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IEEE Mini-Conference Presentation

PID Based Control of a Pneumatic Spool and Sleeve Valve

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Overview

- Introduction to Enfield Technologies Pneumatic Proportional Control Products
- Model Development for an Enfield Technologies LS-V15 Pneumatic Spool and Sleeve Proportional Control Valve
  - Identification of Key Performance Criteria
  - Development of Physics Equations Describing Valve Operation
  - Development of Frequency Domain Transfer Function (2 methods)
- Analysis of Model Performance
- Design and Analysis of Control Methods
  - Open Loop (voltage applied to coil)
  - Closed Loop on Current (trans-conductance amplifier)
  - Closed Loop on Position (P, Compensation, PID)

Introduction to Enfield Technologies
Pneumatic Proportional Control Products

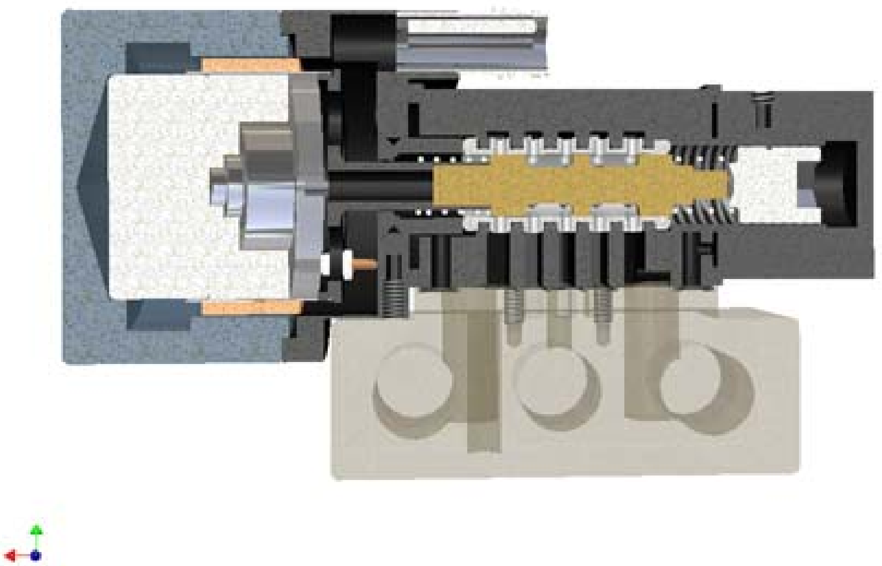
Variable Position Control

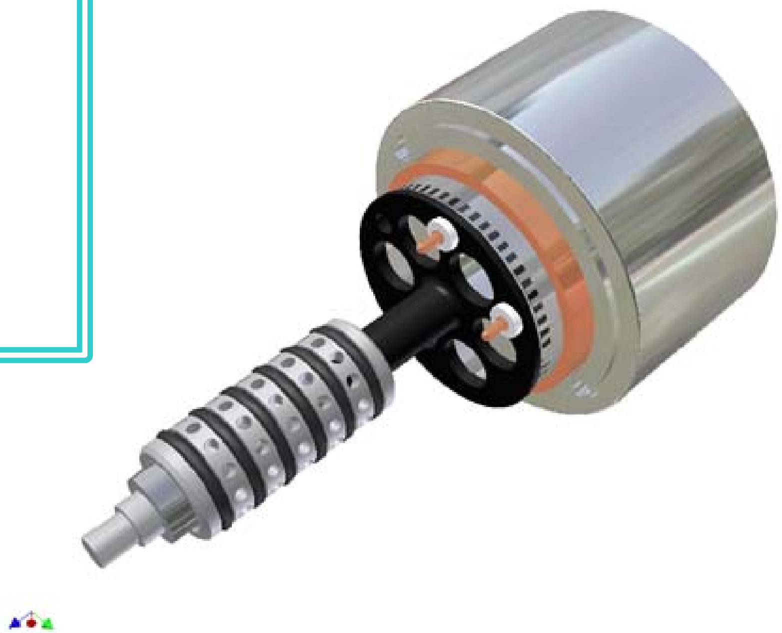
Variable Pressure Control

Variable Force Control

Variable Flow Control

Introduction to Enfield Technologies
Pneumatic Proportional Control Products





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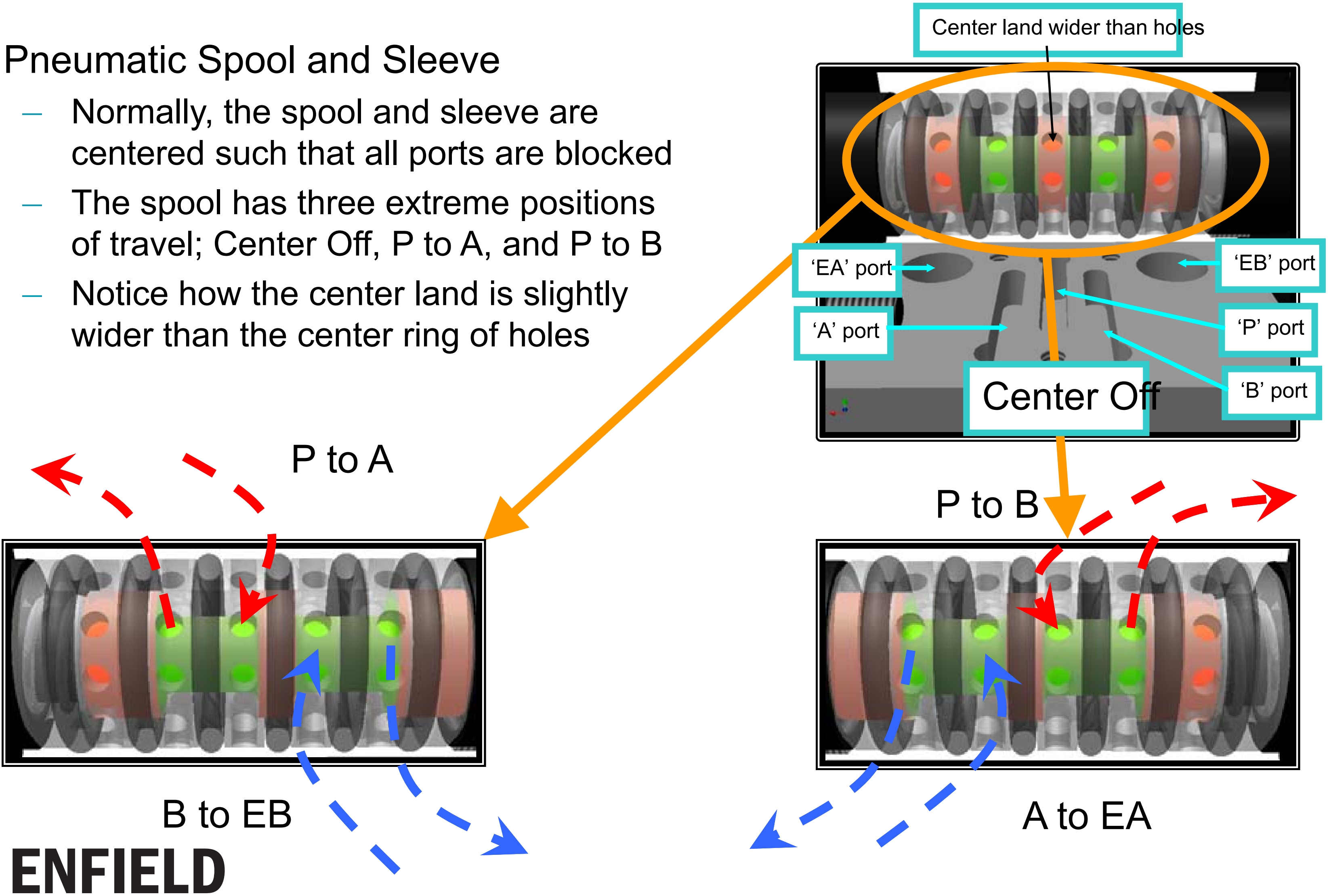
Introduction to Enfield Technologies
Pneumatic Proportional Control Products

- Pneumatic Spool and Sleeve
  - Normally, the spool and sleeve are centered such that all ports are blocked
  - The spool has three extreme positions of travel; Center Off, P to A, and P to B
  - Notice how the center land is slightly wider than the center ring of holes



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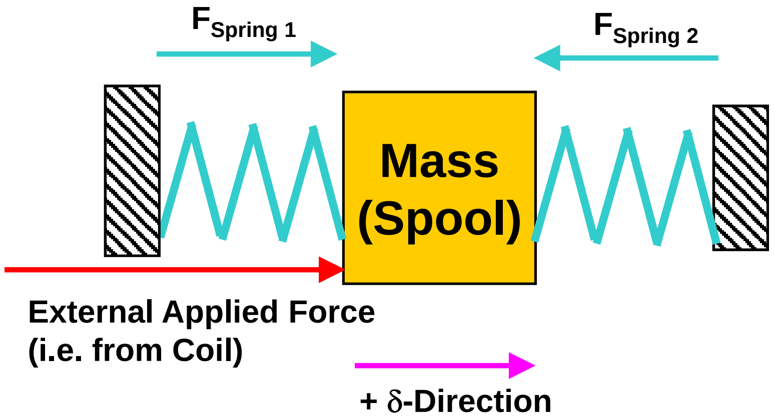
Development of LS-V15 Dynamic Model
Identification of Key Performance Criteria

- Performance Criteria
  - *Response Time* – Very small response times reduce operating costs in high speed manufacturing applications by increasing throughput. Additionally, faster response times improve overall system performance and ease control system design.
  - *Bandwidth* - Very desirable attribute in high performance systems. Higher bandwidth components allow for higher bandwidth systems which allow machine designers to follow an arbitrary command profile with higher fidelity.
    - In the pneumatics industry, these two criteria (in addition to flow capacity) are the key parameters desired by designers. For this reason, improving these two parameters alone is very desirable and enhances product marketability.
  - *Accuracy & Hysteresis* – Improving spool position accuracy and reducing hysteresis is advantageous to a machine designer; allows for a simpler control interface (typically provided by a low power PLC)
- Design Limitations
  - *Overshoot & Amplitude Peaking at Resonance* – Maximum valve displacement must be controlled under all conditions to prevent impact of valve internals with valve body structure
  - *Maximum Voltage and Current Required* – Dictates the power supply that must be provided
  - *Power Consumption* – Portable and low power budget applications demand lower power consumption
  - *Size & Weight* – Driven mostly by portable applications
  - And of course…*Cost*!

