Introduction to Servo Control & PID Tuning

Presented to:

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Agenda

- Introduction to Servo Control Theory
- PID Algorithm Overview
- Tuning & General System Characterization
- Oscillation Characterization
- Feed-forward Terms
- Dual-loop Control

Introduction to Servo Control Theory

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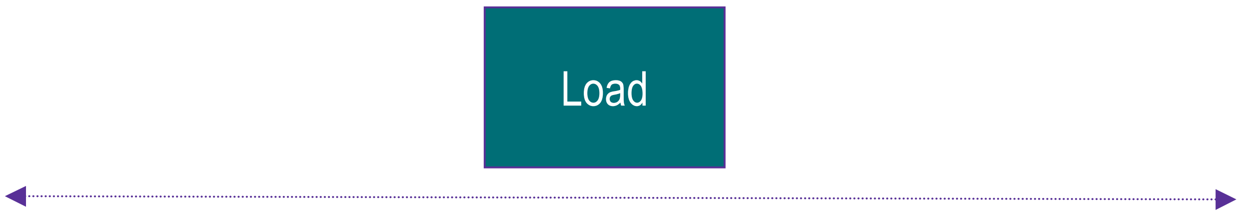
Positioning a Load

- Servo positioning systems are designed to precisely move a load along an axis of a coordinate system.



Axis of movement

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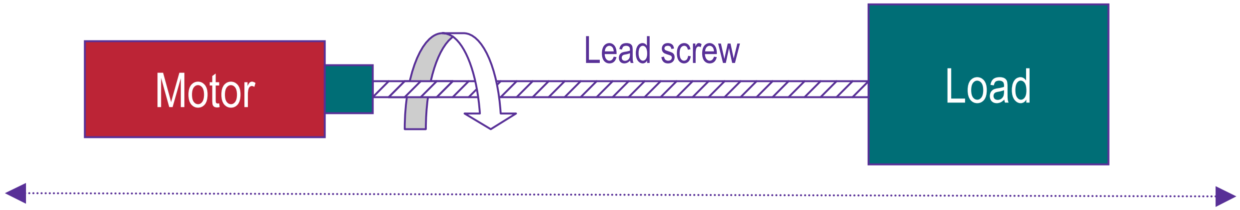
Positioning with Servo Motors

- A servo motor can be used to move a load in conjunction with a *lead screw*.



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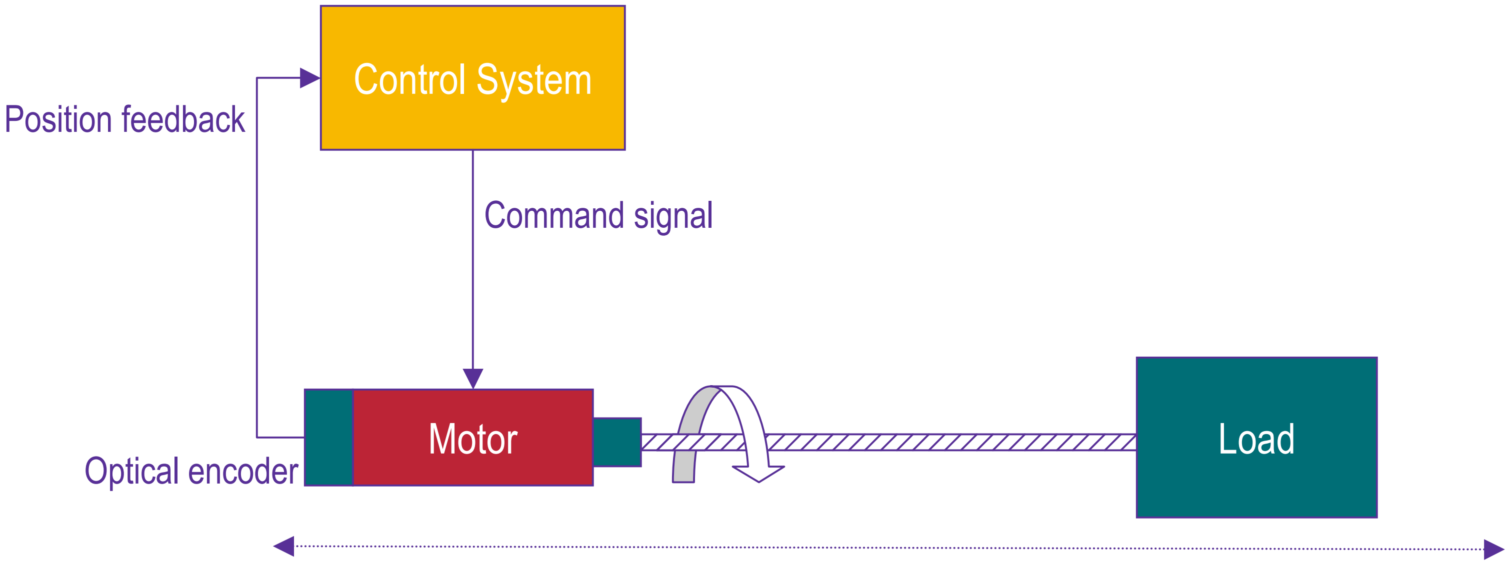
Position Feedback

- It is theoretically possible, but not practical, to *calculate* the required motor current
  - *Exact physical properties of system components must be identified and must not change*
- Position feedback is used to provide the control system with motor shaft position
  - *Enables the control system to ensure that the load gets to the commanded position*

Servo Positioning with Feedback

- An optical encoder is used to provide the control system with position feedback



