Hydraulic Proportional and Closed Loop System Design

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Electrohydraulics

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2. Proportional Valves
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Electrohydraulics

Proportional Components

- Operate under electronic control
  - Pressure Relief
  - Pressure Reducing
  - Throttling
  - Flow Control
  - Directional Control
  - Pump Control
    - Flow
    - Pressure
    - HP Limiting
4 Main Control Principles

- Force Controlled Solenoid

- Position Controlled Solenoid

- Servo Solenoid

- Servo Valves
Proportionals

Proportional Force Solenoid

- Solenoid current is proportional to armature force, unlike on/off solenoid
- Proportional force is linear, within a working stroke (approx 1.5 mm)
- A steady current keeps solenoid force constant within the working stroke
Proportional Solenoid on a Pressure Relief

- Solenoid force opposed by pressure $P \times A$ at seat (3)
- Input to amplifier changes solenoid current (output Force)
  - 20% input => 20% pressure
  - 80% input => 80% pressure
Proportional Solenoid on a Throttle Valve

- Solenoid force opposed by spring force = spring rate \times \text{displacement}
- Spool position is constant, when forces are balanced
- Solenoid Current is directly proportional to spool position
  - 40% input => 5% flow (due to spool overlap, dead-band)
  - 80% input => 50% flow
Proportionals

Proportional Solenoids on a Directional Valve

- Solenoid force vs. spring force positions spool
- Select one solenoid to control direction and flow
  - 40% input Sol-a => 15% flow P-to-B
  - 80% input Sol-b => 80% flow P-to-A
- Hysteresis <5 to 6 %
Proportionals

Stroke Controlled Solenoid

- Improve accuracy and performance with position feedback on solenoid
- LVDT – Linear Variable Displacement Transformer
  - Position transducer – short stroke
  - High resolution
  - Non-contacting
  - Robust
Proportionals

Stroke Controlled Pressure Relief

- Adding LVDT position feedback greatly improves resolution
- 0.2% Hysteresis
Proportionals

Stroke Controlled Directional Valve

- LVDT position feedback improves performance
  - Increased flow capacity
  - Higher Power Limit
  - Better Response Sensitivity
  - Better Hysteresis < 0.3%
Construction of Proportional Valves

- Proportional spools slide in cast body
  - No sleeve, in main stage (unlike a servo valve)
  - Robust construction similar to on/off directional valves
  - High flow capacity
  - Low cost
- Throttle area normally formed by notches cut into spool
- Notch size and geometry determine flow capacity for a given housing
Notch shape determines flow characteristic

- “Square” opening
- “D” opening
- “V” opening
Proportionals

Nominal Flow Rating of Proportionals

- “Nominal Flow” for proportional spools is rated at $\Delta p = 10$ bar (145 psi) total, 5 bar per land
- Example 4WRA “Nominal Flow” is 7 to 60 LPM rated @ $\Delta p = 10$ bar (145 psi)
- Only 145 psi pressure drop across valve!
  - This is not typical for applications
  - Avoid the common mistake:
    Supersizing spool = poor resolution

72 psi (5 bar)

145 psi (10 bar)
Proportionals

Flow Rating of Proportional Valves

- Required Flow is normally given, $Q_{\text{req}}$
- Nominal valve drop $\Delta p = 10$ bar (145 psi)
- You must estimate your pressure drops, $p_{\text{system}} - p_{\text{load}} = p_{\text{valve}}$
- To find a spool, solve for “Nominal flow”
  - Estimate required valve pressure drop
  - $Q$ is proportional to square root of corresponding $\Delta p$

\[
Q_{\text{nominal}} = Q_{\text{req}} \cdot \sqrt{\frac{\Delta P_{\text{nominal rating}}}{\Delta P_{\text{real valve drop}}}}
\]

- Then, go to valve data sheet and select the closest spool to this value

\[
\begin{align*}
Q_n &= c A \sqrt{\Delta P_n} \\
Q_{\text{req}} &= c A \sqrt{\Delta P_{\text{real}}}
\end{align*}
\]

c = orifice flow co-efficient
A = Area of orifice
(same values for both equations)
Using Flow Diagrams

- Estimate $\Delta p$ required across valve in both flow paths,
  System pressure – Load pressure
- Each housing size may have several spool flow options
  Find a spool curve that fits the target nominal flow around 90%
  Command, with a reasonable $\Delta p$, close the your estimated valve $\Delta p$
Proportionals

Can Valve Pressure Drop Be Too High?