Development of LS-V15 Dynamic Model
Simplified Physics Model

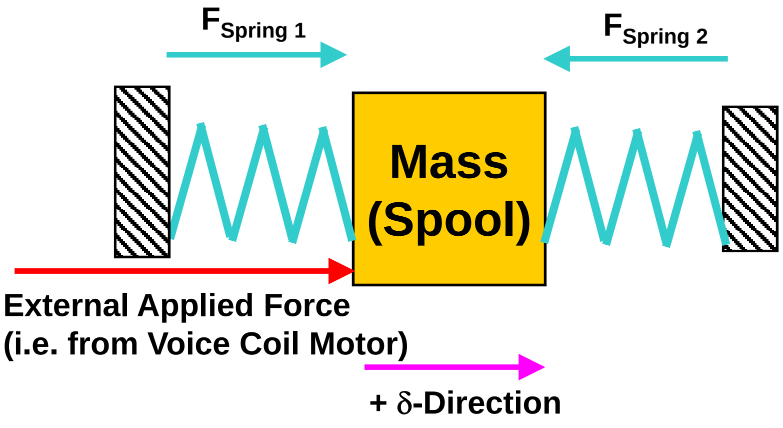


$$\boxed{F_{Motor} - (F_{Spring\,1} - F_{Spring\,2}) - F_{Friction} - F_{Inertial} = 0}$$

- For now, we will treat the coil force blindly (ignoring the physics of the coil and motor and simply treating it as an ‘ideal’ force)
- The valve is constructed in such a manner that the opposing springs are always in pre-load (compressed to be shorter than the ‘free length’) even when the mass is at maximum displacement (positive or negative)
- With no external force applied, the mass centers due to Newton’s Laws (any displacement away from ‘zero’ creates an unbalanced spring force until the spool returns to the ‘zero’ position)

Development of LS-V15 Dynamic Model
Key Physics Equations - Mechanical

- Knowing the following:
  - A force ($F_{Inertial}$) is required to accelerate (α) a mass (m)
  - Friction force ($F_{Friction}$) will be proportional to the viscous friction coefficient (B) and the velocity (υ); we will consider only viscous friction on the spool and sleeve assembly and neglect other sources of friction
  - The springs will provide a force proportional to the effective spring constant (*k*) and the spring displacement (δ) [Hooke's Law]
- We may write an expression for the spring-mass system as a sum of the independent forces acting on the system as shown:
- We may then re-write in differential form as shown:



$F_{Spring\ 1}$

$F_{Spring\ 2}$

Mass (Spool)

External Applied Force (i.e. from Voice Coil Motor)

+ δ-Direction

$$\boxed{F_{Motor} = m\alpha + Bv + k\delta}$$

$$\boxed{F_{Motor} = m\ddot{\delta} + B\dot{\delta} + k\delta}$$

Development of LS-V15 Dynamic Model
Key Physics Equations - Electrical

- Any voice coil motor will exert a force (F_{Motor}) proportional to the coil current (I_{Coil}) and the motor constant (K_{Motor})
  - **$F_{Motor} = I_{Coil} * K_{Motor}$**
  - The current is tightly controlled by a high bandwidth (>10kHz) trans-conductance power amplifier
  - The motor constant (K_{Motor}) is determined by a nearly countless set of variables dealing with voice coil motor design.

$$F_{Motor} = K_{Motor} i_{Coil}$$

Development of LS-V15 Dynamic Model Mathematical Model Development – 1st Pass

- We may gather the necessary equations to describe the coil motion
  - We make basic substitutions for F_{Motor} to relate coil current to spool position
  - Simple algebraic manipulation and use of the Laplace Differential Operator [s] allows for the development of a system transfer function X(s)/I(s)
  - From this, a study of the system dynamics may be performed
- Advantages and Disadvantages
  - This method is simple and effective
  - The spool position response may be modeled in response to a current step I(s)
  - Current steps are practically impossible to create with high fidelity in an inductive circuit
  - Unfortunately, several key parameters are not modeled here (coil inductance and the effects of V_{EMF})
- We shall explore an alternate method to develop a more complete model…

$$F_{Motor} = m\alpha + Bv + k\delta$$

$$F_{Motor} = m\ddot{\delta} + B\dot{\delta} + k\delta$$

$$F_{Motor} = K_{Motor} i_{Coil} \Rightarrow$$

$$K_{Motor} i_{Coil} = m\ddot{\delta} + B\dot{\delta} + k\delta$$

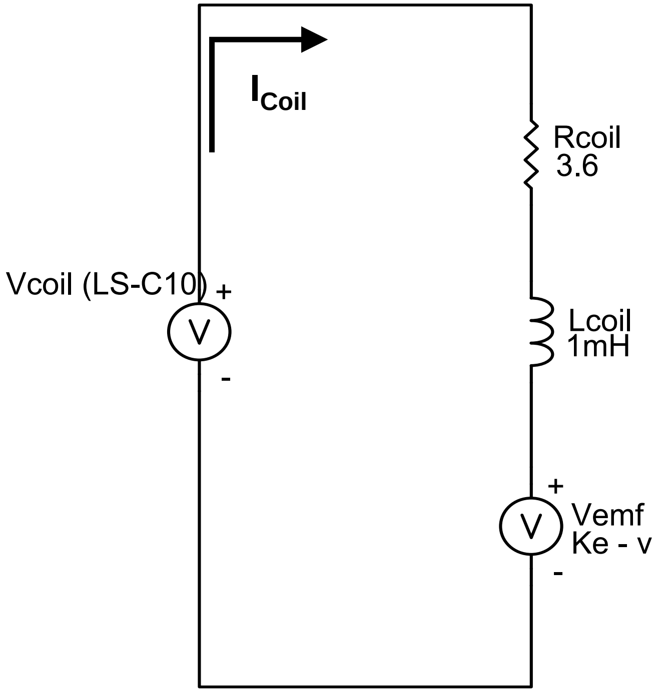
$$K_{Motor} I(s) = ms^2 X(s) + BsX(s) + kX(s)$$

$$K_{Motor} I(s) = \left(ms^2 + Bs + k\right) X(s)$$

$$\frac{X(s)}{I(s)} = \frac{\dfrac{K_{Motor}}{m}}{s^2 + \dfrac{B}{m}s + \dfrac{k}{m}}$$

Development of LS-V15 Dynamic Model
Key Physics Equations - Electrical

- At right is a simplified schematic representation of the electrical side of the voice coil spool valve
  - V_{Coil} is the total voltage across the coil (generated by the LS-C10; ±10V maximum)
  - R_{Coil} is the DC resistance of the coil (proportional to total length of the coil wire, and inversely proportional to the cross-sectional area of coil wire)
  - L_{Coil} is the inductance of the coil (by-product of winding wire in the form of a coil)
  - V_{EMF} is the voltage generated when an electric conductor is moved through a magnetic field (proportional to velocity and the generator constant, K_E)
- Summing the loop voltages yields the equations at right:

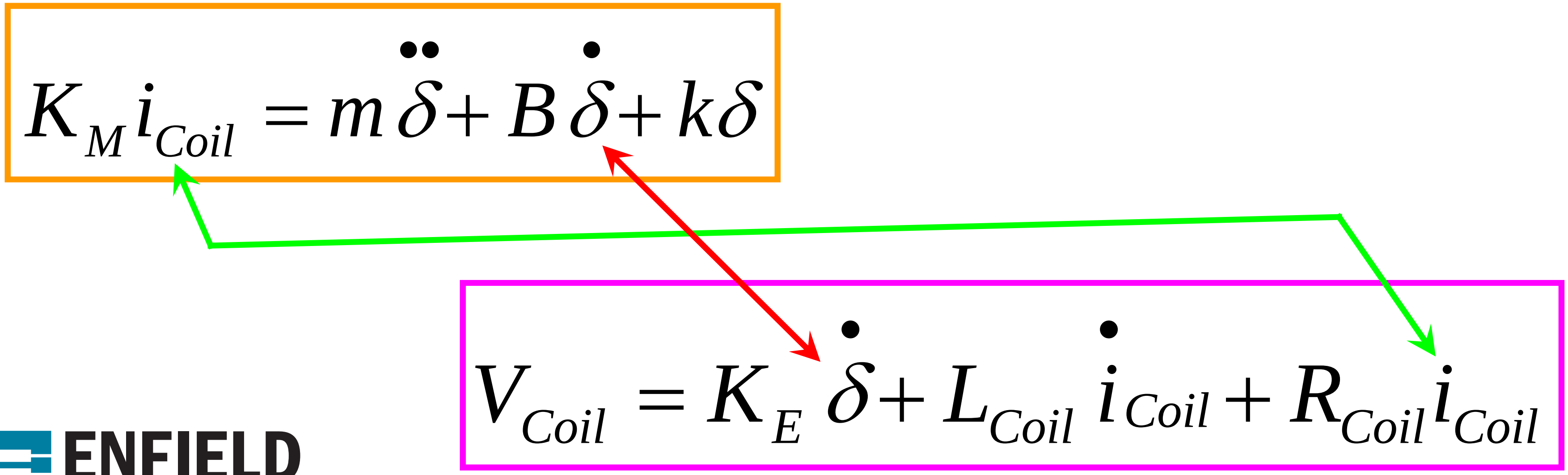


$$\boxed{V_{Coil} = R_{Coil} i_{Coil} + L_{Coil} \frac{di_{Coil}}{dt} + K_E v}$$

$$\boxed{V_{Coil} = R_{Coil} i_{Coil} + L_{Coil} \dot{i}_{Coil} + K_E \dot{\delta}}$$

Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass

- We now have two (2) differential equations that are related by two variables (position and it’s derivatives; current and it’s derivatives)
  - The first equation describes the mechanical motion of the spool
  - The second equation describes the electrical effects associated with the coil voltage, coil current, and coil velocity
  - Notice how the two equations share variables of common order; coil velocity and coil current



$$\boxed{K_M i_{Coil} = m\ddot{\delta} + B\dot{\delta} + k\delta}$$

$$\boxed{V_{Coil} = K_E\dot{\delta} + L_{Coil}\dot{i}_{Coil} + R_{Coil} i_{Coil}}$$

Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

$$Let:$$

$$x_1 = \delta$$

$$x_2 = \dot{\delta}$$

$$x_3 = i_{Coil}$$

$$Therefore;$$

$$\dot{x}_1 = \dot{\delta} = x_2$$

$$\dot{x}_2 = \ddot{\delta}$$

$$\dot{x}_3 = \dot{i}_{Coil}$$

- State Space Model
  - The equations thus far represent voice coil valve behavior using derivatives of spool position and coil current
- We carefully select the State Variables to reflect this relationship and define the derivatives
- Once this step is accomplished, we may assemble the state matrix with V_{Coil} as the input variable

Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass

$$\dot{x}_1 = \dot{\delta} = x_2$$

$$K_{Motor} i_{Coil} = m\ddot{\delta} + B\dot{\delta} + k\delta \Rightarrow$$

$$\ddot{\delta} = -\frac{k}{m}\delta - \frac{B}{m}\dot{\delta} + \frac{K_{Motor}}{m} i_{Coil} \Rightarrow$$

$$\dot{x}_2 = -\frac{k}{m}x_1 - \frac{B}{m}x_2 + \frac{K_{Motor}}{m}x_3$$

$$V_{Coil} = K_E\dot{\delta} + L_{Coil}\dot{i}_{Coil} + R_{Coil} i_{Coil} \Rightarrow$$

$$\dot{i}_{Coil} = -\frac{K_E}{L_{Coil}}\dot{\delta} - \frac{R_{Coil}}{L_{Coil}} i_{Coil} - \frac{1}{L_{Coil}} V_{Coil} \Rightarrow$$

$$\dot{x}_3 = -\frac{K_E}{L_{Coil}}x_2 - \frac{R_{Coil}}{L_{Coil}}x_3 + \frac{1}{L_{Coil}}u$$

--- State Equations ---

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -\frac{k}{m}x_1 - \frac{B}{m}x_2 + \frac{K_{Motor}}{m}x_3$$

$$\dot{x}_3 = -\frac{K_E}{L_{Coil}}x_2 - \frac{R_{Coil}}{L_{Coil}}x_3 + \frac{1}{L_{Coil}}V_{Coil}$$

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

Development of LS-V15 Dynamic Model
Mathematical Model Development – 2nd Pass

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -k/m & -B/m & K_{Motor}/m \\ 0 & -K_E/L_{Coil} & -R_{Coil}/L_{Coil} \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1/L_{Coil} \end{bmatrix} V_{Coil}$$

$$\begin{array}{r} \textbf{Position} \\ \textbf{Velocity} \\ \textbf{Current} \end{array} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

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Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

$$\text{Take Laplace Transform; x(0)} = 0$$

$$sX(s) - x(0) = AX(s) + BU(s)$$

$$X(s)[sI - A] = BU(s)$$

$$X(s) = [sI - A]^{-1} BU(s)$$

$$Y(s) = CX(s); D = 0$$

$$Y(s) = [sI - A]^{-1} BCU(s)$$

- We may develop a more complete set of transfer functions based on the state matrix we now have
- From these transfer functions, be may analyze various performance criteria

$$\frac{Y(s)}{U(s)} = \left\{ \begin{bmatrix} s & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & s \end{bmatrix} - \begin{bmatrix} 0 & 1 & 0 \\ -k/m & -B/m & K_{Motor}/m \\ 0 & -K_E/L_{Coil} & -R_{Coil}/L_{Coil} \end{bmatrix} \right\}^{-1} \times \begin{bmatrix} 0 \\ 0 \\ 1/L_{Coil} \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass

Symbolic Processor Magic!

