Hydraulic Proportional and Closed Loop System Design

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Industrial Valves and Electrohydraulics
Electrohydraulics

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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
Electrohydraulics

4 Main Control Principles

- Force Controlled

Position Controlled Solenoid

Servo Solenoid

Servo Valves
Proportional Force Solenoid

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

- Solenoid force opposed by pressure $P \times A$ (area seat 3)
- Input to amplifier changes solenoid current (output force)
  - 20% input => 20% pressure
  - 80% input => 80% pressure
Proportionals

Proportional Solenoid on a Throttle Valve

- Solenoid force opposed by spring force = rate x displacement
- Spool position is constant, when forces are balanced
- Input (coil current) is directly proportional to output force
  - 40% input => 5% flow (due to spool overlap, deadband)
  - 80% input => 50% flow
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 <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

LVDT Armature Sol. Coil
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
Proportionals

Notch shape determines flow characteristic

- “Square” Cut
- “D” Cut
- “V” Cut

Flow vs. Stroke / Command for each notch shape.
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

145 psi (10 bar)
Flow Rating of Proportional Valves

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

\[
Q_n = cA\sqrt{\Delta P_n}
\]
\[
Q_{req} = cA\sqrt{\Delta P_{real}}
\]

$c =$ orifice flow co-efficient

$A =$ Area of orifice

(same values for both equations)

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

- Estimate Δp 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 Δp, close the your estimated valve Δp
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 \( Q_{\text{valve}} \cdot \Delta p_{\text{valve}} \)
- Bernoulli forces try to center spool at high \( \Delta p_v \)
- Power Limit decreases if flows are unequal
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

![Graph showing pressure in bar vs. volume in L/min](image)

$P \rightarrow A / B \rightarrow T$

oder

$P \rightarrow B / A \rightarrow T$

![Graph showing pressure drop vs. flow rate](image)
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
  - 1% underlap allows housing variation
  - *Only* for closed loop control

- **W-spool**: 2% to 3% open A to T, B to T
  - Primarily for differential cylinders
  - *Only* for open loop applications
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-:

- $P \rightarrow A$: $q_{V_{\text{max}}}$
- $P \rightarrow B$: $q_{V_{\text{max}}}/2$
- $B \rightarrow T$: $q_{V_{\text{max}}}/2$
- $A \rightarrow T$: $q_{V_{\text{max}}}$
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**: for injection molding cylinders
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!
    Extending force = rod area x pressure bore
- **W9-spool**: improved W3 (decel like W8)
- **W4-spool**: 4-position, regen spool
  - Full tonnage below 33% (P-to-A and P-to-B, like W1)
  - Regen above 33% (P-to-A and B blocked, like W3)
Proportionals

Spools with Internal Regen

- **R-spool**: Internal hydraulic regeneration
  - Combines B to P in spool!
  - Blocked center, so cylinder could creep
- **R3-spool**: Internal regen
  - Connects B-to-P path inside housing
  - Center P blocked, A and B to T
- **R5-spool**: Internal regen with 4-position press-regen spool
  - P-to-A full tonnage below 33%
  - Regen above 33% (like R3)
- Internal regen flow can not exceed limits of main valve (lower flow than external regen)
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
- 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 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 on a system operating at 5000 psi, should 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, pressure) may not match your application
- If only given a time, you must know measurement criteria
  - 0 to 100%
  - 10 to 90%
  - 20% to 80%
Proportionals

Bode Diagrams

- Valve frequency response @ -3dB amplitude
- Phase Lag @ -90 degrees

-3 dB

90 Degrees
Phase Lag
Proportionals

Tester for Integrated 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 tester
Servo Solenoid Basics
Servo Solenoid – Direct Operated

- Very Fast Stroke Solenoid
- Directly Positions Spool
- No Flapper/Nozzle
- No Jet-pipes
- No Pilot Leakage
Servo Solenoid – Direct Operated

- Spool and Sleeve Assembly
  - Zero Overlap
  - Accurate
  - Symmetrical
  - Linear
- Normal filtration
- Main sleeve means Nominal Flow @ Δp 70 bar or 1000 psi!
  - 2 to 100 Lpm (size 6 & 10) like a Servo Valve @ 70 bar Δp

4WRPEH - Direct Operated
Servo Solenoid Valves

Nominal Flow Conversion

- Easily convert between
  - Sleeve/Spool rated Nominal Flow @1000 psi $\Delta p$
  - Proportional rated Nominal Flow @ 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
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
**Servo Solenoid Valves**

**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
- Pilot stage has sleeve/spool (4WRPEH)
- Nominal Flow rated at 10 bar $\Delta p$ for pilot operated Servo Solenoid valves
- E, W, V, Q4-spools like proportional
- V-spool at spring-center has 1 to 6% offset P-to-B
- Failsafe of pilot (C3) allows main spool to spring center

4WRLE
RE 29088
RE 29089
Servo Solenoid Valves

Linear Characteristic

- V-Spool with Linear flow characteristic can improve system performance
- Higher P-gain in controller reduces following error
- Easier tuning of close loop application
Servo Solenoid – Pilot Operated