- Yes, valve $\Delta p$ over 50% system pressure is high
- Avoid over-flowing valve! curve 5
- High flow forces try to center spool on direct operated proportional valves
- High $\Delta p$ in a proportional valve creates a high rotational force
- Anti-rotation design prevents spinning spools, but limit time at extreme conditions to avoid problems
- Sleeve and Spool valves do not have rotational forces
Proportionals

Power Limits

- All direct operated proportional valves have Power Limits ($Q_{valve} \cdot \Delta p_{valve}$)
- Bernoulli forces try to center spool at high $\Delta p_v$
- Power Limit decreases if flows are unequal

![Graph showing performance limits](image)
Proportionals

Power Limits

- Power limit diagrams may be plotted in different ways, but they represent the same thing
- Sometimes performance limits are only listed in a table
Proportionals

Common Proportional Spools

- **E-spool**: All ports blocked
  - Overlap 10% to 20% on each side
  - Differential cylinder may creep, due to leakage in cylinder and spool
  - Closed loop positioning requires a more advanced controller
- **V-spool**: No deadband (no overlap)
  - 1% underlap allows housing variations
  - *Only* suitable for closed loop control
- **W-spool**: 2% to 3% open A to T, B to T
  - *Only* suitable for open loop control
  - Primarily for differential cylinders
Asymmetrical Spools

- Asymmetric spools like E1-, W1-, V1-
  - 2:1 flow area (4 notches vs. 2 notches)
  - For differential area cylinders
- Balances $\Delta p$ across each flow path, due to unequal flows to/from cylinder
  - Can prevent cylinder cavitation
  - May improve cycle time
    - Better deceleration
    - Shorter reversal time
- This is more important with larger flow valves

With spool symbol E1-, W1-, V1-:

- $P \rightarrow A$: $q_{V_{\text{max}}}$
- $B \rightarrow T$: $q_V/2$
- $P \rightarrow B$: $q_V/2$
- $A \rightarrow T$: $q_{V_{\text{max}}}$
Additional Spool Types

- **W6-spool**: improved W-spool
  - crossover all ports are closed (to stop)
  - then decompress at center, open 2% A to T and B to T
- **W8-spool**: improved W1-spool, like W6 but 2:1 flow area
- **Q2-spool**: special for injection molding cylinder
Regen Spools with external bypass

- **W3-spool**: hydraulic regeneration extends cylinder quickly. Rod side is blocked by B port. High pressure on rod end pushes flow over external check valve
  - Fast traverse. but rod pressure is high!
  - Tonnage reduced!
    - Area bore – Annulus area = Area rod
    - Extending force = Area rod \times Pressure bore

- **W9-spool**: improved W3

- **W4-spool**: 4-position, Regen spool
  - Full tonnage below 33% (P-to-A and P-to-B)
  - Regen above 33% (P-to-A and B blocked)
Proportionals

Performance Terms

Hysteresis $\leq 5\%$  Reversal Error $\leq 1\%$  Response Sensitivity $\leq 0.5\%$

- **Hysteresis** is max. position error which depends on direction history
- **Reversal Error** is the smallest signal that moves spool in the opposite direction. (Range of Inversion)
- **Response Sensitivity** is the smallest signal to move spool in the same direction, after stopping (resolution of valve)
Proportionals

Performance Terms

- **Repeatability** - Ability to achieve the same spool position (or same pressure) given the same valve, under the same conditions, with the same command input
  - Force controlled valves: 2% to 3%
  - Stroke controlled: 0.1% to 0.5%
  - Typically half the Hysteresis