PID Algorithm Overview

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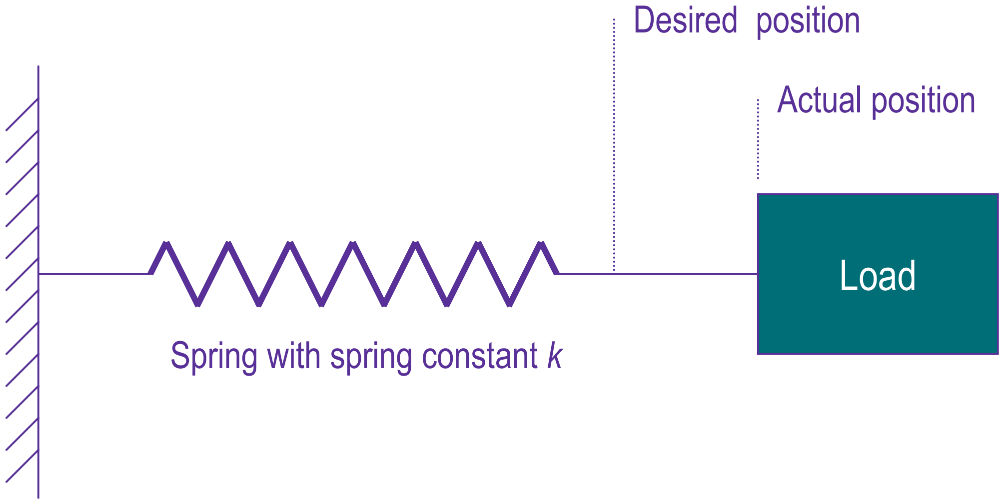
Servo Control with PID

- PID is the most commonly used servo control algorithm
  - *Proportional*
  - *Integral*
  - *Derivative*

- PID systems can be understood by way of analogous physical models

Understanding the Proportional Term

- Proportional term is analogous to the *spring constant* in a damped harmonic oscillator system
- Error = Desired position - Actual position



Hooke's law:

$F = k * (- \Delta x)$

PID Equivalent:

$Output_P = P * (Error)$

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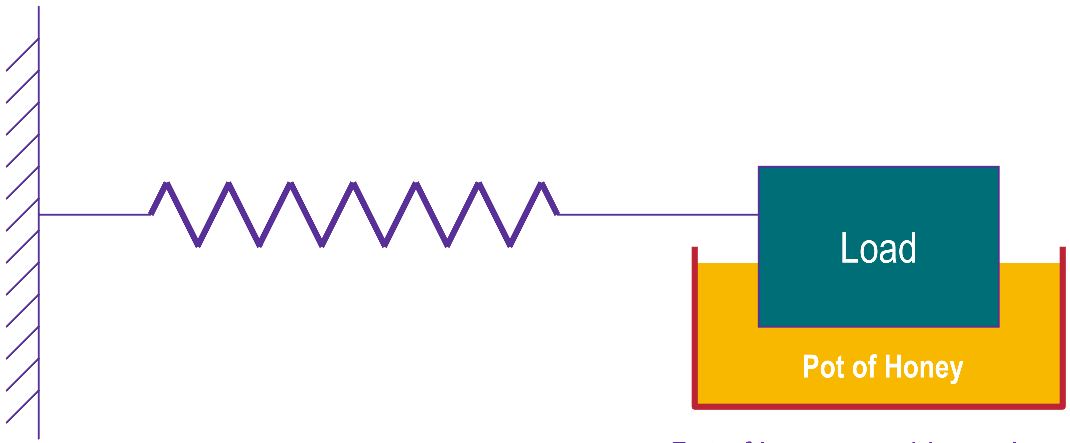
Understanding the Derivative Term

- Derivative term is analogous to a "*pot of honey*" in a damped harmonic oscillator system



Pot of honey provides a damping force proportional to velocity

<u>Damping effect</u>:

$F = - b * v$

Where –b is a damping term proportional to velocity

<u>PID Equivalent</u>:

$Output_D = D * \Delta \text{ error}$

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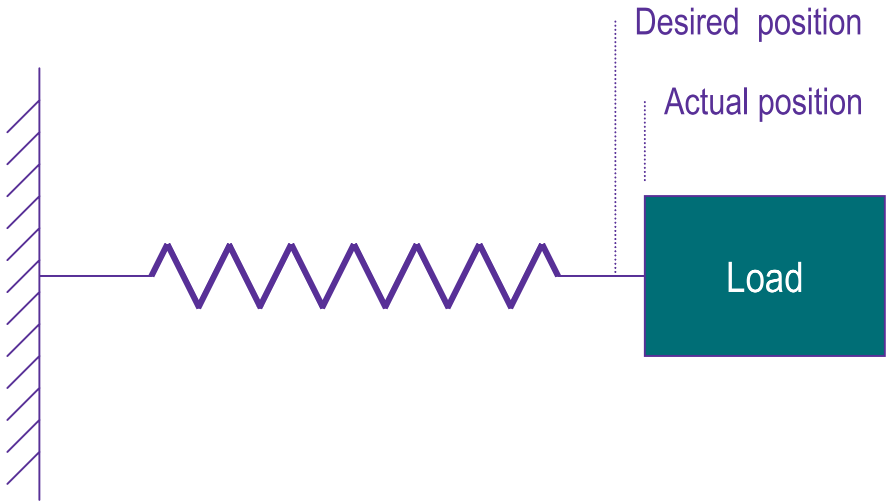
Limitations of "PD" Control

- "PD" systems are very effective for servo control, but they break down when friction in the system is high

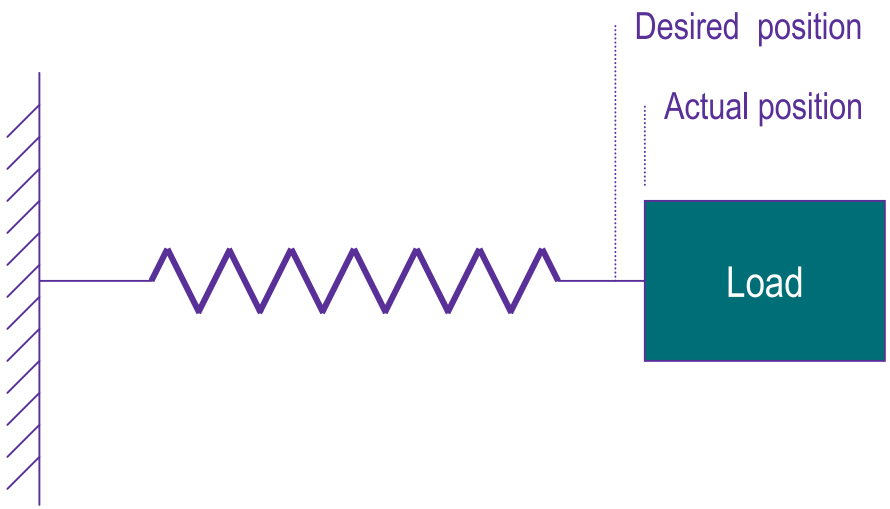


When the actual position is very close to the desired position, both *error* and Δ *error* are very small.

