position loop



- Improved phase response means better tracking behavior
- Stronger integrator means better disturbance resistance



- Best speed command tracking behavior
- Best disturbance resistance
- Least robust to changes: reduction in inertia will cause overshoot and oscillations at 40, 90, 250, 750 Hz

expert knowledge is needed to notice the subtle differences in Bode plots that nevertheless represent important differences in axis behavior

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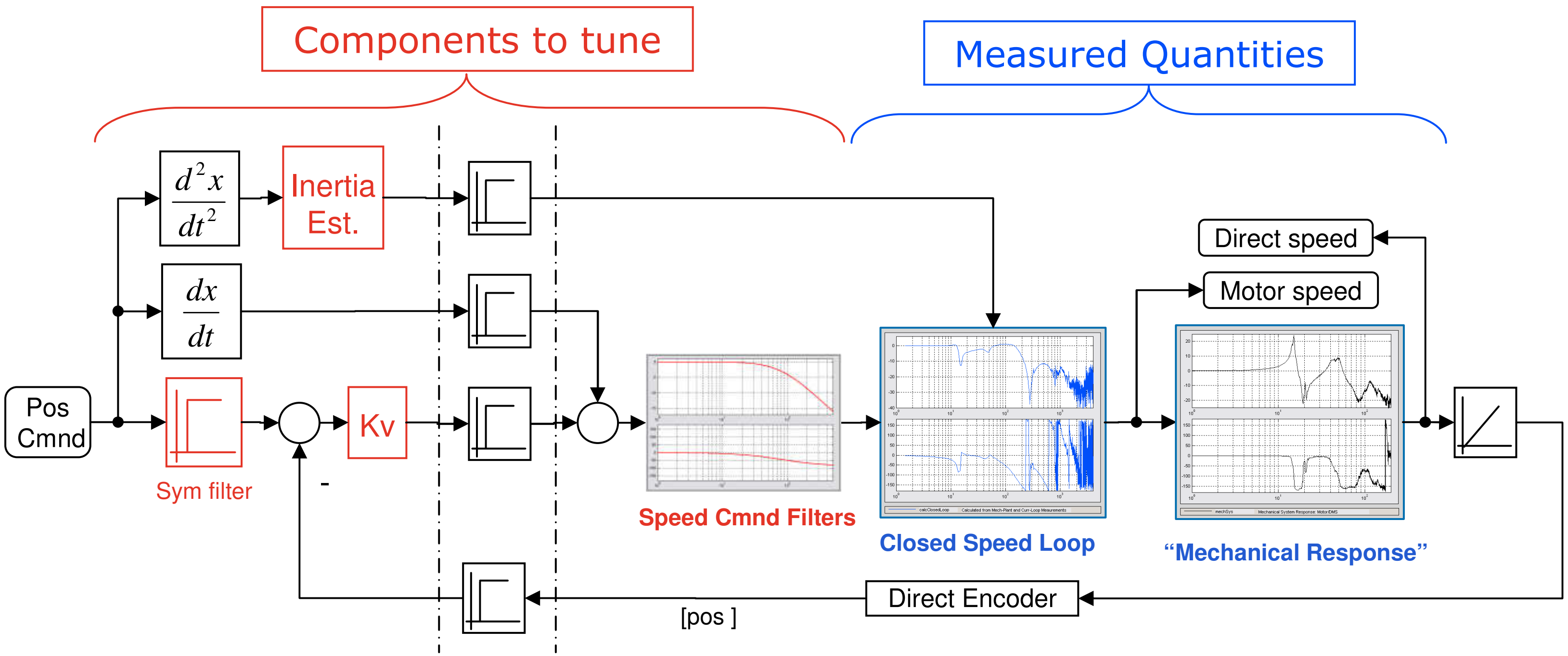
Tuning a position control loop