- Question… if you need to achieve 100 psi pressure repeatability from a proportional relief valve with a 5000 psi maximum pressure, can you use a proportional relief valve with a repeatability of 3%?
  - No… maximum repeatability is 0.03 x 5000 psi = 150 psi
Proportionals

Step Response

- Time for spool transition given a stepped input
- Standard test conditions (fluid temp, viscosity, pressure) may not match your application
- If only given a time value, you must know conditions and measurement criteria
  - 0 to 100%
  - 10 to 90%
  - 20% to 80%
Bode Diagrams

- Valve frequency response @ -3dB amplitude (+/-10%, 25%, 100%)
- Phase Lag @ -90 degrees
Servo Solenoid Basics
Servo Solenoid Valves

Servo Solenoid – Direct Operated

- Very Fast Stroke Solenoid
  - Single Solenoid
  - Directly Positions Spool
- No Flapper/Nozzle
- No Jet-pipes
- No Pilot Leakage

![Servo Solenoid Diagram]

- Position feedback
- Armature
- Solenoid spool
- Sleeve
- Spring plate
- Spring
Servo Solenoid – Direct Operated

- Spool and Sleeve Assembly
  - Like most servo valves
  - Zero Overlap
  - Linear
  - Symmetrical
  - Accurate
  - Long service life
- Normal filtration (No control orifices or jet pipes)
- Main sleeve means Nominal Flow @ $\Delta p$ 70 bar (1000 psi)!
  - 2 to 100 Lpm @ 70 bar $\Delta p$
  - (size 6 to 10)
Servo Solenoid Valves

Nominal Flow Conversion

- Easily convert between Nominal Ratings
  - Sleeve/Spool rated Nominal Flow @70 bar (1000 psi) $\Delta p$
  - Proportional rated Nominal Flow @10 bar (145 psi) $\Delta p$

\[
\sqrt{\frac{70}{10}} = \sqrt{7}
\]

• Servo to Proportional nominal rating, divide by square root 7
• Proportional to Servo nominal rating, multiply by square root 7

Given: 50 Lpm @ 70 bar $\Delta p$ (Servo Solenoid)

What is flow at 10 bar $\Delta p$ rating?

\[
\frac{50}{\sqrt{7}} = 18.9 \text{ Lpm}
\]
Servo Solenoid Valves

Spool/Sleeve in Direct Operated Servo Solenoid

- Zero overlap matched spool and sleeve
- Failsafe position with overlap, by spring offset during power off / fault), which may eliminate need for an external blocking valve

C5, C1 have 2:1 flow ratios
Servo Solenoid - Direct Operated

- Smooth cross-over (through center) like Servo, important to
- Most Reliable OBE Available
- 25g mechanical shock and vibration for 24 hours in 3 Axis
- Long Service Life
- 60 to 100 Hz @ -90 Deg, small signal
- Ideal for many closed loop applications

4WRPH6, 4WRPEH6, 4WRPEH10
RE29035, RE29037
Fuse OBE on Servo Solenoids

- Protect each OBE with 2.5 Amp, Fast acting Fuse!
Pilot Operated Servo Solenoid Valves
Servo Solenoid – Pilot Operated

- Main stage has proportional spool in cast housing
- Nominal Flow rated at 10 bar $\Delta p$
- Pilot stage has sleeve/spool (4WRPEH6)
- E, W, V, Q4-spools
- Failsafe of pilot (C3) allows main spool to spring center (E, W)
- V-spool at spring-center Failsafe means 1 to 6% offset P-to-B, to creep this direction

4WRLE
RE 29088
RE 29089
Linear Characteristic

- V-Spool with Linear flow characteristic can improve system performance
- Higher P-gain in external controller reduces system following error
- More leakage improves damping
- Easier tuning of close loop application
Servo Solenoid Valves

Servo Solenoid – Pilot Operated

- Nominal Flow (Size 10 to 35)
  - 50 to 1100 LPM
    @ 10 bar or 145 psi \( \Delta p \), like a Proportional
- Main stage has LVDT feedback
- Many Same Advantages
  - Robust
  - Reliable