This results in an output that is too low to overcome any friction in the system.

Understanding the Integral Term

- Integral term contributes to the output in proportion to the sum of the error over time



$Output_I = I * (\Sigma\ error)$

Since the I term builds up with the sum of the error over time, the effect is to generate a force that pulls the load into the desired position.

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Tuning & General System Characterization

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What is Tuning?

Tuning \ tün·ing *verb* : The art of adjusting PID gains to optimize the motion of your system.

Tuning - First Step is Safety

- Before doing anything related to tuning your servo motors, you must be sure your system is in a safe configuration
  - *Refer to Introduction to Servo Tuning handout*

- Be sure to check wiring and set software limits to appropriate values

Tuning - Getting Started

- Initial tuning will concentrate on P & D gains
  - *Reminder:* *P ≈ spring constant*
    D ≈ damping factor

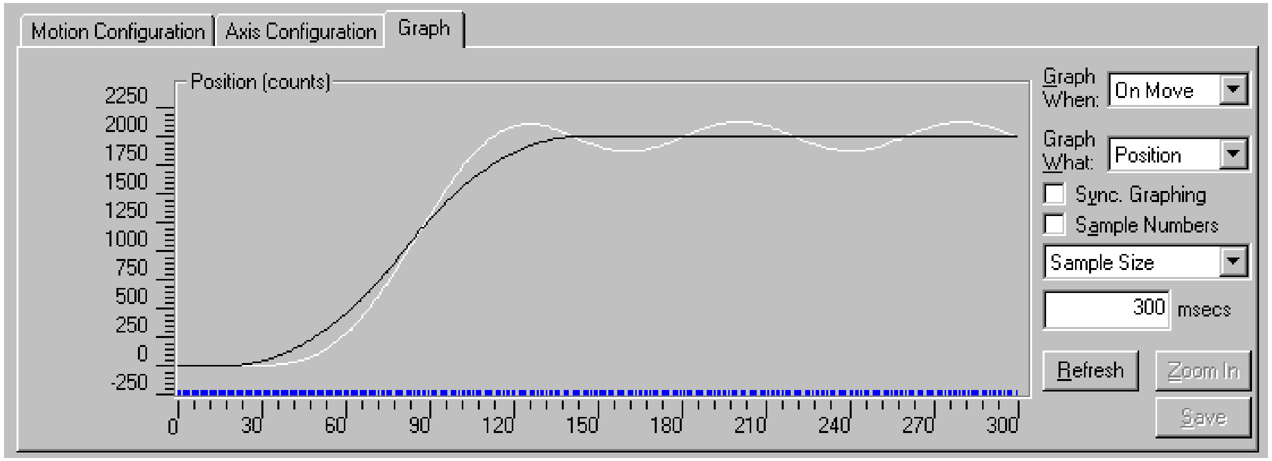
- General guidelines
  - *P is usually a small (0 – 10) positive integer*
  - *D is usually = 10 * P*

Tuning - Setting Initial P & D Gains

1. Set initial values for P & D
2. Command a motion and use Motion Console to graph Actual Position versus Time
3. If the motor doesn't move at all, or doesn't closely reach the target position, try doubling the P gain
4. Analyze graphs if motor is *underdamped*, *overdamped*, or *critically damped*.
5. An ideally tuned system is just under critically damped (underdamped).

Tuning - Underdamped Motor

- If your system is underdamped, you will notice a large oscillation at the end of the move
- Try increasing D gain
  - *You can also decrease P gain, but increasing gains are recommended at this stage*



Actual position

Command position

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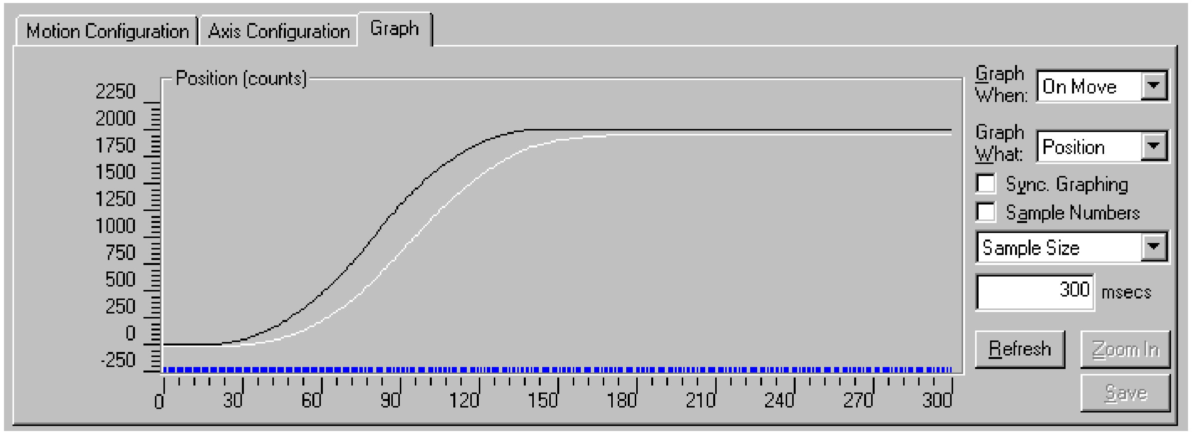
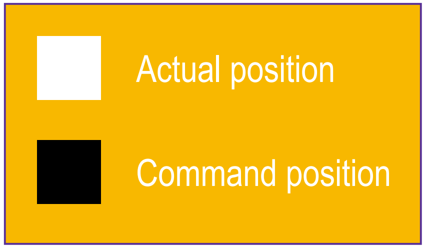
Tuning - Overdamped Motor