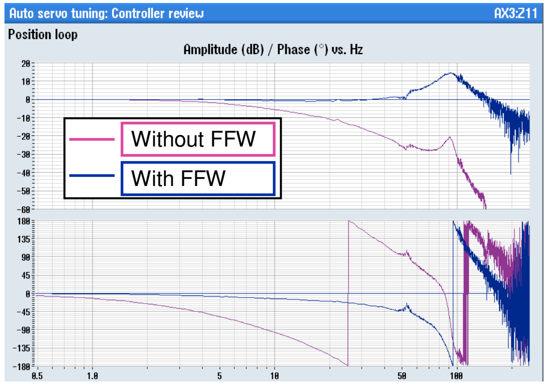
Notes

- Kv factor is primary loop gain.
- Direct feedback means Kv can contribute to dynamic stiffness, but also limits potential Kv
- Speed command filters are occasionally useful for raising potential Kv by countering resonance in "Mechanical response"
- Sym filter prevents overshoot by allowing feedforward branch to dominate
- Inertia estimate is used by feedforward controller for a basic rigid model.

Example: Tuning a position control loop

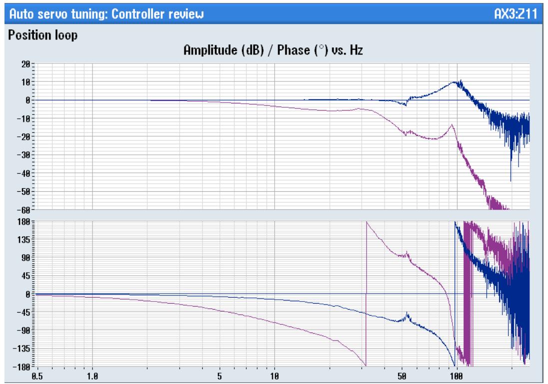
Results from AST with different *objectives* set by user

conservative



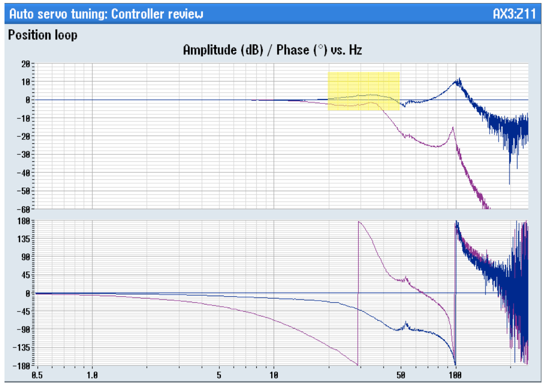
- FFW gives good tracking regardless of Kv
- Torque FFW provides best tracking but is sensitive to changes in total inertia

moderate



- Best overall result

aggressive



- Best (low frequency) disturbance resistance
- Speed controller too rigid: no damping of mechanical resonance by servo.
- Lack of damping causes more overshoot with feedforward control