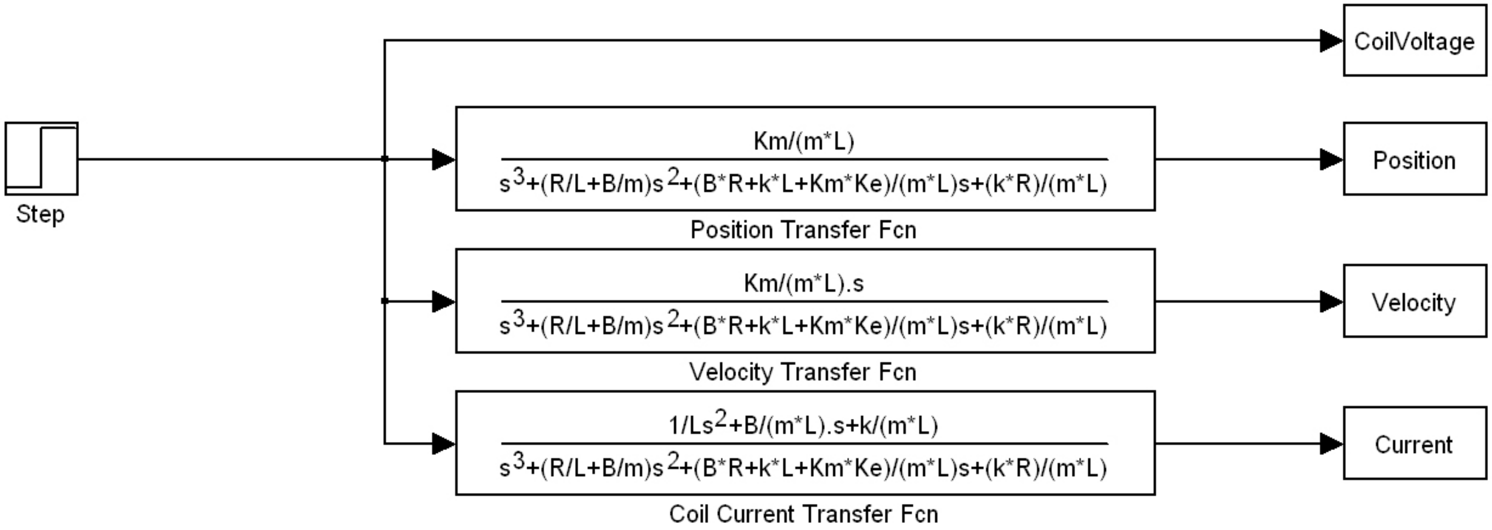
$$\frac{Y(s)}{U(s)} = G_{V15}(s) = \begin{bmatrix} \dfrac{\left(\dfrac{K_{Motor}}{mL_{Coil}}\right)}{s^3 + \left(\dfrac{R_{Coil}}{L_{Coil}} + \dfrac{B}{m}\right)s^2 + \left(\dfrac{BR_{Coil} + kL_{Coil} + K_{Motor}K_E}{mL_{Coil}}\right)s + \left(\dfrac{kR_{Coil}}{mL_{Coil}}\right)} \\ \dfrac{\left(\dfrac{K_{Motor}}{mL_{Coil}}\right)s}{s^3 + \left(\dfrac{R_{Coil}}{L_{Coil}} + \dfrac{B}{m}\right)s^2 + \left(\dfrac{BR_{Coil} + kL_{Coil} + K_{Motor}K_E}{mL_{Coil}}\right)s + \left(\dfrac{kR_{Coil}}{mL_{Coil}}\right)} \\ \dfrac{\left(\dfrac{1}{L_{Coil}}s^2 + \dfrac{B}{mL_{Coil}}s + \dfrac{k}{mL_{Coil}}\right)}{s^3 + \left(\dfrac{R_{Coil}}{L_{Coil}} + \dfrac{B}{m}\right)s^2 + \left(\dfrac{BR_{Coil} + kL_{Coil} + K_{Motor}K_E}{mL_{Coil}}\right)s + \left(\dfrac{kR_{Coil}}{mL_{Coil}}\right)} \end{bmatrix}$$

Development of LS-V15 Dynamic Model Mathematical Model Development – 2^{nd} Pass

- We must identify some physical characteristics of the valve
  - **Mass (m)** – The total moving mass including a portion of the spring mass. Value is approximately **11.2g**
  - **Viscous Friction (B)** – Very difficult to measure directly, however, analysis and testing has shown this value to be ~ **1.5 N-s/m**
  - **Spring Constant (k)** – A single spring is rated for 10 lbf/in (1765 N/m). Since there are two opposing springs that remain in pre-load, the effective spring rate is the sum of the individual spring rates (i.e. **3530 N/m**)
  - **Coil Resistance (R_{Coil})** – This would include all series resistance (including ICW). Direct measurement shows a value of **5.1 Ω**.
  - **Motor Constant (K_{Motor})** – The motor has been designed to exert 5.0 N per amp of current; therefore

    K_{Motor} = **5.0 N/A**
  - **Generator Constant (K_E)** – A phenomena of current conductors in a magnetic field exists where the motor/torque constant is numerically equivalent to the generator constant when the appropriate SI units are used (i.e. K_{Motor} in N/A = K_E in V-s/m). Therefore, K_E = **5.0 V-s/m**.
  - **Coil Inductance (L_{Coil})** – Any number of test methods may be used to determine the coil inductance. Lab testing reveals a value of ~ **1.5 mH**.

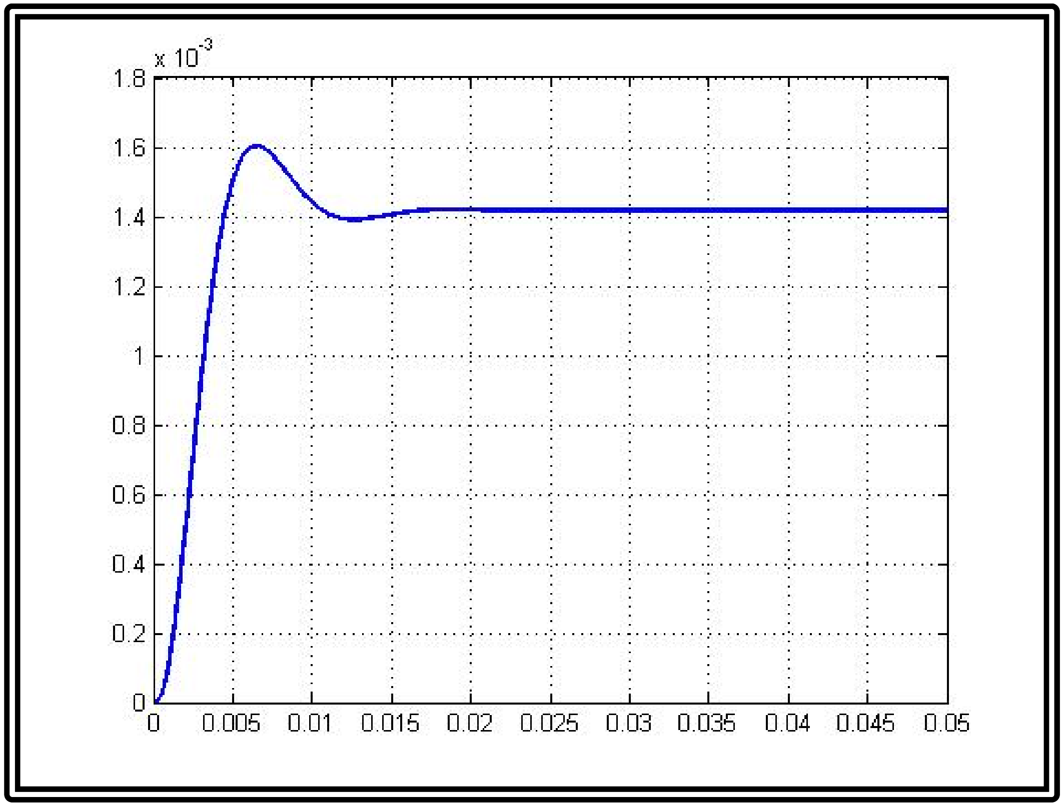
Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass



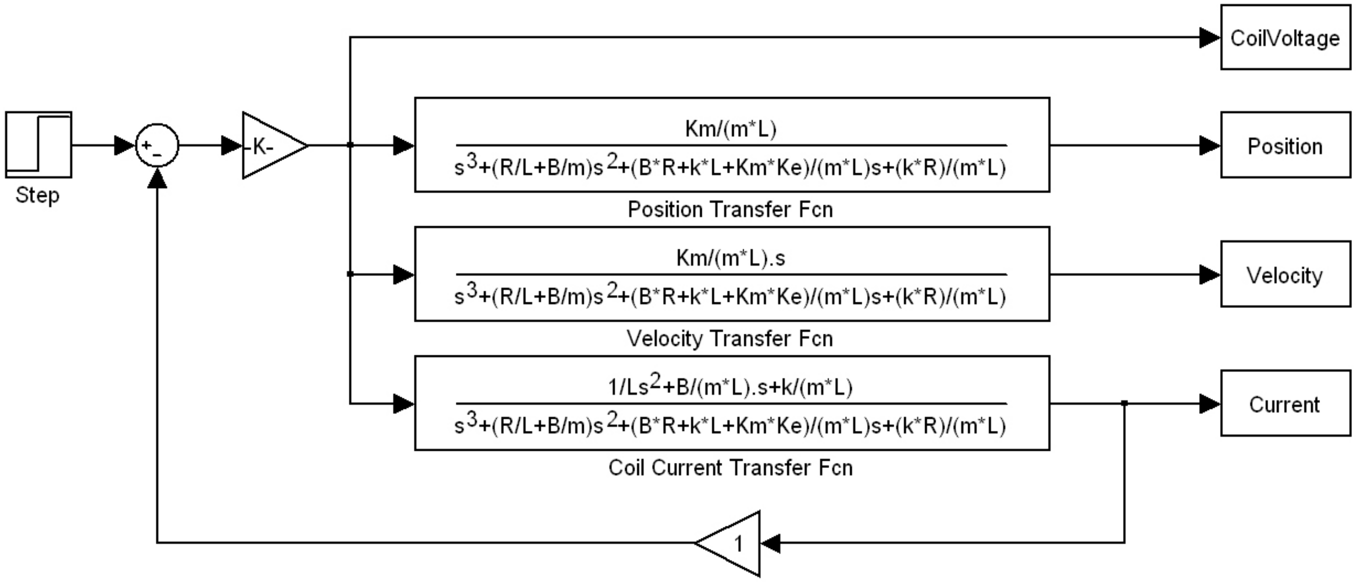
- We may now study the response of the system to a step *voltage* input to the coil.
  - We have selected 5.1V as a step input voltage to ensure that the steady state current is 1A as designed
  - A Simulink model was created using the transfer functions created earlier for Position, Velocity, and Current. The data was exported to the command window

Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass

- Key Performance Idicies
  - Rise Time (T_R) = 2.90 ms
  - Overshoot (%OS) = 13.2%
  - Settling Time (T_S) = 9.87 ms
- While this result seems acceptable, several design and application considerations must be addressed:
  - The valve is often positioned a distance removed from the drive circuit (ICW resistance will affect coil current)
  - Coil temperature is a function of thermal dissipation with respect to time; therefore, coil temperatures will affect coil current.
  - The T_R of 2.90 ms is slower than desired for marketability