4WRLE - Pilot Operated
High Response
Servo Solenoid Valves
High Response Servo Solenoid - Direct Op

- 4WRREH 6: Push-pull, Servo Solenoid
  - Faster response than 4WRPEH 6
  - 250 Hz @ -90 deg, small signal
  - Nearly as fast as 4WS2EM6 servo
- Sleeve/spool assembly
- Nominal Flow 2 to 40 LPM @ 70 bar $\Delta p$
Servo Solenoid Valves

High Response Servo Solenoid - Direct Op

- Failsafe of spool is not defined
  - Spring centers, but not to a failsafe condition
- 12-Pin Onboard Electronics
  - Enable input
  - Fault output
- Makes a great pilot valve

4WRREH6
Servo Solenoid Valves

High Response Servo Solenoid - Pilot Op

- 4WRVE higher dynamics
  - Pilot 4WRREH 6
  - Main Stage Same as 4WRL

Size 10

\[ p_{\text{syst.}} = 100 \text{ bar} \]

- ± 100 % → 42 Hz Freq.
- ± 5 % → 79 Hz \( \varphi \)
- ± 1 % → 103 Hz \(-90^\circ\)

\[ \pm 100 \% \quad =12 \text{ ms} \]

\[ =200 \]

\[ =20 \]

\[ =10 \]

\[ =3 \text{ dB} \]

4WRVE
Servo Solenoid Valves

High Response Servo Solenoid - Pilot Op

- 12-pin Elec. Connector
- Higher performance
- Sizes 10 to 27 Only
- Main stage like 4WRLE
- No Failsafe Position (Center main spool with Z4WE6 under pilot)
- Linear V-spool characteristic available
- Robust OBE
Servo Valves Basics
Servo Valves

4WS2EM Servos

- Servo Valve always has a Sleeve and Spool in Main Stage
- Servo Torque Motor and Orifices Control Pressure Balance to Position Main Spool
- Small Signal Response @ -90 degrees = 200 to 300 Hz
Servo Valves

4WSE3E (16,25, 32) Servo

- Flows to 1000 Lpm at 70 bar $\Delta p$
- Sleeve/Spool in main stage
- Cast body reduces weight & cost
- Long life with HFC-water glycol, at high pressures
- Small Signal Response 100 to 140 Hz @ -90 degrees

4WSE3
RE29620, RE29621, RE29622
Proportional Valves and High Response Valves

- So Many Proportional and Servo Valves
- Where do I begin?
Considerations for Basic Applications

- Most Important Issues Are
  - Flow Requirement (Easy to Define)
    - Cycle Time or Desired Actuator Speed
    - Limits by Pump Flow, HP, and Budget
  - Dynamic Performance
    - Acceleration
    - Repeatable Deceleration
    - Fast and Accurate cycle (Productivity)
    - High performance requires better valves
Closed Loop

RE 08200 Position Control - Engineering Tool

- Valve Matrix & Project Worksheet (suitable for Hyvos simulation)

Position-controlled actuators with proportional directional valve and external closed-loop control electronics

Engineering aid
## Valve Selection

### Matrix of proportional directional valves

<table>
<thead>
<tr>
<th>Valve model</th>
<th>Nominal flow (l/min)</th>
<th>Nominal P (bar)</th>
<th>Data sheet RE..</th>
<th>Overlap compensation (w/ E, P, E)</th>
<th>Valve dynamics (natural frequency)</th>
<th>Typical application²</th>
<th>Open control loop</th>
<th>Closed-loop position control</th>
<th>Closed-loop pressure control</th>
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<td>4WRPE(H)</td>
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Amplifiers Basics for Proportional Valves
Amplifiers

Amplifier Features

- **Ramp Times**
  - Single ramp controls acceleration and deceleration
  - Ramp Up / Ramp Down control acceleration and deceleration
  - Quadrant ramps change all 4 quadrants independently
Amplifier Features

- **Presets**
  - Preset Pots (w1-w4) set internal speed commands
  - Call-ups (Solid state relay) are discrete inputs
Amplifier Adjustments