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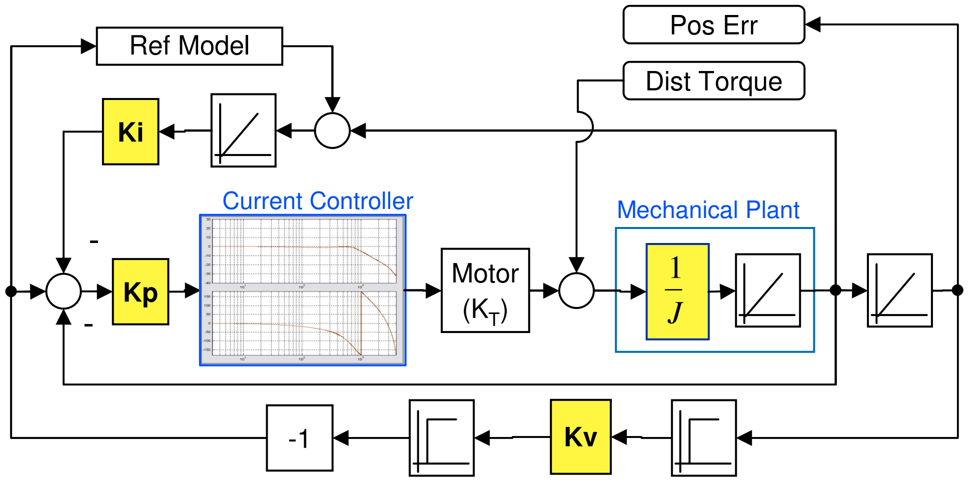
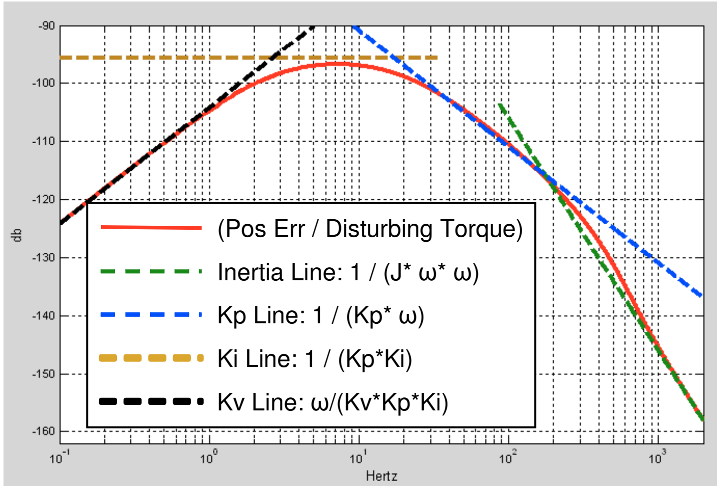
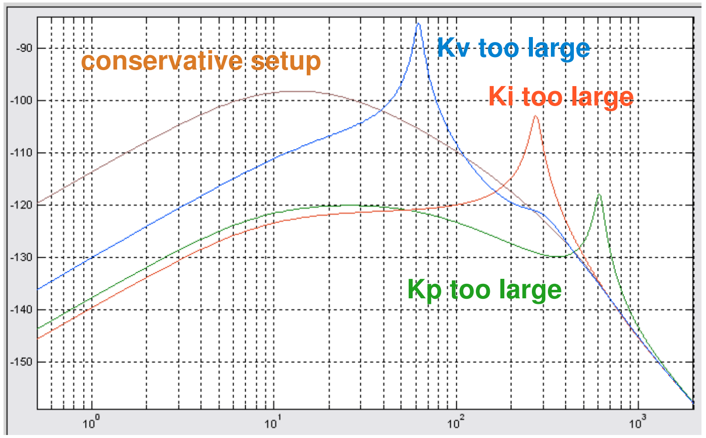
Disturbance Resistance (rigid mechanics model)







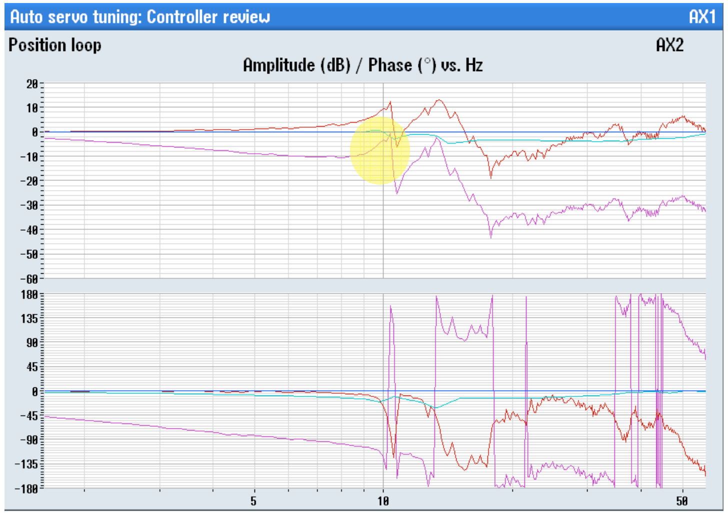
- Increasing **J** (inertia) improves DR at high frequencies
- Increasing **Kp** improves DR at medium frequencies
- Increasing **Kv** improves DR at low frequencies
- Increasing **Ki*** improves DR at low and medium frequencies (*Ki=1/Tn)
- Increase any gain (Kv, Kp, Ki) too much and servo resonance is introduced (caused by system lags)
- Mechanical resonance is often the critical factor
- Increased inertia facilitates increased Kp
- Rigid mechanics facilitates increased Ki and Kv