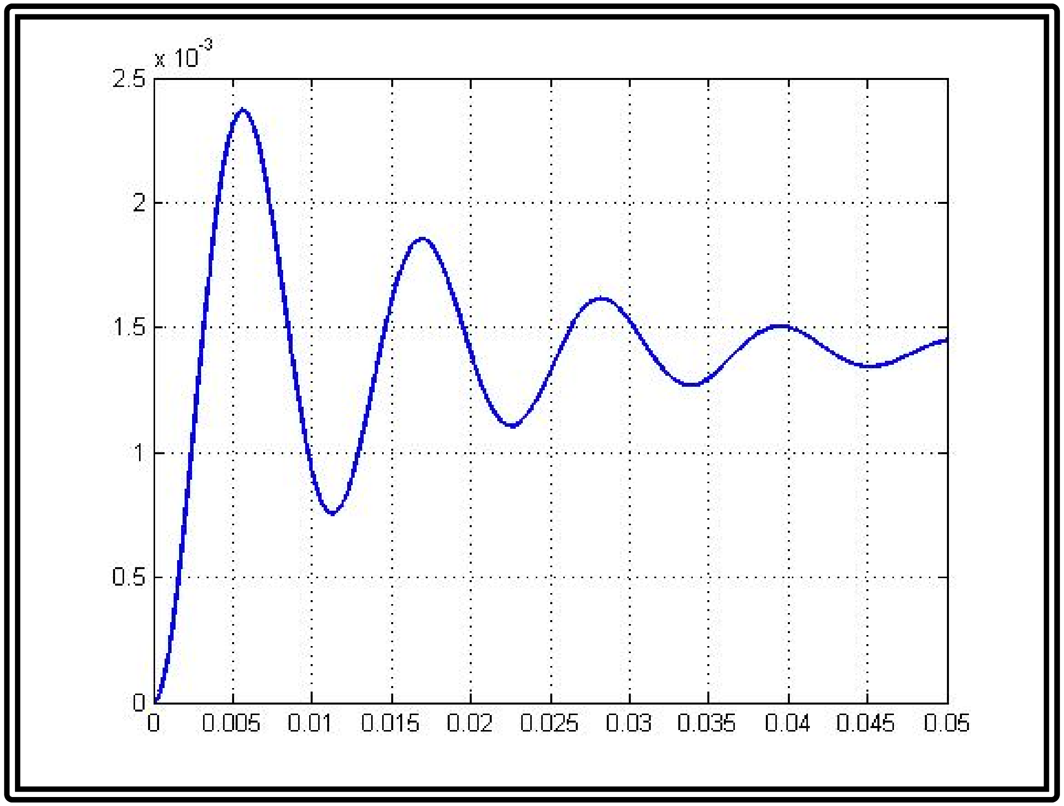
Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass



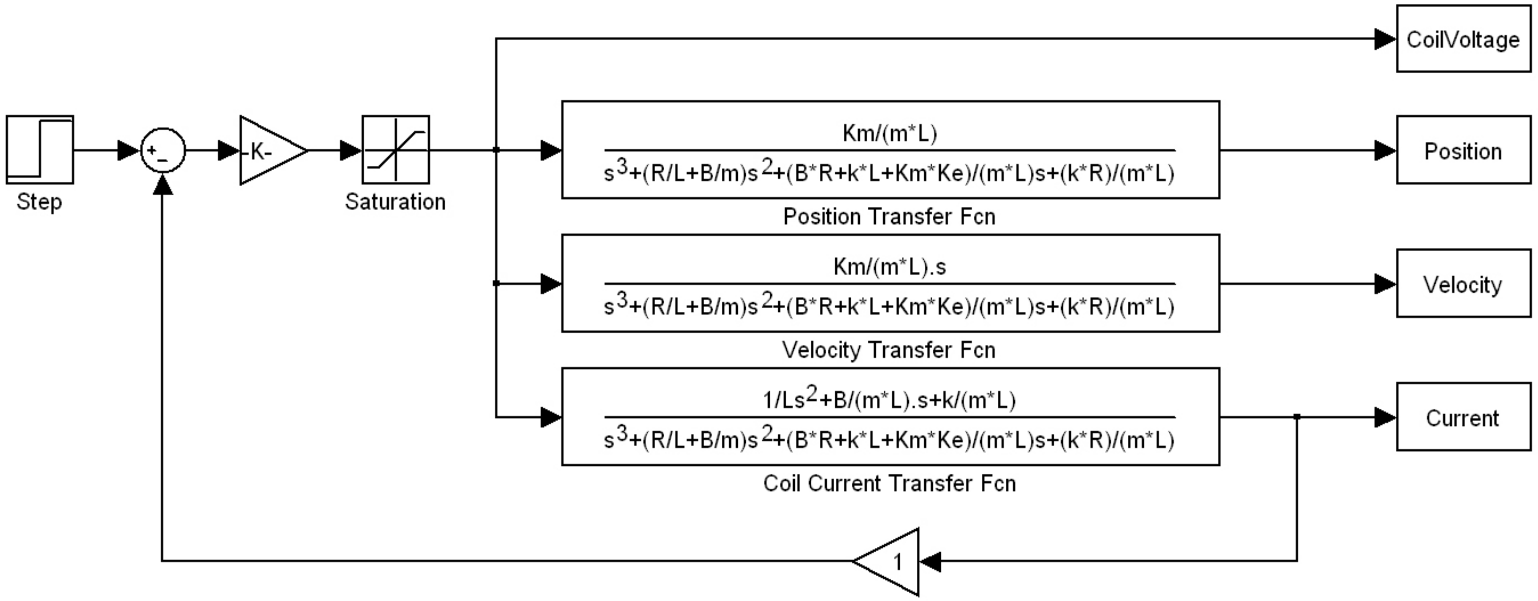
- We include the functionality of a high gain Trans-conductance amplifier (here, K=1000; actually much higher). Using this arrangement, we may study the effects of a regulated current source on dynamic performance.

Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass

- Key Performance Idicies
  - Rise Time (T_R) = 2.00 ms
  - Overshoot (%OS) = 67.3%
  - Settling Time (T_S) = >50 ms
- The response time is certainly more acceptable, however, certain issues exist with this particular solution:
  - The T_R is 2.00 ms, currently faster than the 2.50 ms advertised
  - The %OS is excessive
  - The T_S is excessively long
- An examination of the coil voltage plot reveals an initial calculated voltage spike of 1000 Volts! This is obviously not practical



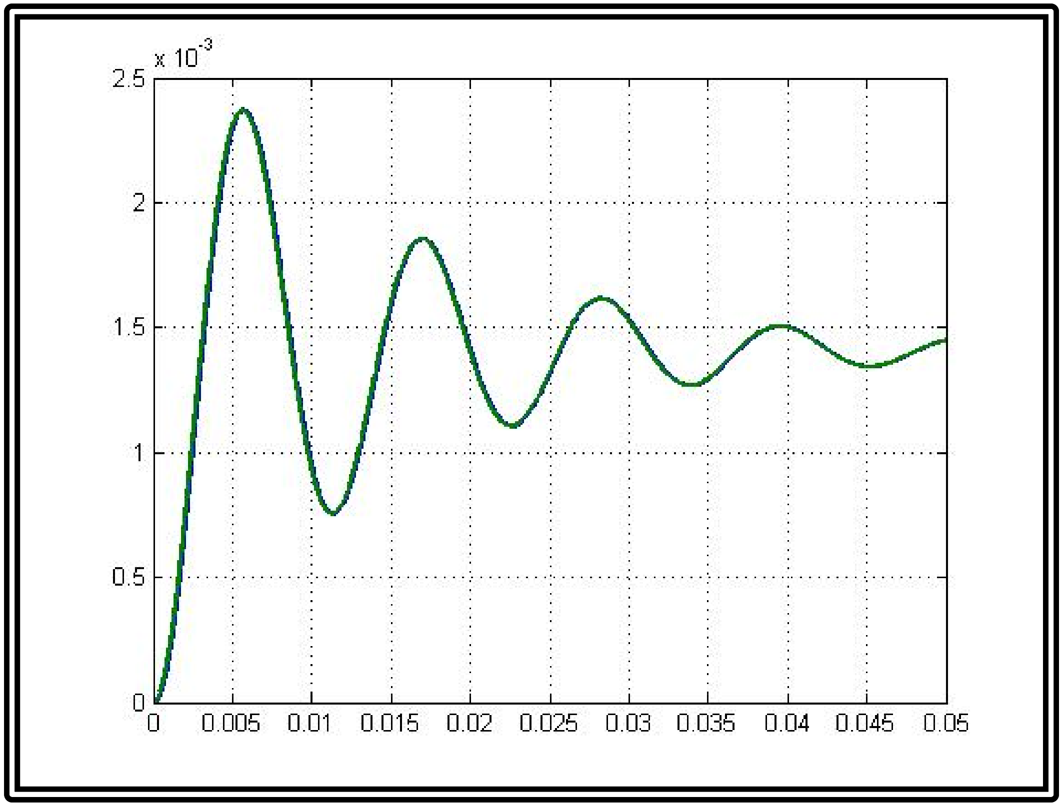
Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass



- Practically, we understand that the output of a linear amplifier will saturate at the supply rails. We may easily model this using Simulink by the addition of a Saturation block (set to +10V and -10V).

Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass

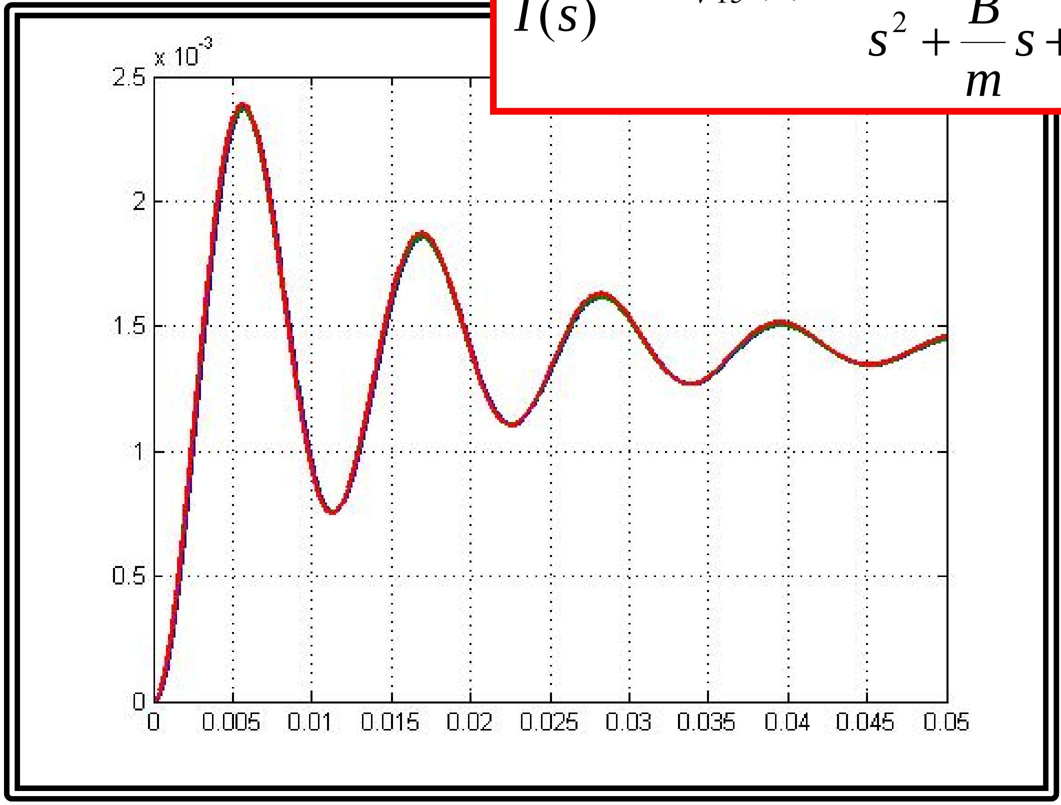
- After analyzing the model output again, we discover that the two outputs are nearly indistinguishable (see two plots at right; model with no saturation in blue, model with saturation in green).
- We now wish to simplify the 3rd order model and attempt to find a suitable 2nd order model with similar dynamic response.
- We shall examine the response of the Spring-Mass model originally proposed.