- If your system is overdamped, the motor will either take very long to complete the move or not get to the target position at all
- Try increasing P gain
  - *You can also decrease D gain, but increasing gains are recommended at this stage*





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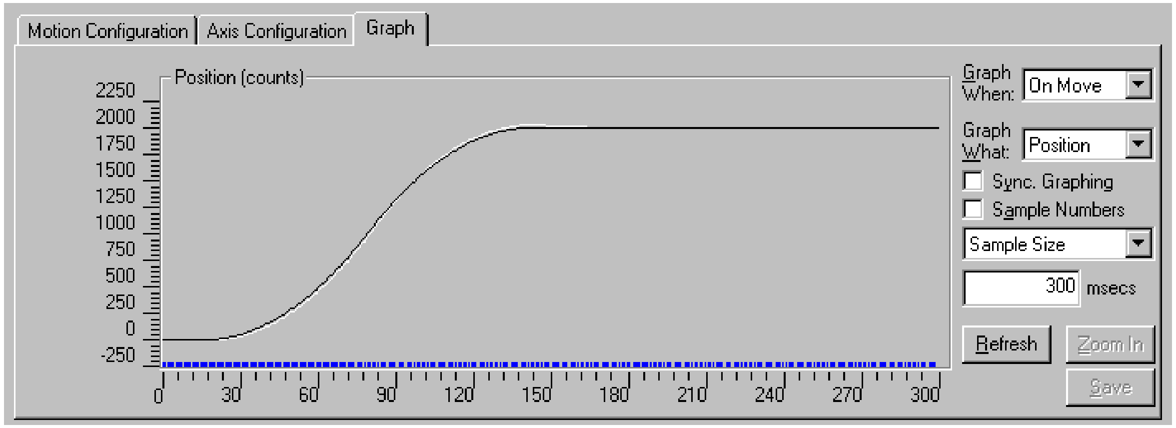
Tuning – Critically Damped Motor

- If your system is critically damped, you should not see much oscillation at the end of the move, and the motor should get to the target position fairly quickly.



Actual position

Command position

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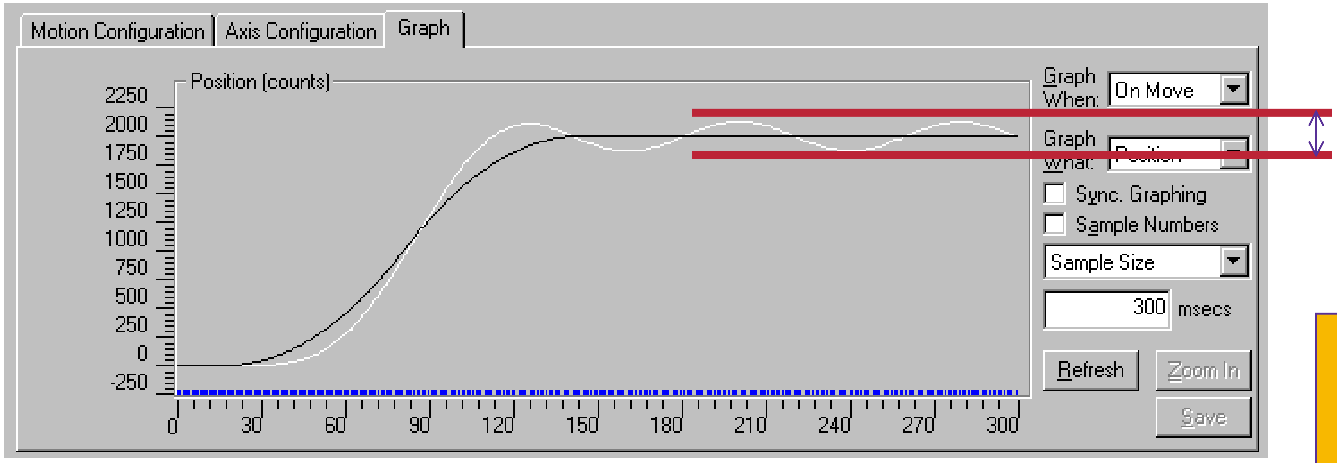
Tuning - Determining "In Position"

- If your final positioning accuracy can vary by several counts, a slightly underdamped system can get to the target position faster.



Range of acceptable error

Actual position

Command position

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Tuning - General Guidelines

- When tuning, use moves that are similar to the moves that you will use in your application
  - *Using the most aggressive moves (highest acceleration and/or longest time) will result in best results.*
- When increasing K & D, use these guidelines:

$$D_{new} = D_{old} * (multiple)$$

$$P_{new} = P_{old} * (multiple)^2$$

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Tuning – Using the Integral Term

- Integral term can be used in two modes:

  1. *Standing only (recommended)*
  2. *Always*

- When used in standing only, the Integral term only contributes to the servo command when the command position has stopped changing

Tuning - Initial Guidelines for I Term

- Start with I = 1
  - *I values are generally very small positive integers*
- Command a move, and graph error versus time
- At the end of the move, the I term should pull the error down to zero
- Keep increasing the I gain until the error begins to oscillate, then revert to previous value.
- After tuning for the I gain, go back and double-check values for P & D gains.
  - *Generally after tuning for the I gain, you will need to either reduce P gain or increase D gain by 1-10%.*

Oscillation Characterization

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Three General Types of Oscillation