Damping optimal tuning strategy

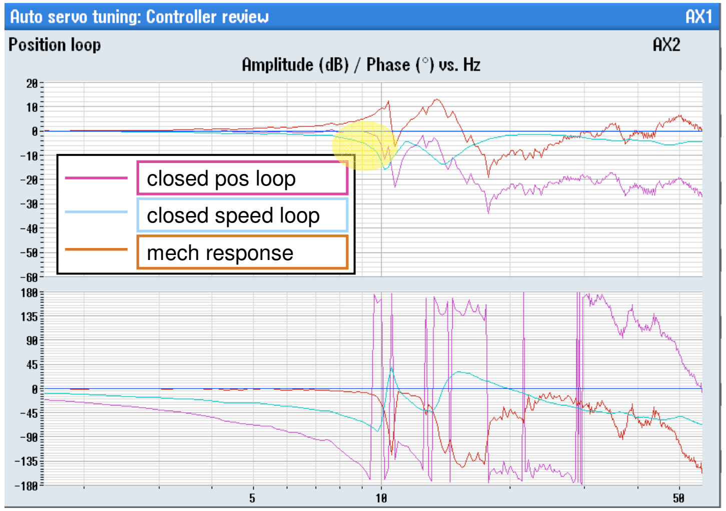
A rigid speed loop is not always the best choice

- Mechanical compliance causes resonance
- A less rigid speed controller allows motor to absorb some of the vibration energy.
- Damping optimal strategy can allow higher Kv (with direct feedback)
- Can reduce vibration at TCP (tool center point)
- Can improve dynamic stiffness
- AST provides a strategy for direct feedback axes to find an optimal speed loop tuning for maximizing position loop's Kv.

Rigid speed controller (max Kv=0.6)



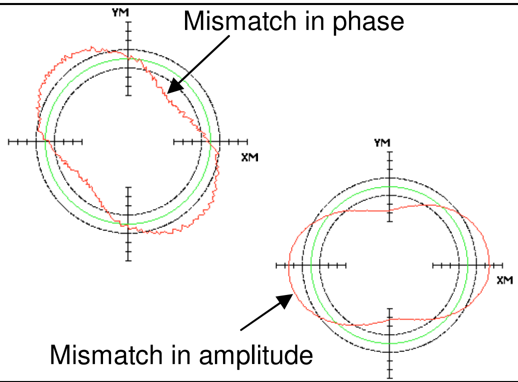
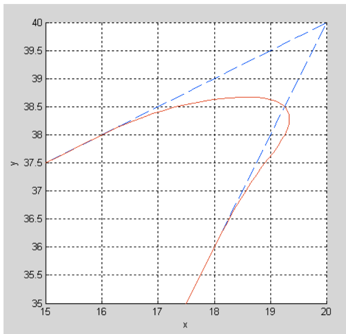
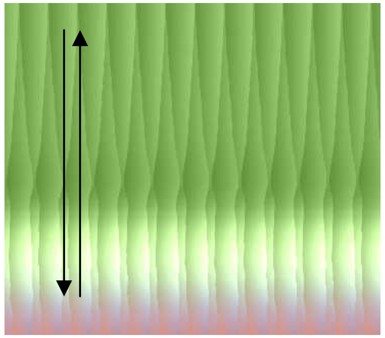
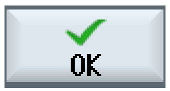
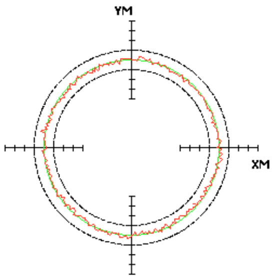
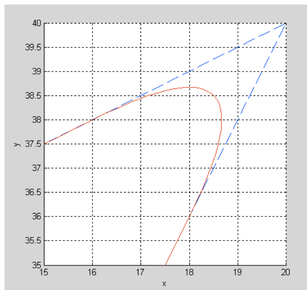
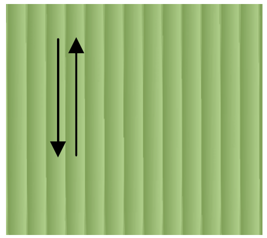
Damping optimal speed controller (max Kv=1.8)



Dynamic path accuracy

Matching dynamics of axes

- Coordinated motion of two or more axes requires matching tracking response.
- Failure to match dynamic response = reduced (high speed) dynamic path accuracy