- **Null (Zero)**
  - Offsets spool
    - Determines starting point at minimum command
    - Corrects for other offsets
    - Set Null before Gain

- **Gain**
  - Gain = Output / Input
  - Normally used to limit maximum valve stroke at full command
Amplifiers

Spool Overlap

- E, W-spools have ±10% to ±20% overlap, mechanical deadband
- Overlap Compensation can reduce deadband to ±3% to ±5%
Amplifiers

Adjustments for Spool

- **Step Spool Compensation**
  - Spool stays centered (FS) at very small commands
  - Increasing small command, spool jumps to edge of opening

- **Zero** (P3, P6) Small flow set at 8% command

- **Gain** (P2, P5), factory set at 80% command
  - Separate gain adjustment is best for differential cylinders
Amplifiers

Amplifier Adjustments

- **Proportional Spool Overlap Compensation**
  - S+ and S- spool opening point
  - 0 to ±2% command proportionally moves spool within overlap zone
  - Best for fine position control applications with E-spool and more advanced controller

- **Gain**
  - Maximum output set by Gw+ and Gw-
Amplifiers

Characteristic Curve Generator

- Linearizes valve output
- Normally fixed design for specific valve types
Dither

- Dither frequency is usually selected to minimize static friction, improve hysteresis
- Low dither frequency better for pumps (low dynamic systems) or where silting is problematic
- Servo valve amplifiers add Dither (AC sine wave) directly to the normal DC output current.
  - Magnitude is low, perhaps 30-50 mV_{p-p}.
  - Frequency is higher than valve, usually 300 to 400 Hz
- Dithering a proportional solenoid generates considerable heat, so high power amplifiers use Pulse Width Modulation
Amplifiers

**Pulse Width Modulation**

- PWM adjusts the average current output to a proportional solenoid by switching a fixed DC voltage on-off, by with a dither circuit
- On vs. Off time varies, within a fixed cycle or period
- PWM is more efficient
- PWM can minimize hysteresis like dither, at 100 Hz to 350 Hz
- Normally a factory setting, but some amplifiers permit user adjustment
Amplifiers

Amplifier Format

- Different styles for application requirements
  - Modules (rail mount)
  - Plug Amplifiers
  - On-Board Electronics
  - Euro Cards (card holder)
## Amplifier Overview RE29012-V

### Proportional pressure control valves
- Direct operated, subplate mounting
- Proportional pressure relief valves

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### Direct operated, block installation

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### Pilot operated, subplate mounting

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Amplifiers

Card Holders

- Confirm edge connector amplifier data sheet matches
  - 32D, 32F, 48F, 64G
Tester for On-Board Electronic Valves

- VT-VETSY-1-1X/1-2-1-1-0/USA
  - R978050422
- Includes 24vdc power supply with US power cord, 2 cables for 7-pin, servo adapter, VET valve tester
Control Valves and Systems
Closed Loop Applications

Closed Loop
Moving to Closed Loop

Closed Loop Structure

- Closed Loop means automatic regulation of
  - Position
  - Force
  - Pressure
  - Velocity
  - Etc...

- Constant correction occurs from error generated
- Every Closed Loop system has Feedback
Closed Loop

Hydraulic Response of Cylinder

- Closed Loop Hydraulic Response Could Be Tested
- \( f_h = \text{Number of Oscillations per Second} \)
- \( T = \text{Time for one cycle (sec)} \)
- Note how this does not include the Control Valve
- Amplitude of oscillation decreases due to Damping (resistance, friction)

\[ f_h = \frac{1}{T} \]
Closed Loop

Modeling a Cylinder

- Calculating a system response for closed loop depends on control valve and hydraulic actuator
  - Hydraulic Natural Frequency $f_h$ (simplified mass-spring model)
    - $C$: Spring Constant
    - $m$: Moving Mass

\[
f_h = \frac{\sqrt{C}}{2\pi m}
\]

Hydraulic Natural Frequency
Closed Loop

Modeling a Cylinder

- Spring Constant $C$ (Hooke’s Law)
  
  $$C = \frac{F_x}{\Delta x}$$
  
  Force acting on Spring
  
  Displacement of Spring

  Hydraulic fluid is compressible.