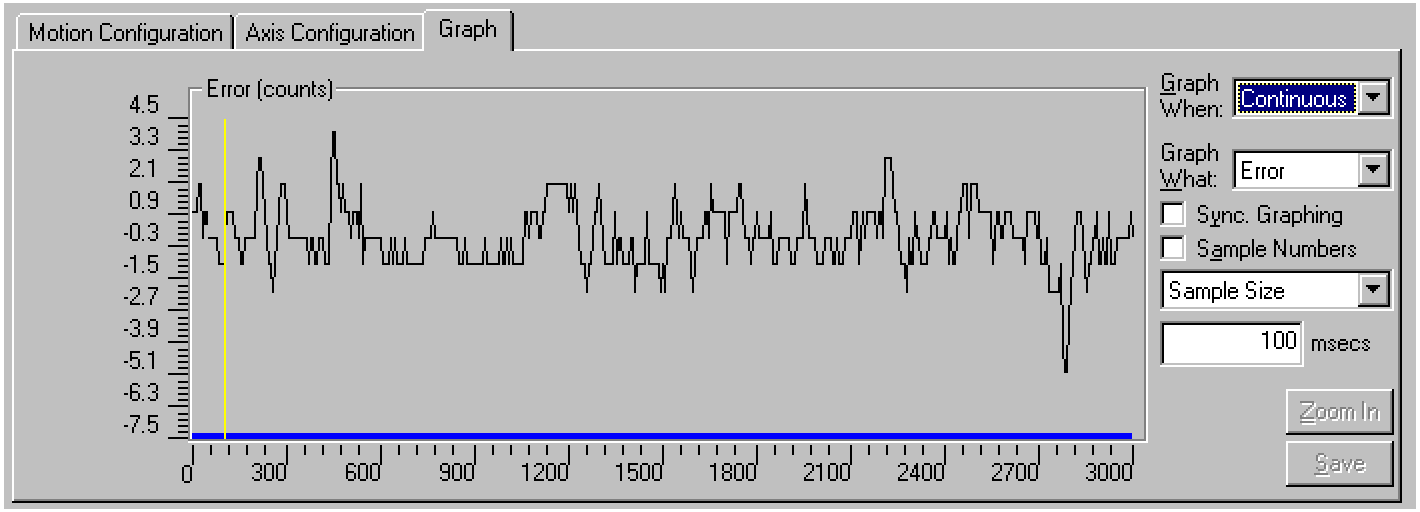
- High-frequency oscillation
  - *Frequency of ½ or less of the sample rate*
  - *Sometimes results in an audible high-frequency hum*
  - *Oscillation is generally imperceptible to the human eye*
  - *Generally indicates a D gain that is too large*
- "Middle" frequency oscillations
  - *Period in between high- and low-frequency oscillations*
  - *Generally indicates a P gain that is too large*
  - *Approximately 1/10 of high-frequency*

Three General Types of Oscillation

- Low-frequency oscillation
  - *Period greater than several samples*
  - *Sometimes results in an audible low-frequency hum or rattle*
  - *Oscillation is sometimes perceptible to the human eye*
  - *Generally indicates an I gain that is too large*
  - *Approximately 1/10 of middle-frequency*

Identifying High-Frequency Oscillations

- This graph indicates a motor tuned with a D gain that is too large



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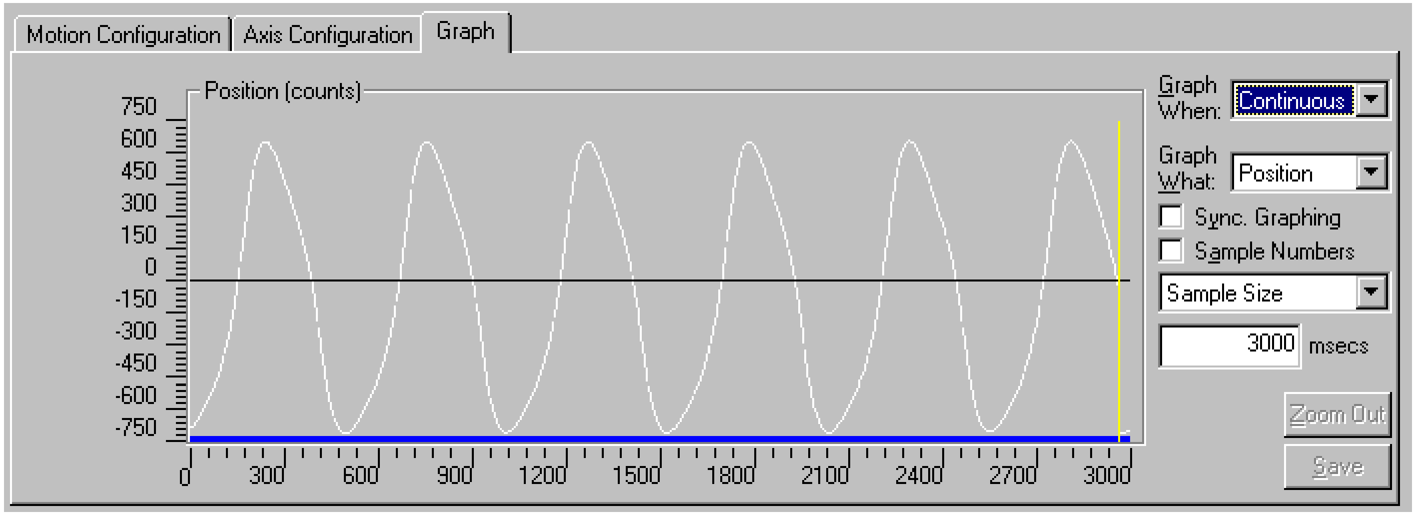
Identifying Low-Frequency Oscillations