	Circular interpolation	High speed corners	Free form surfaces
Mismatched Axes 			
Matched Axes 			

Dynamic path accuracy

Strategies for matching axis dynamics

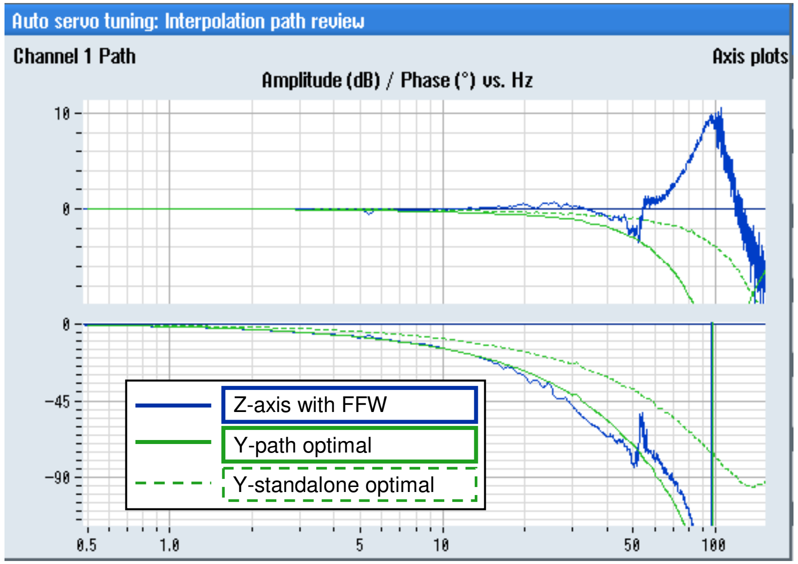
- Reduce the response of “faster” axes to match the “slowest” axis in the group
  Advantage: matches both amplitude and phase
  Disadvantage: weakened disturbance resistance

- Pre-filter set points of “faster” axes to match lag of “slowest” axis
  Advantage: maintain individual axis disturbance resistance
  Disadvantage: typically effective only over lowest frequency range

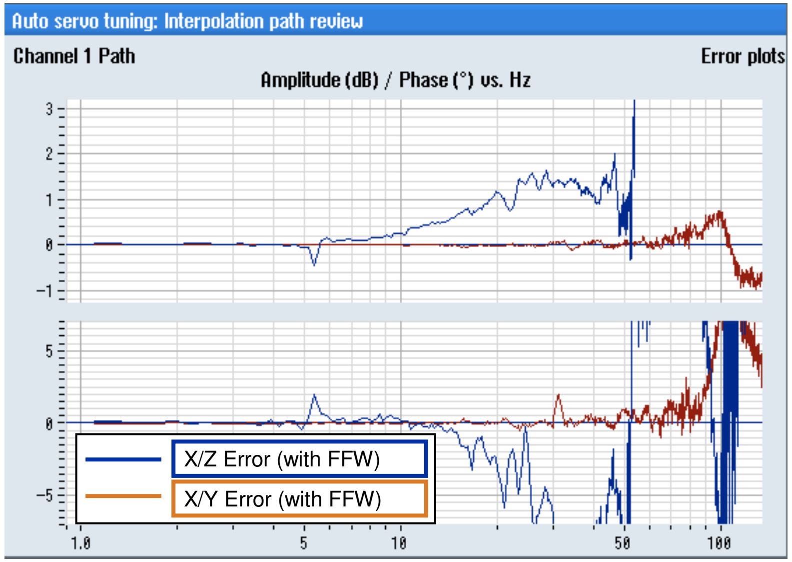
- Activate Torque Feedforward on all axes for near perfect command tracking
  (At least up until lowest frequency of mechanical vibration)

Dynamic path accuracy: Representation on Bode Plots

Compare individual tracking responses for all interpolation group member axes



Error plot: quotient of tracking response of two axes, e.g. Gx(ω)/Gy(ω)



Error plot predicts circle test results for all circle frequencies at once!

- circle frequency ω=Feedrate/(60*Radius)
- circularity error = **f** (Gx(ω)/Gy(ω), ω, Radius)

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Part 3.