Development of LS-V15 Dynamic Model Mathematical Model Development – 2nd Pass

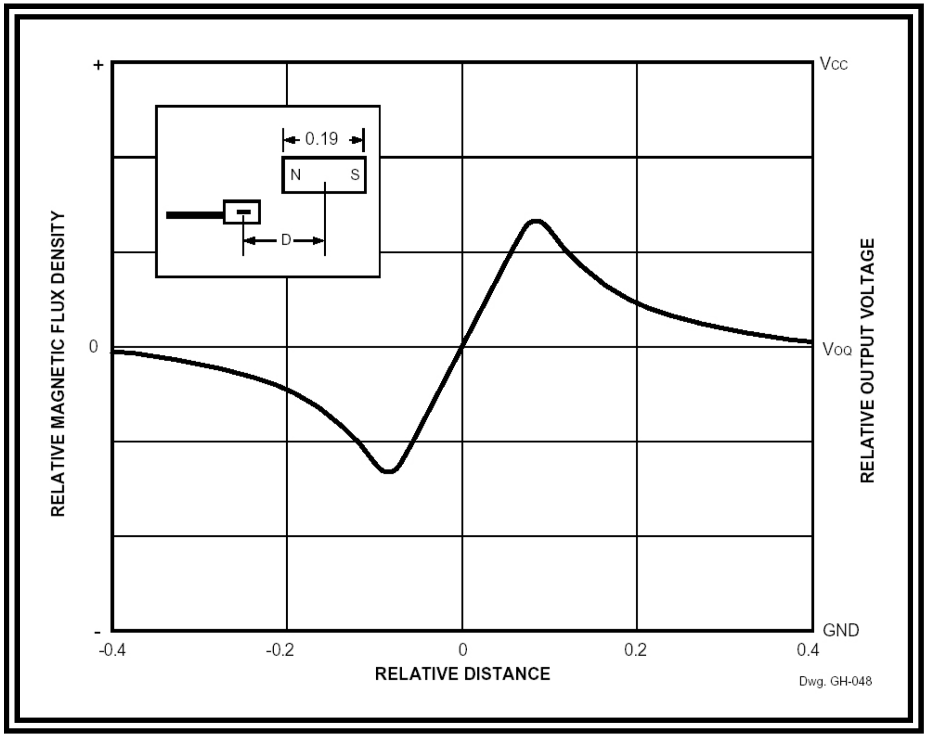
- Here we see three step response results plotted against each other:
  - Closed Loop on Current Step Response from 3rd Order Model (Blue)
  - Closed Loop on Current Step Response from 3rd Order Model; with Saturation (Green)
  - Open Loop Step Response from Simplified Spring Mass Model (Red)
- We can see that the simplified spring mass model should be adequate for further controller design

$$\frac{Y(s)}{I(s)} = G_{V15}(s) = \frac{\dfrac{K_{Motor}}{m}}{s^2 + \dfrac{B}{m}s + \dfrac{k}{m}}$$



Design of Spool Position Controller
Sensing Method

- There are several methods of spool position sensing available:
  - The sensing stroke is only about 1-2mm
  - The desired bandwidth of the spool motion is approximately 100Hz, so we would desire a relatively fast sensor
  - The expected service life of a pneumatic proportional valve is in excess of 100 million cycles
- Given these criteria, a hall effect position sensor is selected based on the following:
  - High sensitivity over short strokes (0-5V over a stroke as small as 0.050”). This allows for the use of a very small rare earth magnet (minimize additional moving mass)
  - A published bandwidth of ~50kHz
  - Non-contact (no parts to wear out over 100 million cycles)
  - DISADVANTAGE – Susceptible to external magnetic fields and EMI from high current sources
- Since the sensing magnet mass is very low (< 0.1g) and the device is non-contact, the dynamic equation is unaffected.
  - A short stroke potentiometer would add friction and mass
  - Ultrasonic sensing would be very slow
  - Optical sensing would likely be very expensive



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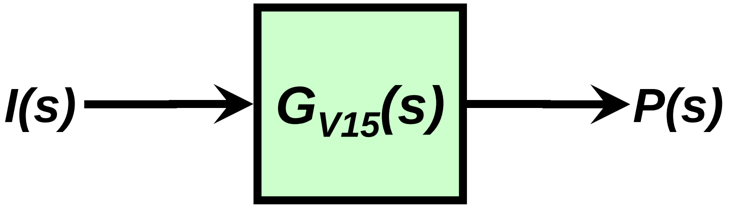
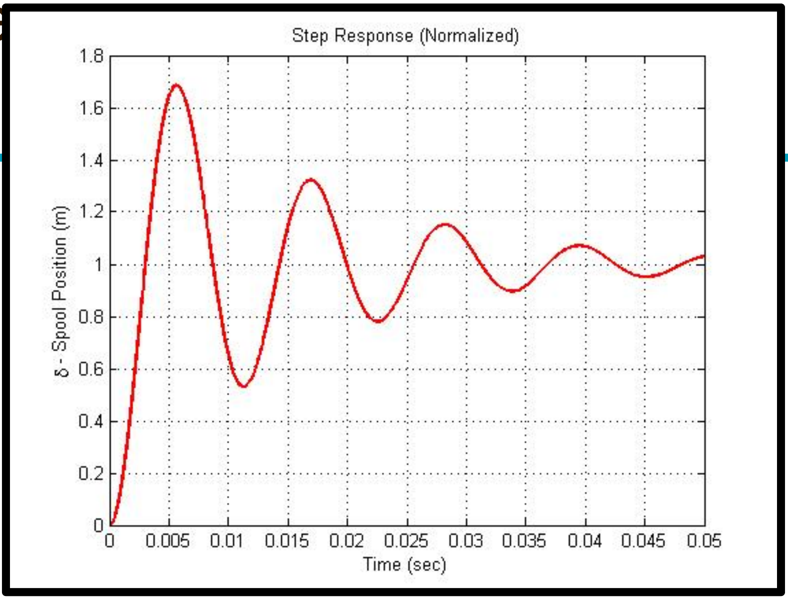
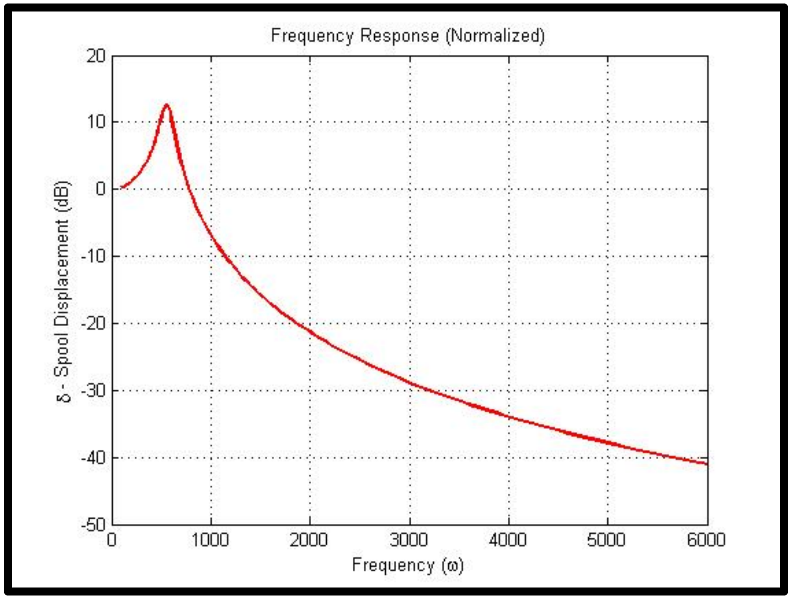
Design of Spool Position Controlle
Open Loop Response

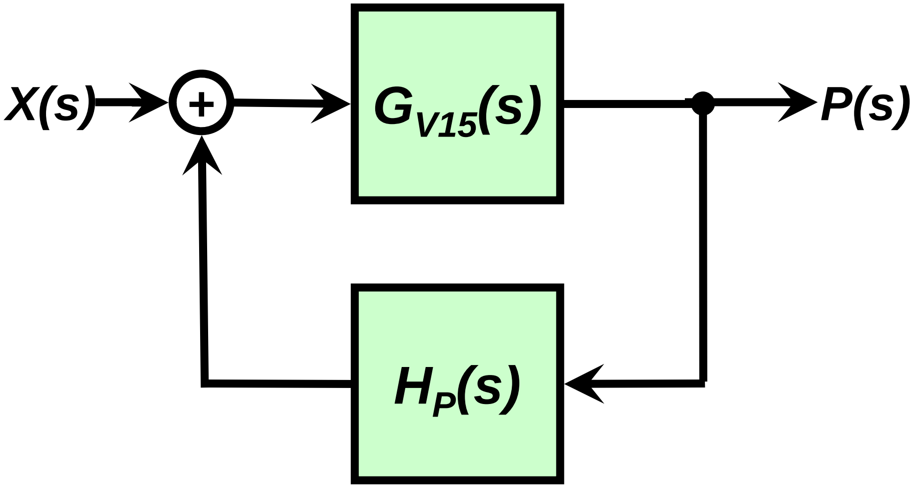


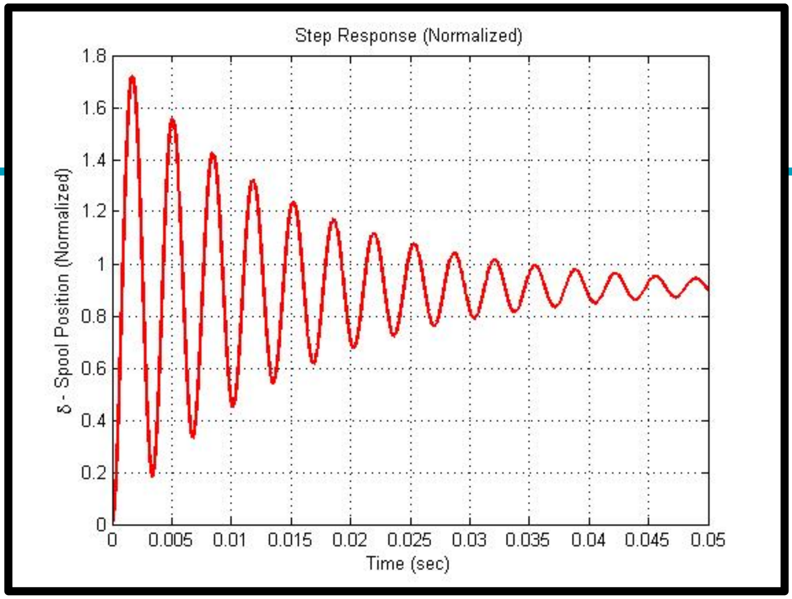


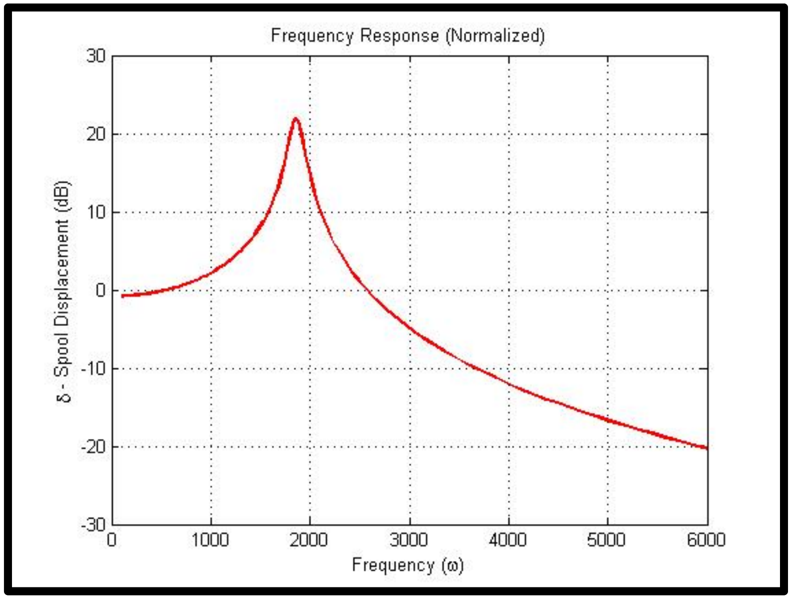


- Baseline Response for Open Loop 2nd order simplified model
  - Normalized Step Response for 1A current step
  - Normalized Frequency Response
- Note oscillatory behavior and 12dB peaking at approximately 88Hz

Design of Spool Position Controlle
‘P’-Type Controller







- Simple ‘P’ type proportional controller for position
- Here, $H_P(s)$ = K_P (proportional gain). The input level, $X(s)$, is scaled accordingly.
- The plots at right show $K_P = 10$
  - The step response is much more oscillatory (as expected)
  - The steady state error is approximately 9.1%
  - The frequency response shows significant peaking of ~22dB at approximately 302 Hz.
  - By inspection we note that the bandwidth has improved appreciably at the expense of other key performance criteria.