- This graph indicates a motor tuned with an I gain that is too large



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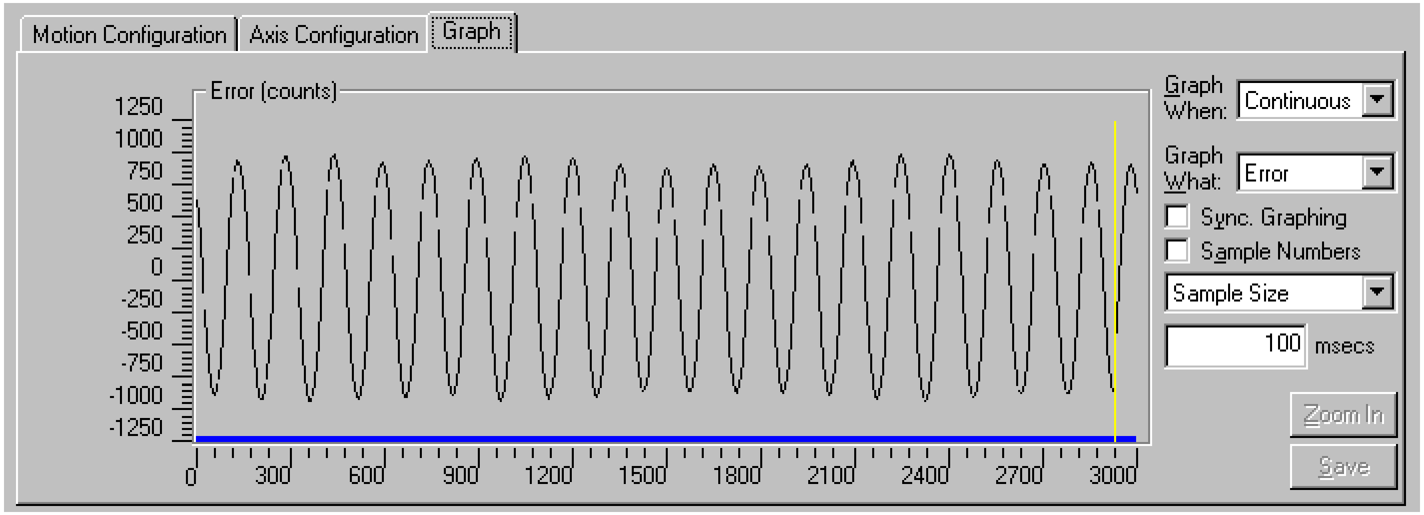
Identifying Middle-Frequency Oscillations

- This graph indicates a motor tuned with an P gain that is too large



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Oscillations due to Mechanical Issues

- Some kinds of oscillations can be caused by problems with the mechanical system
- Can be identified when changing PID gains doesn't affect the period of the oscillations
- If period of oscillation is proportional to the velocity of the move, a mechanical problem is usually the cause
- Only solution is to fix the mechanical problem.

Feed-forward Terms

Introduction to Feed-forward

- Feed-forward terms use the commanded trajectory to send a signal to the amplifier that predicts the required signal
  - *Since PID systems respond based on error, this can almost always improve system response*

- PID does not have to “wait” for large error to build up before trying to catch up

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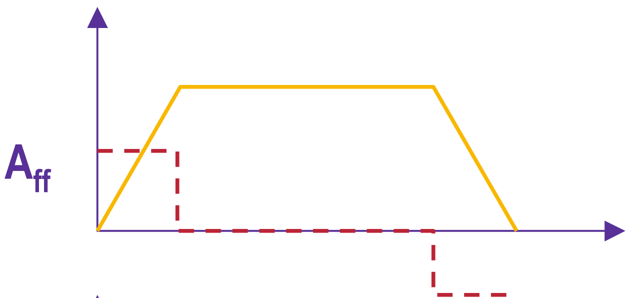
Three Types of Feed-forward

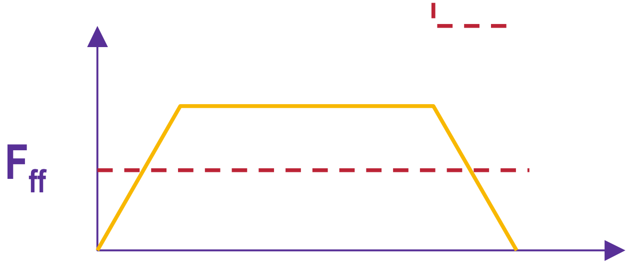
- Acceleration feed-forward (A_{ff})
  - *Used to compensate for inertia*
- Friction feed-forward (F_{ff})
  - *Used to compensate for classical kinetic friction*
- Velocity feed-forward (V_{ff})
  - *Used to compensate for viscous friction (friction that is proportional to velocity)*

Feed-forward Effect on Servo Command

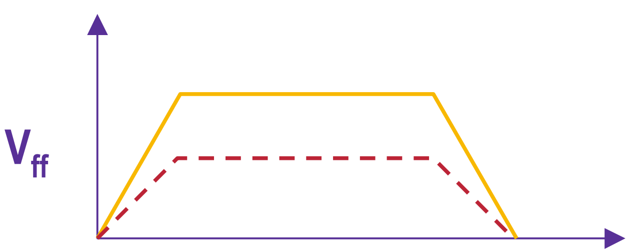
Commanded trapezoidal velocity profile



Acceleration feed-forward has additive effect on servo command during acceleration, no effect during slew, and subtractive effect during deceleration



Friction feed-forward has additive effect on servo command at all times during move.