Auto Tuning and AST

Auto tuning: Benefits for the machine tool builder

Commissioning a series prototype machine

- <u>Productivity</u>: Reduced time and cost of machine commissioning. Required expertise level not high
- <u>Consistency</u>: no variations between machine setups due to preferences of different technicians
- <u>Reliability</u>: many details about drive structure, time delay, and configuration are not accidentally overlooked or misunderstood by the software

Startup of a series machine

- Check suitability of standard gains for machine-specific behavior
- Informs production control of any significant of machine-to-machine variability in axis dynamics

Customer Support

- Tuning results files database can be used to better understand field problems.
- Enables field service technicians without expert servo knowledge to perform retuning at customer site after machine installation.
- Simplifies in-the-field commissioning of machine modifications.

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Auto tuning: benefits for the end customer (factory)

- Adapt for changing work-piece
  - Can narrow the tradeoff between performance and robustness
  - New work-piece
  - Work-piece dynamics changed due to material removal
  - Changing inertia
  - Changed natural vibration modes
  - Especially relevant with direct drive linear and torque motors

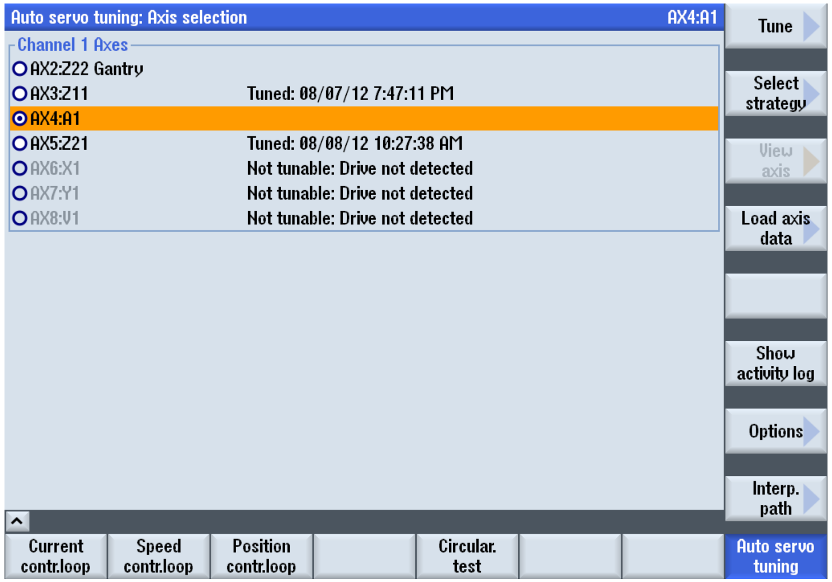
- Factory maintenance
  - Check suitability of original servo settings after replacement of machine components
  - Check for changes as machine ages
  - Automatically generated reports can be used for diagnosing machine health

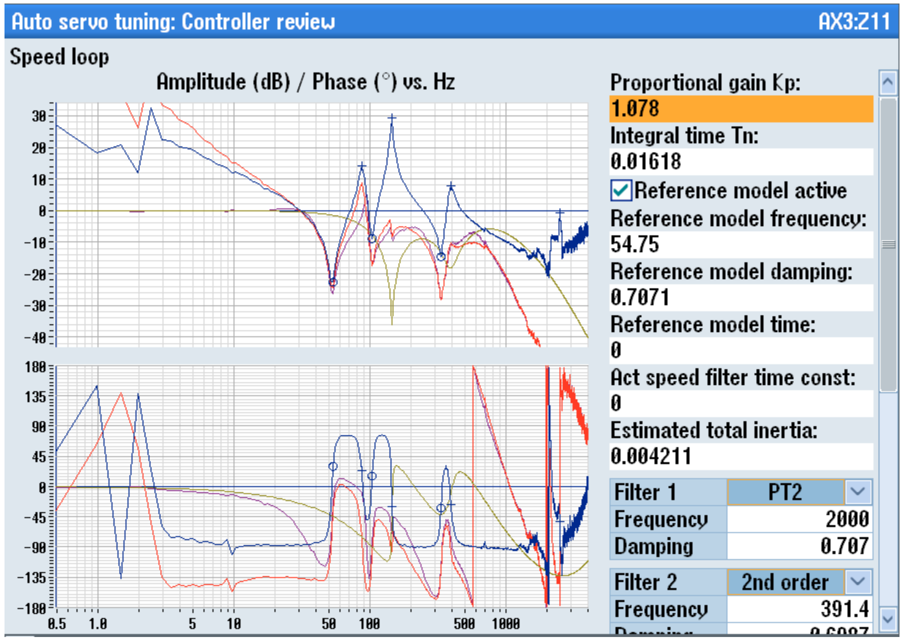
Due to the complexity of the topic, a reliable auto-tuning software is essential for situations where retuning an axis servo is required to occur at the end customer.