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

High Response
Servo Solenoid Valves
Servo Solenoid Valves

High Response Servo Solenoid - Direct Op

- 4WRREH 6: Push-pull, servo solenoid for faster response than 4WRPEH 6
  - 250 Hz @ -90 deg, small signal
  - Nearly as fast as 4WS2EM6
- 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 position
- 12-Pin Onboard Electronics
  - Enable input
  - Fault output
- Makes a great pilot valve
Servo Solenoid Valves

High Response Servo Solenoid - Pilot Op

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

![4WRVE Graph](image)

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Servo Solenoid Valves

High Response Servo Solenoid - Pilot Op

- 12-pin Elec. Connector
- No Failsafe Position (Center main spool with Z4WE6 under pilot)
- Higher performance
- Sizes 10 to 25 Only
- Linear V-spool characteristic available
- Extremely Reliable OBE
Servo Valves Basics
Servo Valves

Flapper-Nozzle Servo

- Torque Motor
- Electrical coils
- Variable orifices (Nozzle)
- Fixed orifices
- Spool
- Sleeve
- Aproximate clearance is 20 - 25 micron

Hydraulic amplifier

1000 PSI

500 PSI

P
A
T
B
P

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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

Jet Pipe Servo

Not from Bosch Rexroth

- The pressure tube feeds oil to the jet pipe. In the null position the jet pipe sprays oil equally to two recievers (250 micron).

- The torque motor moves the jet pipe making the oil pressure in one reciever greater than the other, Thus causing spool movement.

- Feedback linkage, similar to that of the flapper - nozzle, centers the jet pipe after the spool has moved (1-3% hysteresis).

- There is a zero adjustment on the torque motor.

- There is a zero adjustment on the Main stage of the valve.

- Tank line pressure spikes affect the null.

- Pressure line spikes affect the null.

- Wear occurs on the recievers.

- Internal filter requires cleaning.
Servo Valves

4WSE3E (16,25, 32) Servo

- Flows to 1000 Lpm at 70 bar Δp
- 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 deg

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, Budget
  - **Dynamic Performance**
    - Acceleration
    - Repeatable Deceleration
    - Fast and Accurate (Productivity)
    - Especially in Closed Loop Applications
    - Higher performance normally requires Closed Loop
Amplifiers Basics for Proportional Valves
Amplifiers

Amplifier Format

- Different styles for application requirements
  - Modules (rail mount)
  - Plug-in Euro Cards
  - On-Board Electronics
  - Plug Amplifiers
Amplifiers

Amplifier Functionality

- **Euro Card analog**
  - 4 Presets
  - Analog (10v or 4-20ma)
  - More Ramps
  - Discrete Inputs
  - Status LED
  - Configuration Options

- **Euro Card digital**
  - 16 Presets
  - Software Setup
  - Extended Configuration Options
  - Backup
  - Field bus (optional)

- **Module**
  - Ramp
  - Enable Input
  - Preset
  - Zero Adj
  - Status LED
  - Test Points

- **OBE On-Board Electronics**
  - Analog (10v or 4-20ma)
Amplifiers

Amplifier Configuration Flexibility

Customer Signals

Analog Command

Call-ups

Analog Command

Call-ups

Analog Command

Command

analog

Command

digital
Amplifiers

On-Board Electronics

- Plug & play - No user adjustments required
- Factory set calibration simplifies installation and replacement
Amplifiers

Plug Amplifiers

- Plug amplifiers are only possible with single, force solenoids (like a proportional relief valve)
- M12 electrical connector for simple installation with molded cables
- Low cost
Amplifiers

Euro Card Amplifiers

- More features included
- Match edge connector to correct card holder
Amplifiers

Card Holders

- Confirm edge connector form required on valve data sheet
  - 32D, 32F, 48F, 64G
Amplifiers

Jump Compensation in Amplifier

- E, W-spool have ±10% to ±20% overlap
- Jump Compensation reduces this deadband to about ±3 to ±5%
Amplifiers

Characteristic Curve Generator

- Linearizes valve output
- Optimized for specific valve type
Amplifiers

Pulse Width Modulation

- PWM adjusts the average output power to a DC prop. solenoid by switching a fixed DC voltage on-off
- On vs. Off time varies, within a fixed period
- PWM frequency is typically 100 Hz to 350 Hz, to minimize hysteresis
- Frequency must be high enough, so output is not disturbed
- Normally a factory setting, but some amplifiers permit user adjustment
- PWM is efficient, reducing heat generation
Dither

- Dither is used to create a PWM signal on proportional amplifiers
- Servo valve amplifiers do not require PWM, so a dither signal (sine wave) adds to the desired DC output
- Dither frequency is selected to minimize static friction, improving hysteresis
Amplifiers