Design of Spool Position Controller
Feedback Compensation

$$T_{Desired}(s) = \frac{G_{V15}(s)}{1 + G_{V15}(s) H_C(s)}$$

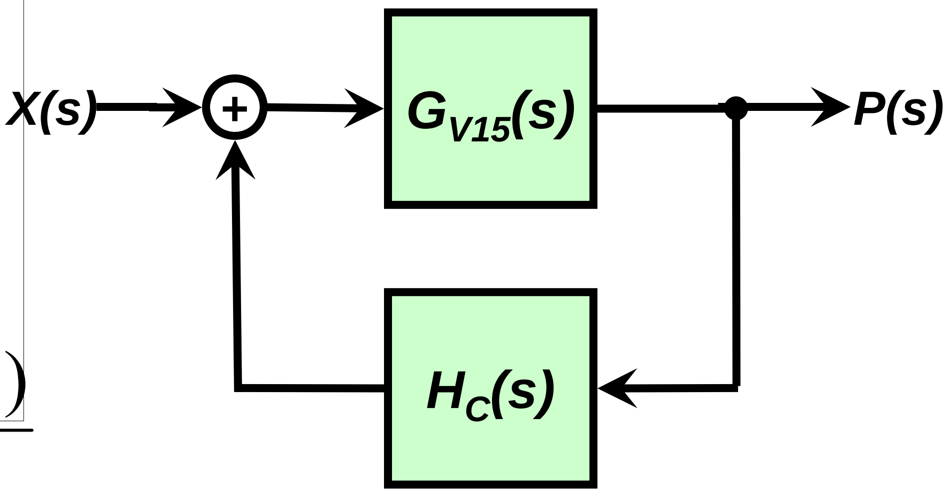
$$Let,$$

$$T_{Desired}(s) = \frac{a}{s^2 + bs + c}$$

$$Therefore,$$

$$H_C(s) = \frac{G_{V15}(s) - T_{Desired}(s)}{G_{V15}(s) T_{Desired}(s)}$$

$$H_C(s) = T_{Desired}(s)^{-1} - G_{V15}(s)^{-1}$$



Design of Spool Position Controller Feedback Compensation

$$T_{Desired}(s) = \frac{a}{s^2 + bs + c}$$

- We shall establish a set of aggressive ‘goal’ or ‘design’ specifications
  - $T_R \leq 1.5$ ms
  - $T_S \leq 10.0$ ms
  - %OS ≤ 10%
  - $M_P \leq 150\%$
  - $\omega_{BW} \geq 750$rad/s (~120Hz)
- We may now specify a desired system transfer function given the above information (derivation at right).

$$T_{Desired}(s) = \frac{2266}{s^2 + 1517s + 1.60 \times 10^6}$$

$$M_{P\omega} = \frac{1}{2\zeta\sqrt{1-\zeta^2}}$$

$$P.O. = 100e^{-\pi\zeta/\sqrt{1-\zeta^2}}$$

$$\text{Let } \xi = 0.6 \text{ for :}$$

$$M_{P\omega} = 1.04 \text{ and } P.O. = 9.48\%$$

$$T_S \leq \frac{4}{\zeta\omega_n} \Rightarrow \omega_n \geq 667\frac{rad}{s};(106\text{ Hz})$$

$$But,$$

$$T_R = \frac{2.16\zeta + 0.6}{\omega_n} \Rightarrow \omega_n = 1264\frac{rad}{s};(201\text{ Hz})$$

$$\omega_{BW} \geq (-1.196\zeta + 1.85)\omega_n \Rightarrow$$

$$\omega_{BW} \geq 1431\frac{rad}{s};(228\text{Hz})$$

Design of Spool Position Controller Feedback Compensation

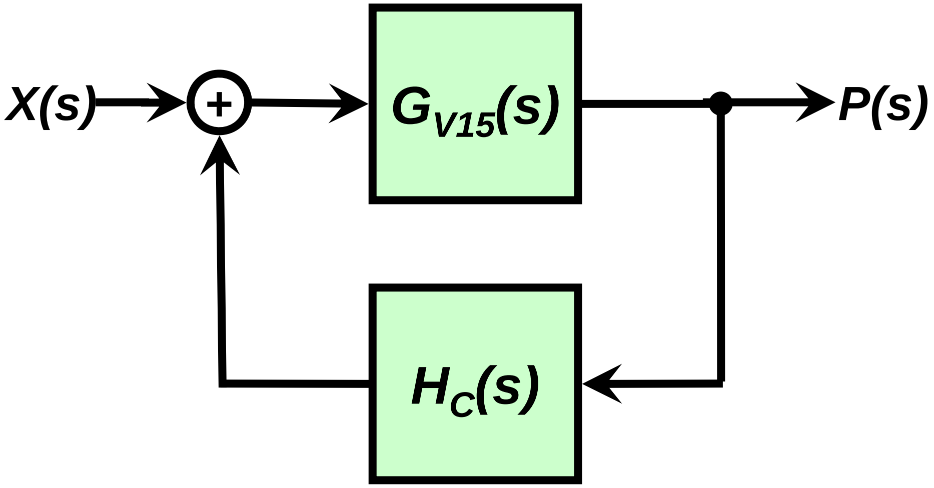
$$G_{V15}(s)=\frac{\frac{K_{Motor}}{m}}{s^2+\frac{B}{m}s+\frac{k}{m}};T_{Desired}(s)=\frac{a}{s^2+bs+c}$$

$$H_C(s)=T_{Desired}(s)^{-1}-G_{V15}(s)^{-1}\Rightarrow$$

$$H_C(s)=\frac{s^2+bs+c}{a}-\frac{s^2+\frac{B}{m}s+\frac{k}{m}}{\frac{K_{Motor}}{m}}$$

$$H_C(s)=\left(\frac{1}{aK_{Motor}}\right)\left[\left(K_{Motor}-ma\right)s^2+\left(bK_{Motor}-aB\right)s+\left(cK_{Motor}-ak\right)\right]$$

$$H_C(s)=\left(-1.80\times10^{-3}\right)s^2+\left(3.70\times10^{-1}\right)s+\left(9.01\times10^{-2}\right)$$



- The solution for $H_C(s)$ contains an ‘s^0’ term, an ‘s^1’ term, and a ‘s^2’ term
  - The 1st order term and 0th order term would be relatively easy to implement, however, the 2nd order term would be difficult to implement (very noisy)
  - We choose to evaluate the performance of this controller concept by implementing only the 1st and 0th order terms

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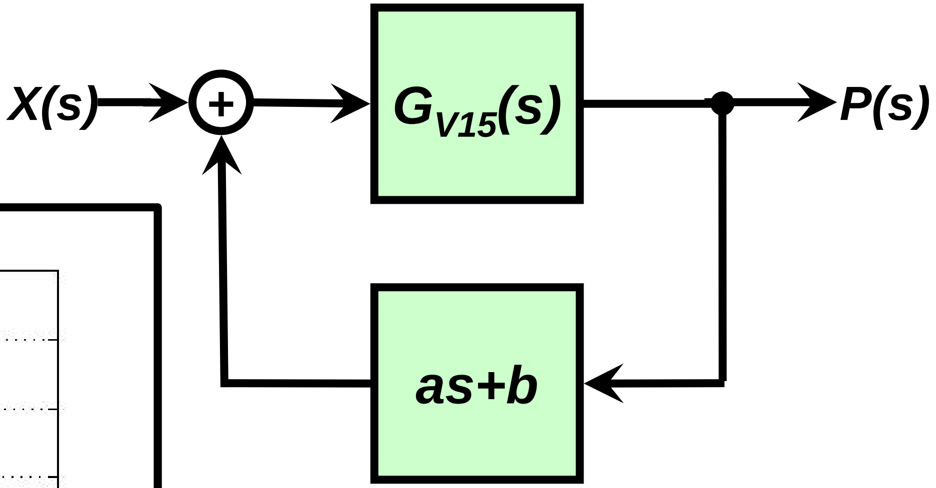
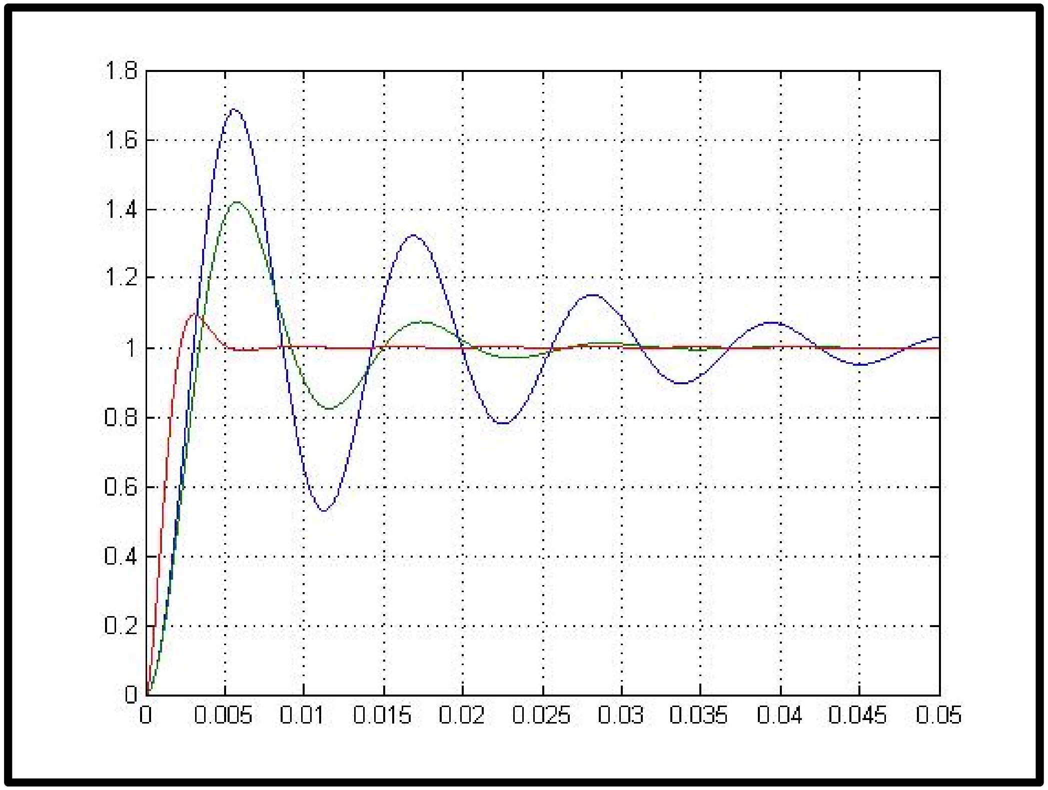
Design of Spool Position Controller Feedback Compensation





- Step Response of:
  - Simple 2nd Order Model (Blue)
  - $H_C(s)$ Controller under consideration (Green)
  - Desirable Performance; $T_{Desired}(s)$ (Red)