Siemens SINUMERIK Auto Servo Tuning (AST)

AST (Auto Servo Tuning) is a comprehensive tool built-in to the Siemens CNC HMI software “SINUMERIK Operate.”

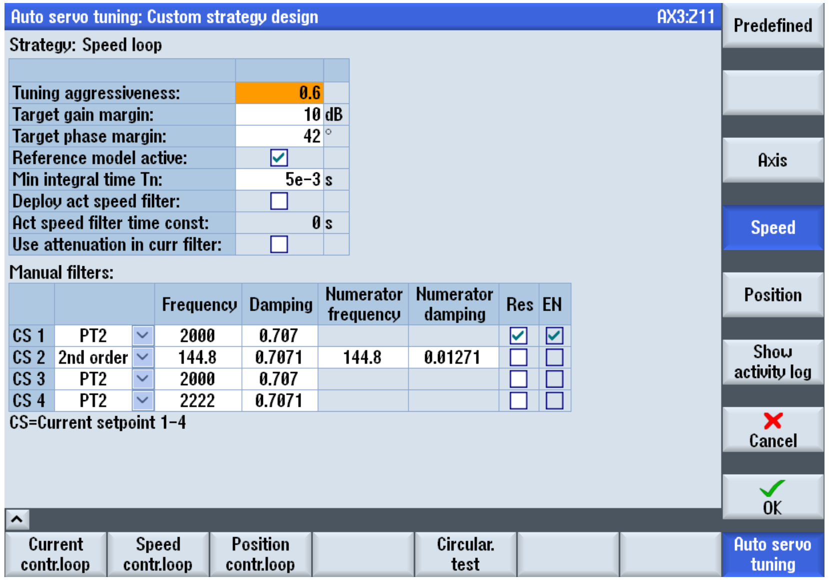
- Requires no servo tuning knowledge: in an automatic mode select an axis and press “Tune”
- Can be used by experts in a manual mode with configurable user interaction



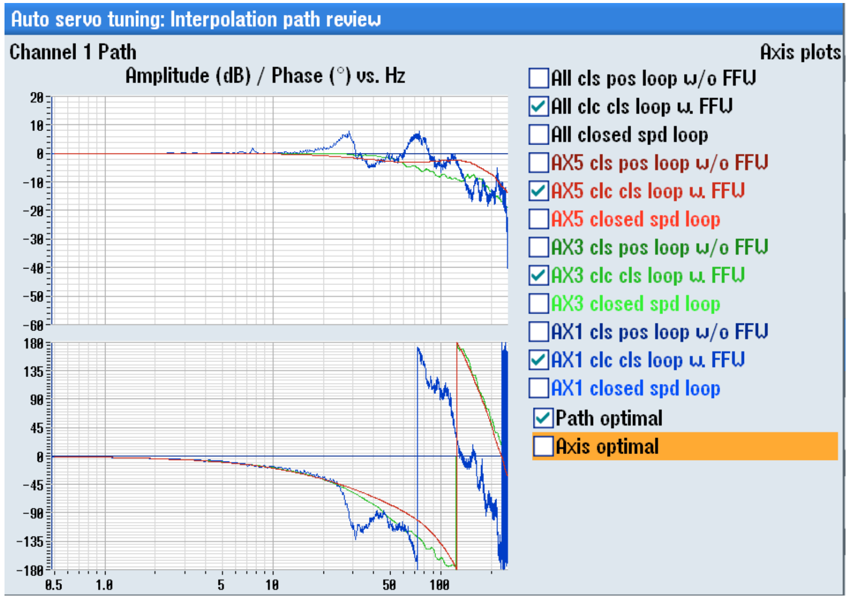


Siemens SINUMERIK Auto Servo Tuning (AST)