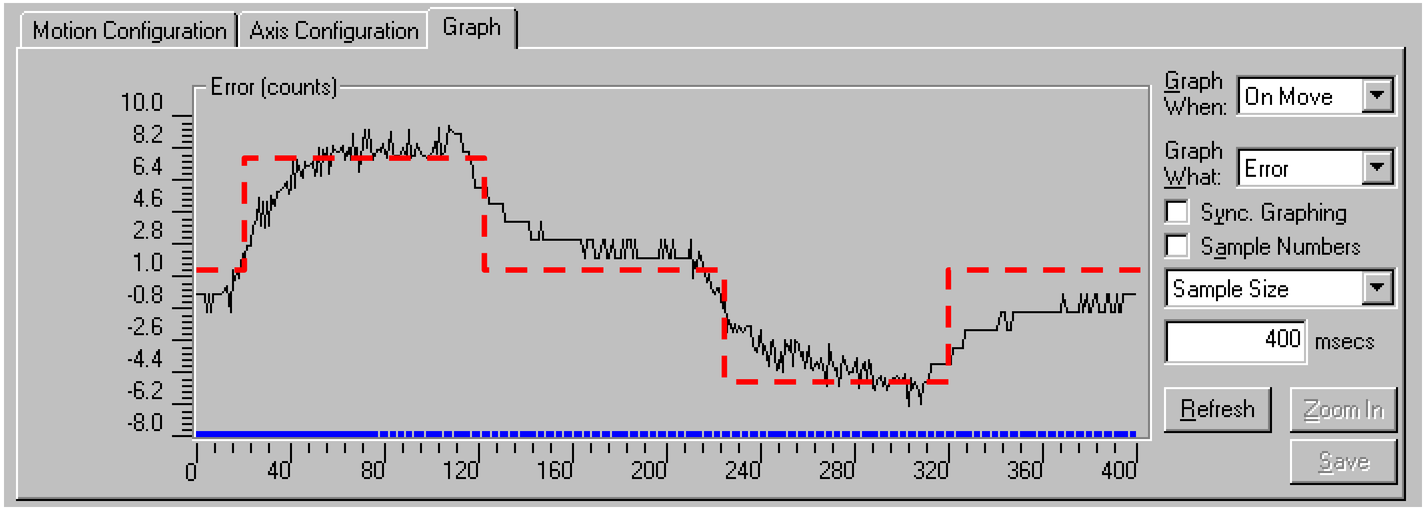
Velocity feed-forward has additive effect on servo command directly proportional to velocity profile.

Tuning for Feed-forward Terms

1. Command a move
2. Graph error versus time
3. Identify shape of error graph and try to match the effect of one or more of the three types of feed-forward
4. Apply feed-forward term and re-test with a move in the same direction

Identifying the need for A_{ff}

- The following graph of error versus time has a profile similar to the effect of A_{ff}, therefore, A_{ff} should be applied.



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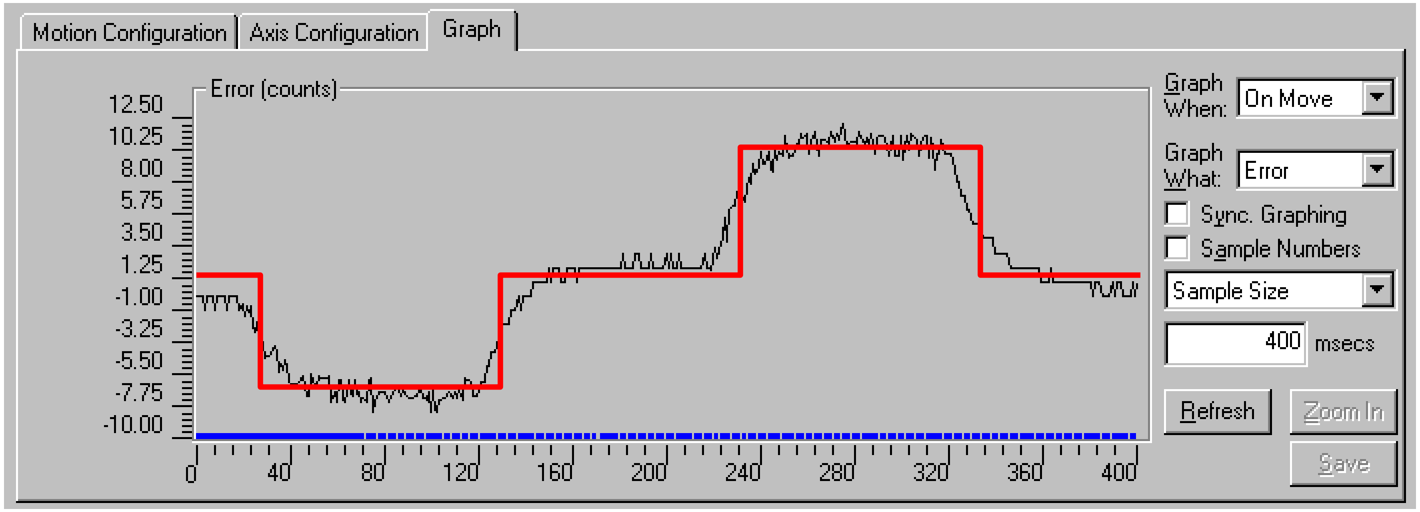
Identifying too much A_{ff}

- The following graph shows when too much A_{ff} has been applied. Therefore, A_{ff} needs to be reduced.