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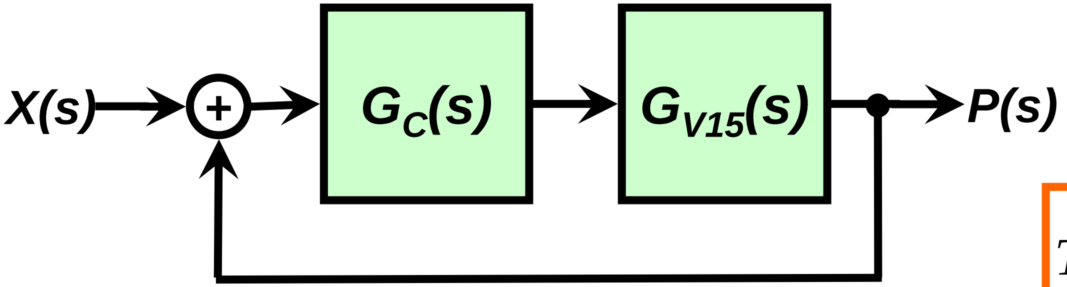
Design of Spool Position Controller
Valve Current Compensation



$$T_{Desired}(s) = \frac{2266}{s^2 + 1517s + 1.60\times10^6}$$

- An alternate method of control/compensation will be considered. This method is typically referred to as a compensator; $G_C(s)$
- The design method is very similar to the previous example. The desired or design goal response has not changed.

$$T_{Desired}(s) = \frac{G_C(s)G_{V15}(s)}{1 + G_C(s)G_{V15}(s)}$$

$$T_{Desired}(s) = G_C(s)G_{V15}(s) - G_C(s)G_{V15}(s)T_{Desired}(s)$$

$$G_C(s) = \frac{T_{Desired}(s)}{G_{V15}(s) - G_{V15}(s)T_{Desired}(s)}$$

$$G_C(s) = \frac{5.075s^2 + 679.5s + 1.60\times10^6}{s^2 + 1517s + 1.599\times10^6}$$

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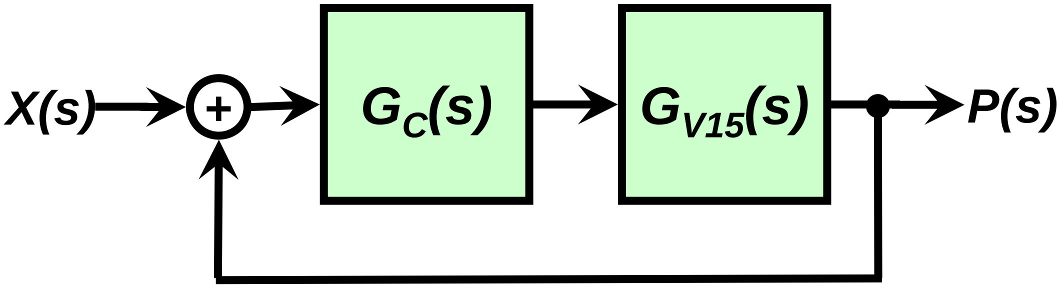
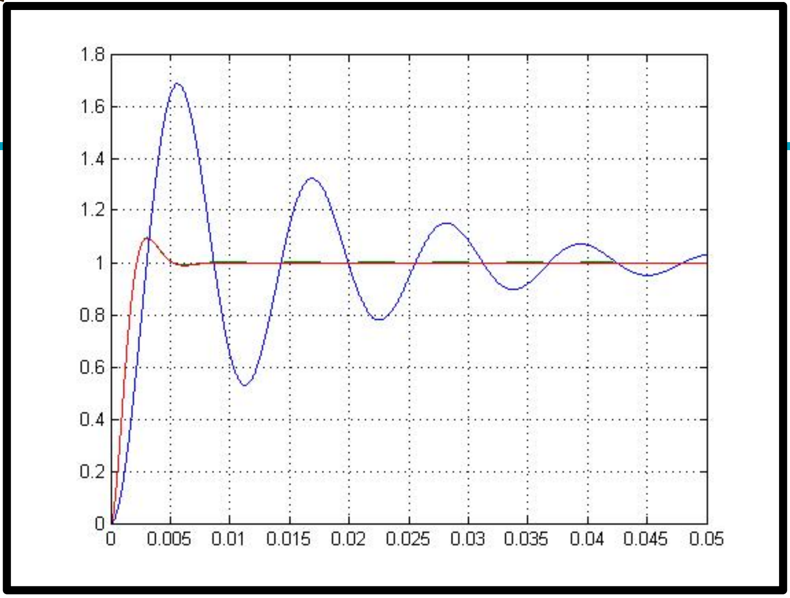
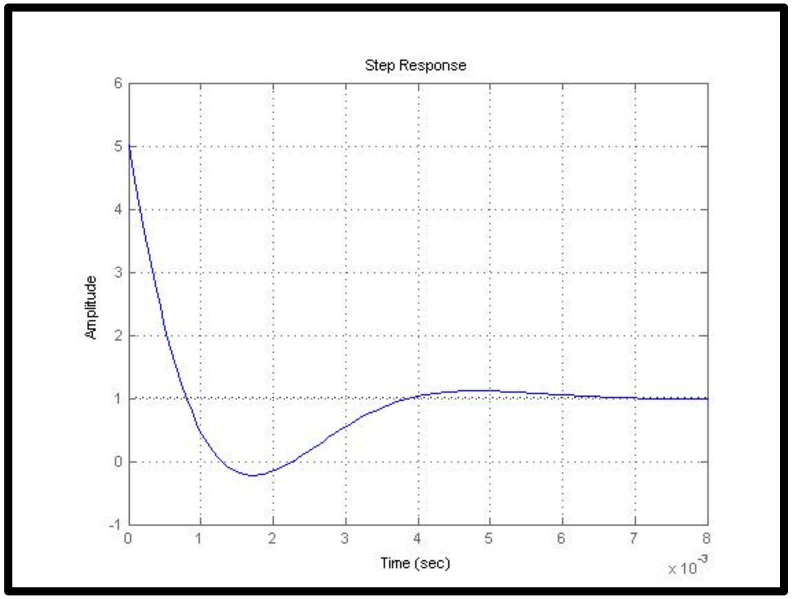
Design of Spool Position Controller
Valve Current Compensation

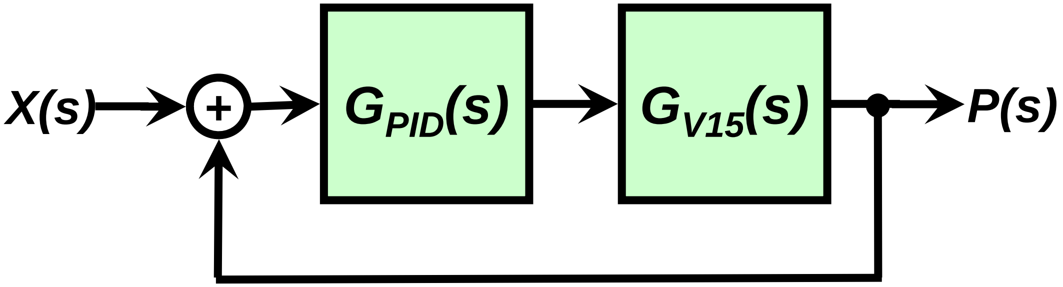




- The valve position step response shows:
  - 2^{nd} Order Model Response (Blue)
  - $T_{Desired}(s)$ (Green)
  - Valve Current Compensation; Valve Position Step Response (Red)
  - Notice that the Red and Green Plots are virtually identical
- The second plot shows the step response of the compensator
  - Represents current flow to the valve for a step input
  - At $t=0^+$, valve current transitions from 0-5A instantaneously (impractical)
  - Current peak magnitude is 5A (impractical)
- It is interesting to note that given a large enough power supply and adequate drive electronics, the aggressive performance specs could be easily met by application of power.



Design of Spool Position Controller
PID Control of Valve Spool Position



$$G_{PID}(s) = \frac{K_D s^2 + K_P s + K_I}{s}$$

- A very popular method of plant control is PID. To design a PID controller, the previous methods will not be sufficient.
- The PID control function takes the form as shown above (notice that this is an improper system)
- By utilizing an adaptation of the Ziegler-Nichols PID Design Method presented in Ref [1], we find:

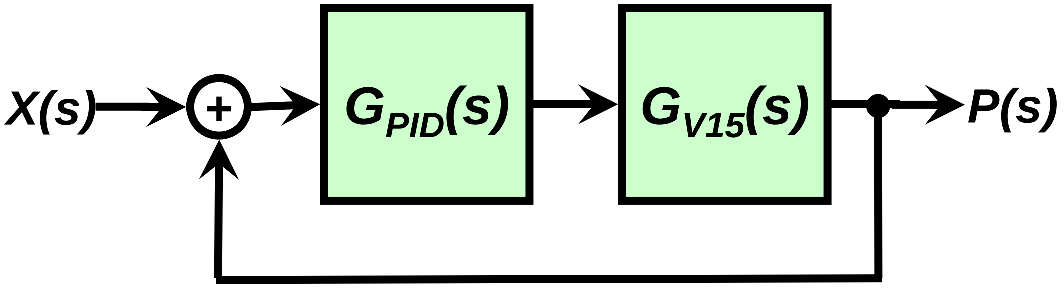
$$K_M = 97500; \omega_M = 565$$

$$K_P = 0.6 K_M = 58500$$

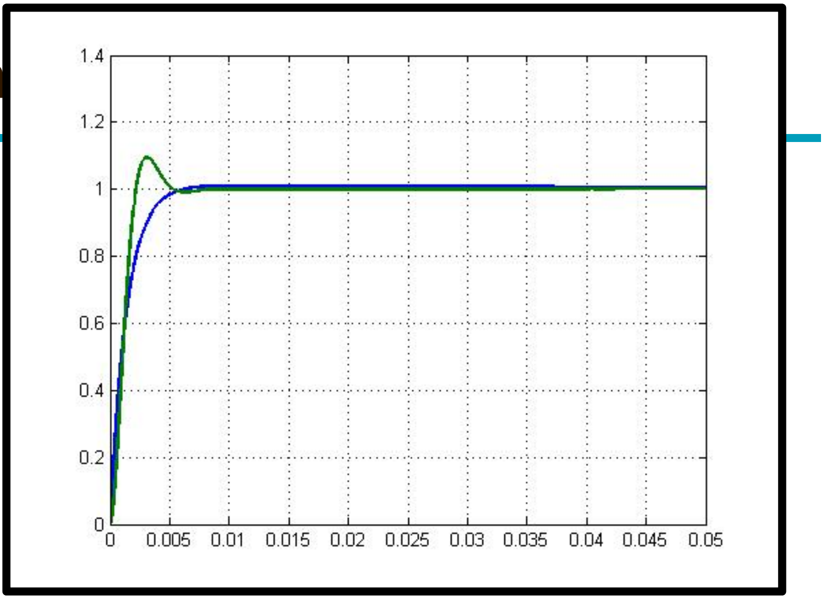
$$K_D = \frac{K_P \pi}{4 \omega_M} = 81.32$$

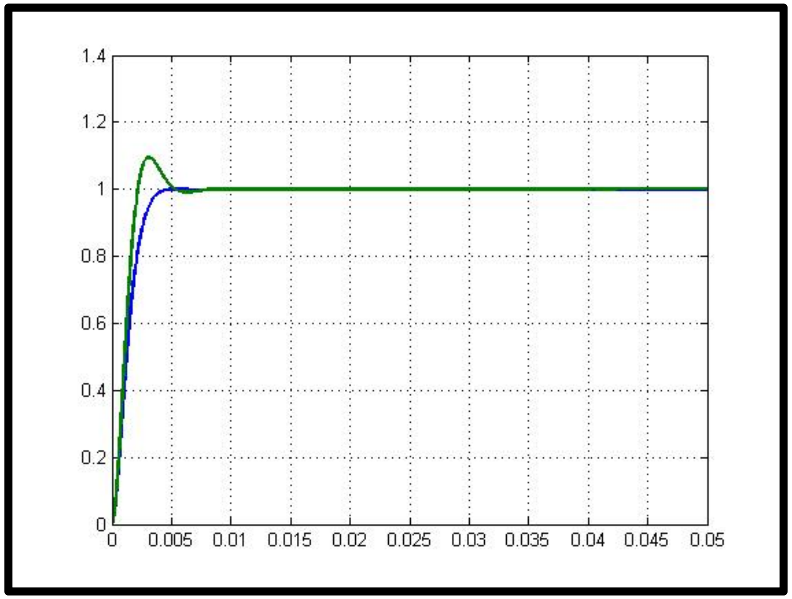
$$K_I = \frac{K_P \omega_M}{\pi} = 1.05 \times 10^7$$