Amplifier Adjustments

- **Gain**
  - Changes input vs. output ratio
  - Limits maximum output

- **Zero (Null)**
  - Offsets spool into a “0” hydraulic condition due to manufacturing tolerances
Amplifiers

Amplifier Adjustments

- **Ramp Time**
  - Single ramp controls acceleration and deceleration
  - Dual ramps control acceleration (ramp up) separate from deceleration (ramp down)
  - Quadrant ramps change all 4 quadrants independently

![Diagram of Amplifier Adjustments](chart.png)
## Amplifiers

### Amplifier Overview RE29012-V

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<td>30523</td>
<td>VT 3002-1.2X/64G</td>
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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

![Diagram of Closed Loop Structure]

Σ

Controller

Command

Amplifier

Valve

Actuator

Feedback
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 Matrix

### 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</th>
<th>Overlap compensation</th>
<th>Valve dynamics</th>
<th>Typical application ²</th>
<th>Open control loop</th>
<th>Closed-loop position control</th>
<th>Closed-loop pressure control</th>
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<tr>
<td>4WRA(E)</td>
<td>Size 6: 7, 15, 30</td>
<td>10</td>
<td>29035</td>
<td>Yes</td>
<td>Very low</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td></td>
<td>Size 10: 30, 60</td>
<td></td>
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<tr>
<td>4WRP(E)</td>
<td>Size 6: 8, 18, 32</td>
<td>10</td>
<td>29022 29025</td>
<td>Yes</td>
<td>Low</td>
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<td>✓</td>
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<td></td>
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<td>29081</td>
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<td>Medium</td>
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<td>✓</td>
<td>✓</td>
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<td>29067</td>
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<td>High</td>
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<td>Size 10: 25, 50, 80</td>
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<td>29035 29037</td>
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<td>40 Size 10: 50, 100</td>
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<td>4WS(E)²E</td>
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<td>29554 29553</td>
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<td>✓</td>
<td>✓</td>
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<td>Size 16: 100, 150</td>
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<td>Size 32: 360, 520</td>
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<td></td>
<td>Size 52: 1000</td>
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</table>
Hydraulic Response of Cylinder

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

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

Modeling a Cylinder

- Closed loop performance 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

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

Modeling a Cylinder System

- Spring Constant $C$ (Hooke’s Law)

\[
C = \frac{\Delta x}{\Delta V} \quad \text{Displacement of Spring}
\]

\[
F_x = \text{Force acting on Spring}
\]

\[
\Delta x = \frac{\Delta V}{A}
\]

\[
F_x = pA
\]

\[
p = \frac{\Delta V}{V_o} E
\]

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

$f_h$ = frequency of spring-mass model (hydraulic cylinder)

$\Delta V$ = Volume change in cylinder

$A$ = Area of cylinder (each side)

$E$ = Bulk modulus of fluid

$V_o$ = Volume of trapped fluid

$m$ = effective mass

$2\pi$ radian/sec = 1 Hz

Calculations can get complicated

Results are only approximate
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)
    - $C$: SpringConstant 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)

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

Axis Worksheet

- Define Customer and Application goals
- Cylinder Parameters
- Cylinder Orientation
- Moving Mass
- Frictions
Closed Loop

Axis Worksheet

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

Worksheet for axis sizing and layout

4. Piping

<table>
<thead>
<tr>
<th>Pipe length $l_1$</th>
<th>Value</th>
<th>Unit</th>
<th>Comment (min, max, range, ca., etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l_3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe diameter $d_1$</td>
<td></td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>$d_2$</td>
<td></td>
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</table>

5. Pressure supply

<table>
<thead>
<tr>
<th>System pressure $p_1$ (at valve)</th>
<th>Value</th>
<th>Unit</th>
<th>Comment (min, max, range, ca., etc.)</th>
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<tbody>
<tr>
<td>Tank pressure $p_2$</td>
<td></td>
<td>bar</td>
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<tr>
<td>Max. pump flow $q$</td>
<td></td>
<td>l/min</td>
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</table>

6. Valve

Type:

7. Counterforces

$F_1$

Indication of counterforces $F_1$ as a function of position $x$ or time $t$.

Enter only the forces, which result from the process (do not specify counte

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 to confirm proper valve selection and system response
Hyvos simulation analysis

- Collect all relevant machine information (Hyvos worksheet or RE 08200)
- Your system design should already use much of this information
- Critical systems can be confirmed by simulation.
Other Updates
**Update**

**Hydraulic Training**

[www.boschrexroth-us.com/hydtraining](http://www.boschrexroth-us.com/hydtraining)

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### Principles of Hydraulics (POH)

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### Maintenance, Repair & Set-up of Mobile Hydraulic Systems (MRSM)

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### Proportional and Servo Circuit Design (PSD)

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### Pump and Controls, Open Loop (PCO)

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### Pump and Controls, Closed Loop (PCC)

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### Design Considerations for Industrial Hydraulic Systems (DCH)

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### Electronic Controls for Hydraulic Systems (ECH)

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### Design Considerations for Mobile Hydraulic Systems (DCHM)

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