  Static ram moves under load change.

\[ f_h = \sqrt{\frac{C}{m}} \]

\[ f_h = \sqrt{\frac{E A^2}{V_o m}} \]

$f_h = \text{frequency of spring-mass model (hydraulic cylinder)}$

$A = \text{Area of cylinder} \ (\text{each side})$

$p = \text{Pressure}$

$E = \text{Bulk modulus of fluid}$

$\Delta V = \text{Volume change in cylinder}$

$V_o = \text{Volume of trapped fluid, orig.}$

$m = \text{effective mass}$

$2\pi \ \text{radian/sec} = 1 \ Hz$

Results are only approximate
Closed Loop

Modeling a Cylinder

- A simple cylinder model becomes a mass between 2 springs
  - Equal area cylinder has the same Spring Constant on each side
  - Minimum Natural frequency occurs at center of stroke

Calculations get more complicated with a differential cylinder, where there are two different springs
Closed Loop

Modeling a Cylinder

- Is Moving Mass at end cylinder rod? \( m = m_{\text{eff}} \)
- If not, remember inertia of point mass? \( I = m (r)^2 \)
- Moving Mass reflected at rod end can be much higher when levers are involved!

\[
m_{\text{eff}} = m \times \left( \frac{a}{b} \right)^2
\]

Class I lever

\[
m_{\text{eff}} = m \times \left( \frac{a + b}{b} \right)^2
\]

Class III lever
Closed Loop

Modeling a Cylinder and Valve

- Closed loop response $f_o$ depends on valve and cylinder
  - Hydraulic Natural Frequency $f_h$ (simplified as a mass-spring model)
    - $C$: Spring Constant of Fluid under Compression
      (fluid on each side of the piston acts like a spring)
    - $m$: Moving Mass
  - Valve Frequency Response $f_v$ (from data sheet, Bode plot)

$$f_o = \frac{f_v f_h}{(f_v + f_h)}$$

Hydraulic Mass-Spring Model

+ Valve Response
Closed Loop

Axis Worksheet

- Start by defining Customer requirements and application
- Cylinder Parameters
- Cylinder Orientation
- Moving Mass
- Identify levers
- Frictions
Closed Loop

Axis Worksheet

- Piping Parameters
- Supply Pressure
- Opposing Forces or Force Profile

Worksheet for axis sizing and layout

4. Piping
   - Pipe length \( l_1 \)
   - Value: \( \text{mm} \)
   - Pipe length \( l_2 \)
   - Value: \( \text{mm} \)
   - Pipe diameter \( d_1 \)
   - Value: \( \text{mm} \)
   - Pipe diameter \( d_2 \)
   - Value: \( \text{mm} \)

5. Pressure supply
   - System pressure \( p_s \) (at valve)
   - Value: \( \text{bar} \)
   - Tank pressure \( p_t \)
   - Value: \( \text{bar} \)
   - Max. pump flow \( q \)
   - Value: \( \text{l/min} \)

6. Valve
   - Type:

7. Counterforces

\[ F_1 \]

Indication of counterforces \( F_1 \) as a function of position \( s \) or time \( t \).

Enter only the forces which result from the process (do not specify counterweights).

If there are several load cases, base the engineering work on the most critical one.

Do not forget the unit of the force (N or kN)! Use this diagram or an additional page.
Closed Loop

Axis Worksheet

- Command Profile
- Type of Feedback
- Desired Accuracy
- Position vs. Time Diagram
- Desired Velocities
- Acceleration Limits
- Desired Cycle Time
Closed Loop

Hyvos simulation analysis

- For critical designs, use simulation program to confirm proper valve selection and system response.
Position Control – Engineering Tools

Hyvos simulation analysis

- Collect all relevant machine information (Hyvos worksheet)
- Your system design will need this information
- Critical systems can be confirmed by simulation.

HYVOS 7.0
Simulation of valve-controlled cylinder drives
Thank You