- Optional user-configurable strategies for specific tuning objectives

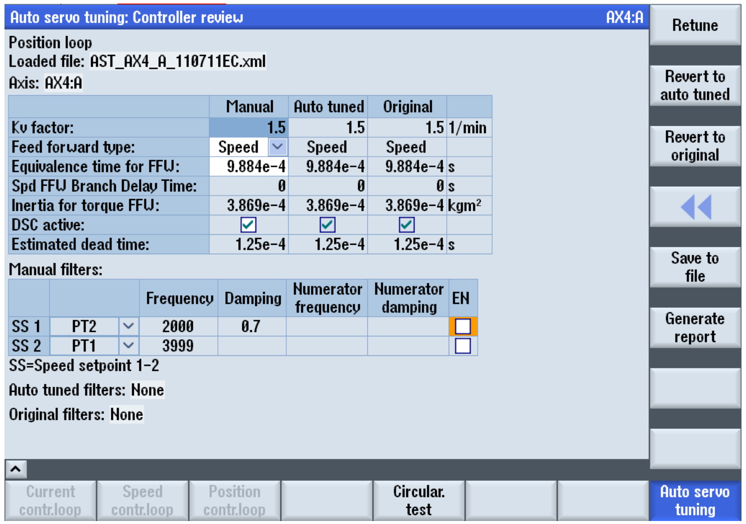


- Interpolation path tuning feature



Siemens SINUMERIK Auto Servo Tuning (AST)

- Stores complete record of measurements and results to a file for later on-line or off-line analysis



- Auto report generation feature with optional user customization

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Siemens SINUMERIK Auto Servo Tuning (AST)

How it works:

- Expert methodology: Uses the same methods, strategies, and decision making processes as Siemens Mechatronic specialists
- Optimal measurement conditions
  - Temporary changes to machine data to optimize conditions for measurement
  - Uses preliminary measurement to determine appropriate excitation and speed offset levels
  - User may override auto-selected conditions.
- User selects default or custom tuning strategy
  - select tuning objective or aggressiveness factor
  - select controller components to tune
  - reserve some components based on fore-knowledge of dynamics
  - damping-optimal strategy
  - verification measurements
  - can measure and model without retuning
- Software does the work: Iterative testing of candidate parameter values while seeking optimum
- Path tuning: Once all individual axes have been tuned, the interpolation path axes matching function uses the individual axis tuning data to match the dynamic response between axes for optimized dynamic path accuracy.

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Siemens SINUMERIK Auto Servo Tuning (AST)

AST optimizes values for the following axis items

- Speed loop proportional gain
- Speed loop integrator time constant
- Current set point filters
- Speed set point filters
- Speed controller reference model
- Position controller gain
- Axis inertia for feedforward
- Feedforward symmetry filters
- Coordination of gantry-coupled axes

AST matches response of axes for path accuracy

- Identifies differences in responsiveness
- One strategy modifies controllers of more responsive axes to match that of least responsive axis
- Must balance disturbance resistance lost with dynamic path accuracy gained
- Feedforward (especially torque FFW) eases the situation greatly
- Consideration for machine designers: “a chain is only as strong as its weakest link”

Review (some key points to remember)

- The configuration of a machine tool’s servo control has an affect on:
  - Trajectory tracking / dynamic path accuracy
  - Disturbance resistance
  - Robustness
- Servo tuning involves trade-offs. It is good to have an objective or goal to shoot for.
- Optimization / tuning of a closed loop controller is a complex task that requires specialized expertise and careful attention to detail.
- A quality auto tuning software package enables reliable, fast, and consistent commissioning of control loops.
- Auto tuning has unique benefits for both the machine tool builder and end customer.
- Siemens’ SINUMERIK Operate HMI has a comprehensive set of auto-tuning features built-in. The functionality is named “AST.”

questions ???

Thank you for your attention!

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