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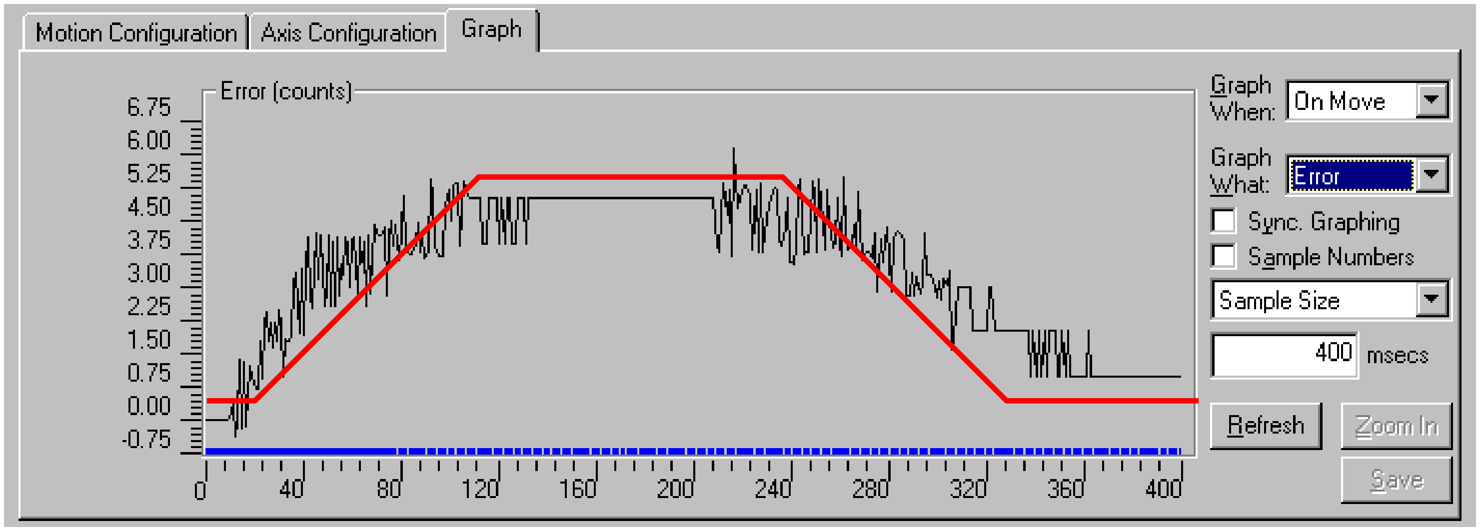
Identifying the need for V_{ff}

- The following graph of error versus time has a profile similar to the effect of V_{ff}, therefore, V_{ff} should be applied.



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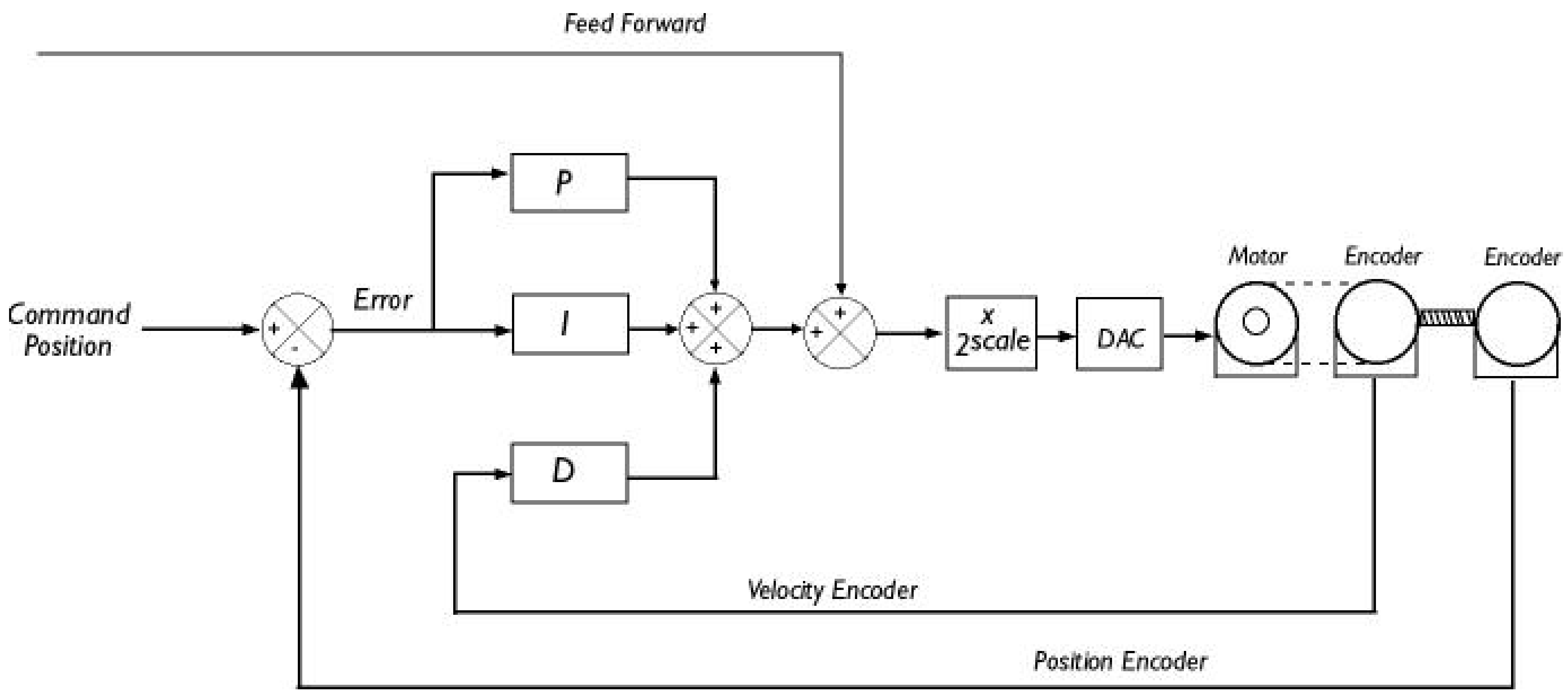
Dual-loop Control

Introduction to Dual-loop Control

- Servo response of systems with backlash caused by lead screw or gearing can be improved through the use of dual-loop control.
- A second encoder is added to the load so that the control system is aware of both the position of the motor shaft as well as the position of the load.
- The encoder on the motor shaft is configured as the velocity encoder, and the encoder on the load is configured as the position encoder.

Dual-loop - Control Algorithm



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Dual-loop Control - Encoder Resolution

- When using dual-loop control, it is recommended that the velocity encoder resolution is higher than that of the position encoder
  - *This results in better velocity estimation, especially at low speeds*

- Optimal ratios for velocity encoder resolution to position encoder resolution are between 3:1 and 10:1
  - *Ratios of greater than 10:1 are possible, but not much more benefit is gained at greatly increased cost*
  - *Ratios of 1:1 or less are generally not recommended*

Thank you!

Questions?