Design of Spool Position Controller
PID Control of Valve Spool Position

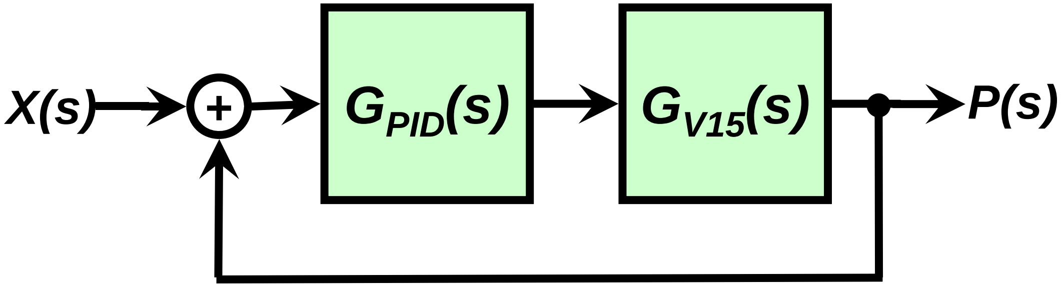


- Top image shows step response of designed PID controller in the valve control loop
- Bottom image shows step response of PID controller with modified gains
  - As often must be done with PID controller, intuition was utilized to select *more appropriate* gain values.
  - The ratio of the gains found during the design effort was used as a guide to begin the tuning process.
  - Incremental adjustments were made to achieve a more appealing step response:
  - $K_P=5$, $K_D=0.007$, $K_I=700$
- As with the compensator design, both of these designs require an initial 5A current spike (impractical).

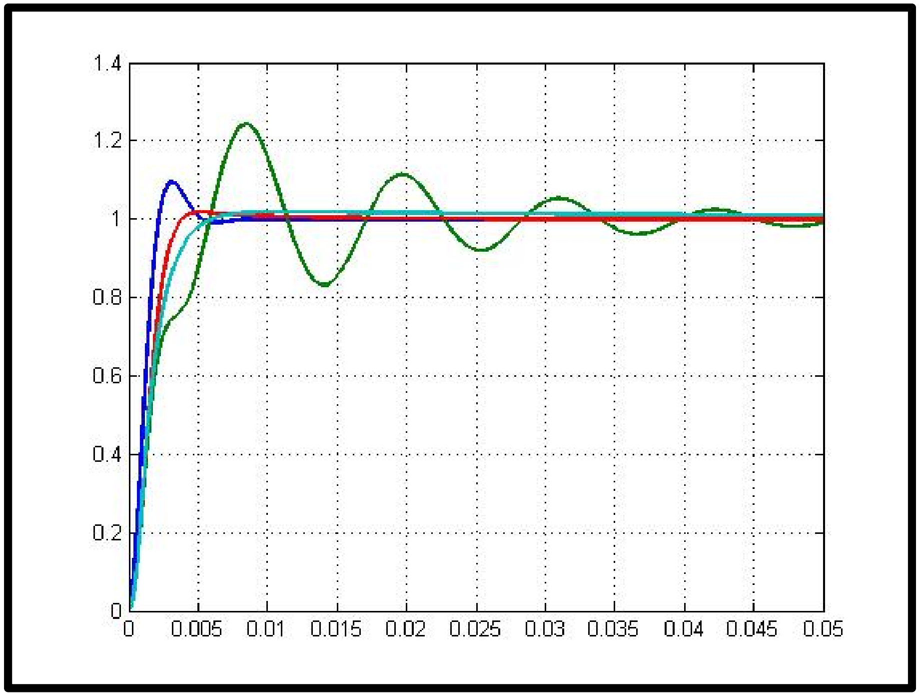




Design of Spool Position Controller
PID Control of Valve Spool Position



- In order to study the feasibility of implementation, a study was performed by limiting the supply current to 2A for each of the competing designs
- The step response plot shows:
  - $T_{Desired}(s)$ (Blue)
  - $G_C(s)$ Compensation (Green)
  - PID #1 (Cyan)
  - PID #2; Intuitive Gain Selection (Red)
- It is clear that the 2A limit had minimal effect on the response of both PID controllers, however, the compensation technique response was dramatically adversely affected.



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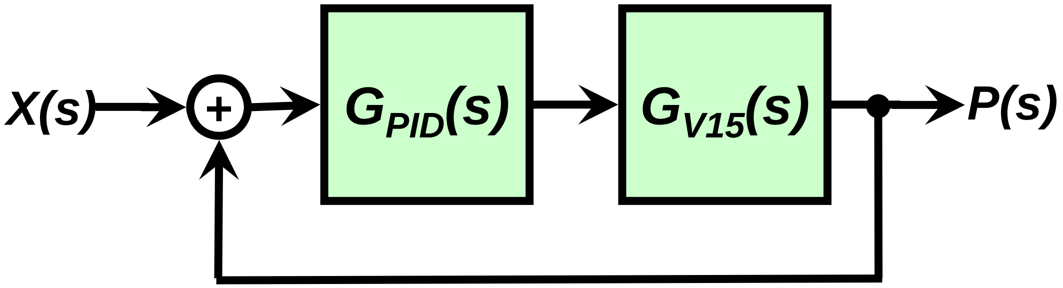
Design of Spool Position Controller
PID Control of Valve Spool Position

- Plot shows:
  - $T_{Desired}(s)$ (Green)
  - PID #2 (Blue)
- Recall the original performance specifications:
  - $T_R \leq 1.5$ ms
  - $T_S \leq 10.0$ ms
  - %OS ≤ 10%
  - $M_P \leq 150\%$
  - $\omega_{BW} \geq 750$ rad/s (~120Hz)
- The performance specifications for the PID controller shown at right are as follows:
  - $T_R = 2.17$ ms
  - $T_S = 3.47$ ms
  - %OS = 1.8%
  - $M_P \leq 106\%$
  - $\omega_{BW} = 1193$ rad/s (~190Hz)
  - Both PID controllers exhibited similar frequency response characteristics.



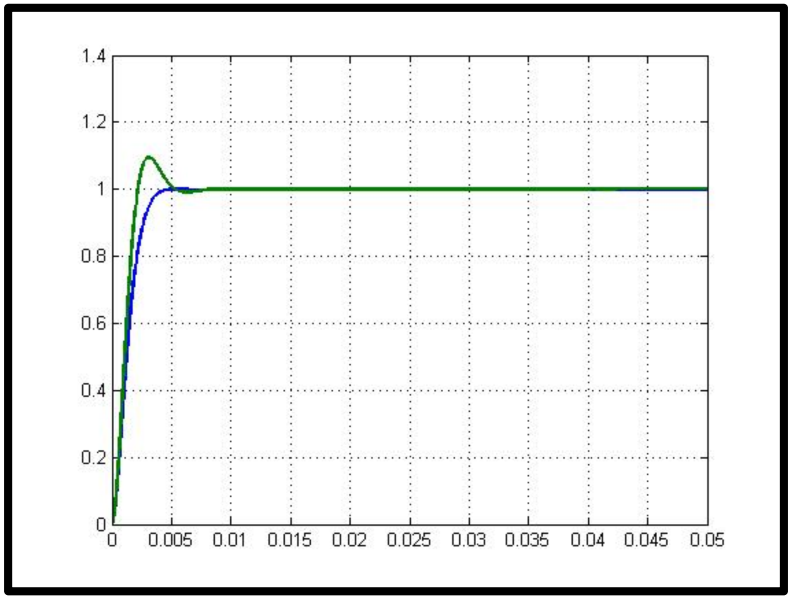
$X(s)$

$+$

$G_{PID}(s)$

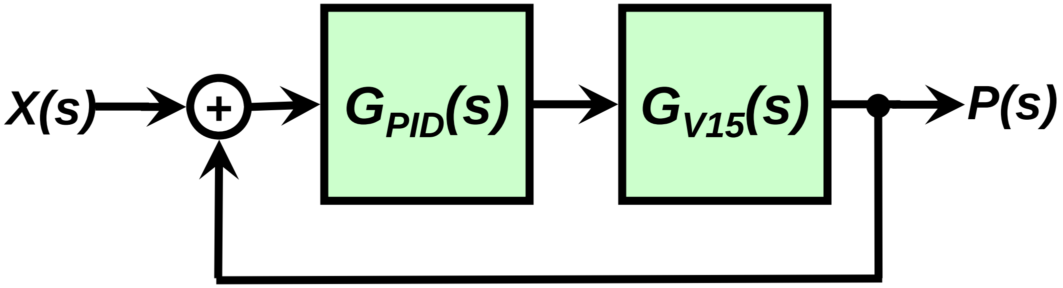
$G_{V15}(s)$

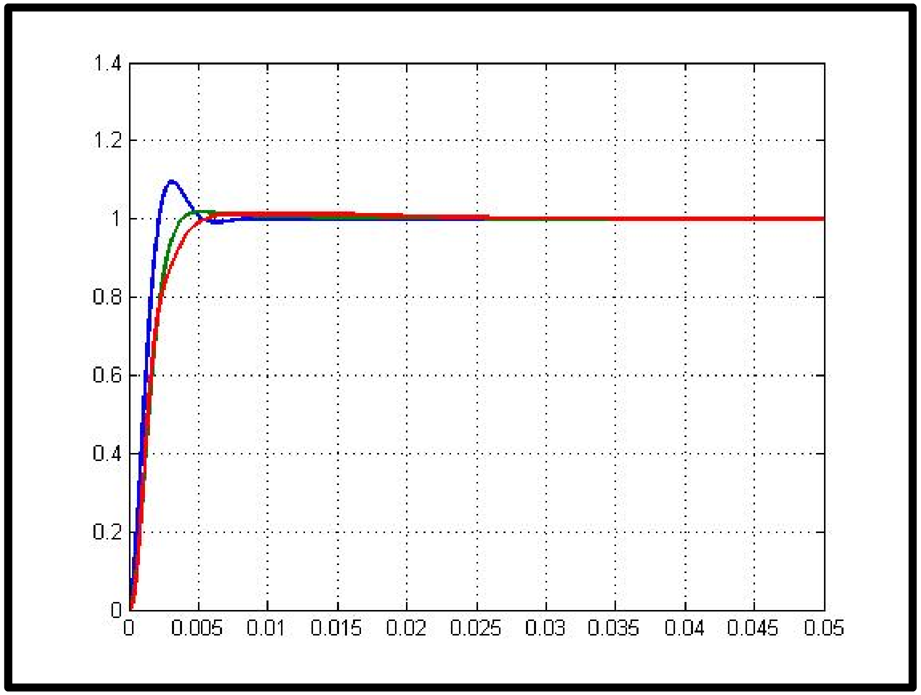
$P(s)$



Design of Spool Position Controller
PID Control of Valve Spool Position

- An empirically refined model exists for the LS-V15. We will examine the performance of the PID controller on the more accurate valve model.
  - Plot showing:
    - $T_{Desired}(s)$ (Blue)
    - PID #2 (Green)
    - PID #2 w/Real Valve Model (Red)
  - We find that the performance of the PID control acting on the *real* valve is very similar to the performance of the PID control acting on the simplified 2nd order model.
- Even though we were unable to meet the 1.5 ms response time specification, we *were* able to exceed all other specifications by using a PID type controller. Furthermore, we have shown the controller to be relatively robust when subjected to ‘current limiting’ or other non-linearities.





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- Comments/Questions?

- References

  - [1] “Control System Design Project”. F. L. Lewis, 1999. http://arri.uta.edu/acs/ee5325/lectures99/pidLL.pdf#search='selecting%20PID%20gains
  - [2] Modern Control Systems (9th Editions). Richard C. Dorf, Robert H. Bishop. Addison-Wesley 1998.