Programmable Valves Enable Both Precision Motion Control and Energy Saving

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Outline

- Development of Programmable Valves
- Control of Programmable Valves
- On-board Modeling of Valve Flow Mapping
- Programmable Valves Bypass Sandwiched Deadband Problem
- Summary

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E/H precision motion control system

Objective:

- Performance
- Energy efficiency
- Cost

Energy usage:

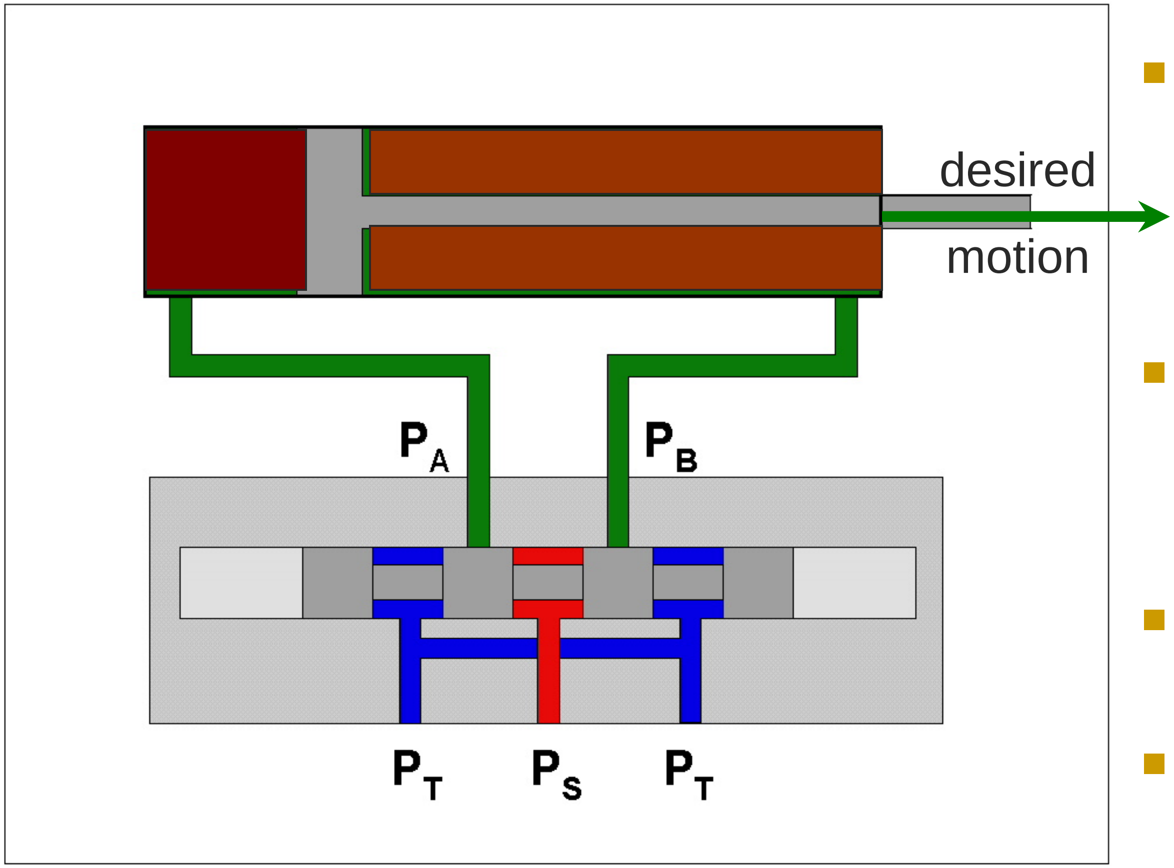
$$E = \int_{t_0}^{t_1} P_s(\tau) Q_s(\tau) d\tau$$

To reduce energy usage:

- Reduce the supply pressure $P_s(t)$
- Reduce the pump flow rate $Q_s(t)$

To reduce supply pressure …

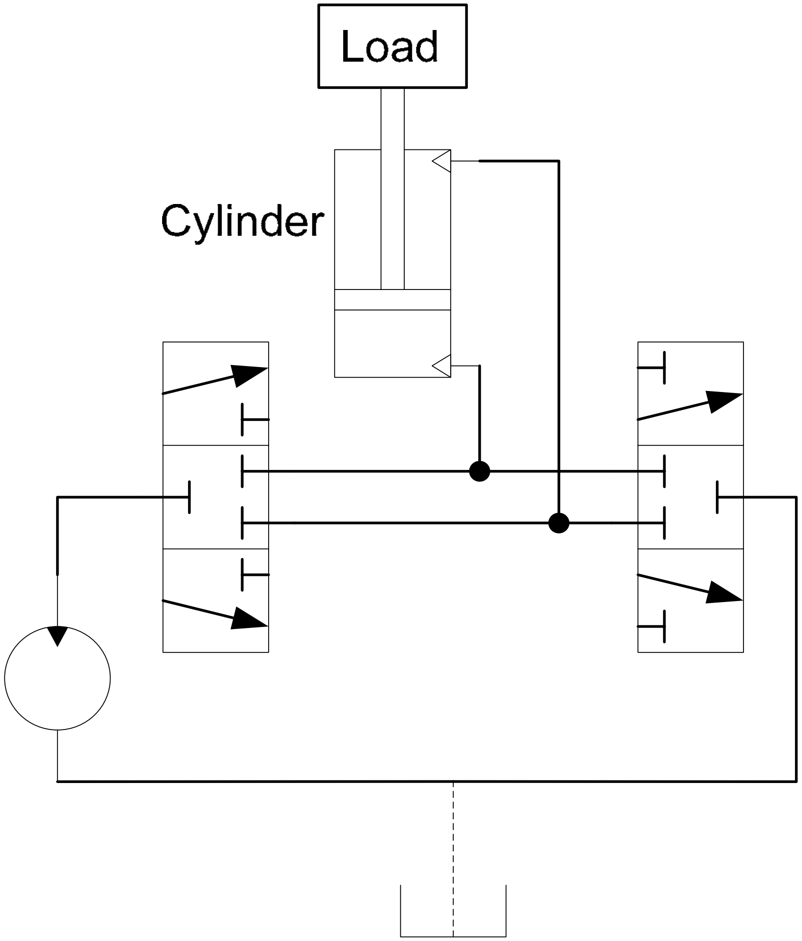
Must break the mechanical linkage between the meter-in and meter –out orifices



- Meter-in and meter-out orifice areas are coupled in 4-way directional control valves
- Cannot control all cylinder states (pressures of both chambers)
- Deadband for PDC valves
- Leakage for servo valves

Arne Jansson and Jan-Ove Palmberg, "Separate controls of meter-in and meter-out orifices in mobile hydraulic systems", SAE Transactions, Vol.99, Sect 2, pp377-383, 1990

Dual-Valve Meter-in and Meter-out



- Two valves:

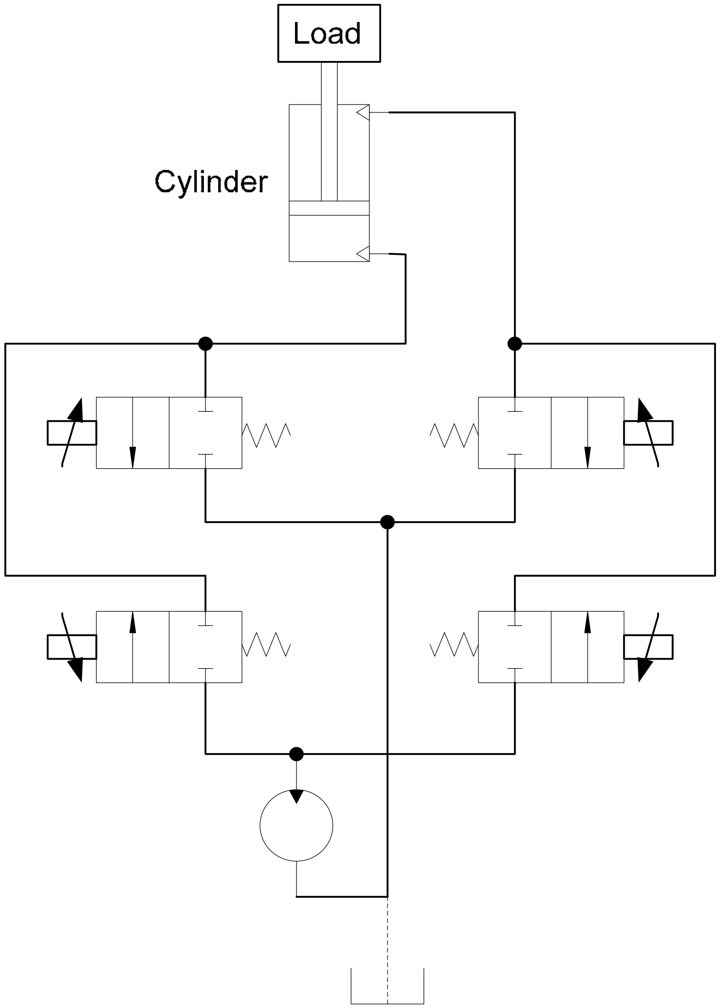
  Patented by:

  J. Ardema, 1996

  Uses two directional control valves to meter flows

J.A. Aardema, Caterpillar Inc., "Hydraulic circuit having dual electrohydraulic control valves", United States Patent 5,568,759, 1996

Four-Valve Meter-in and Meter-out



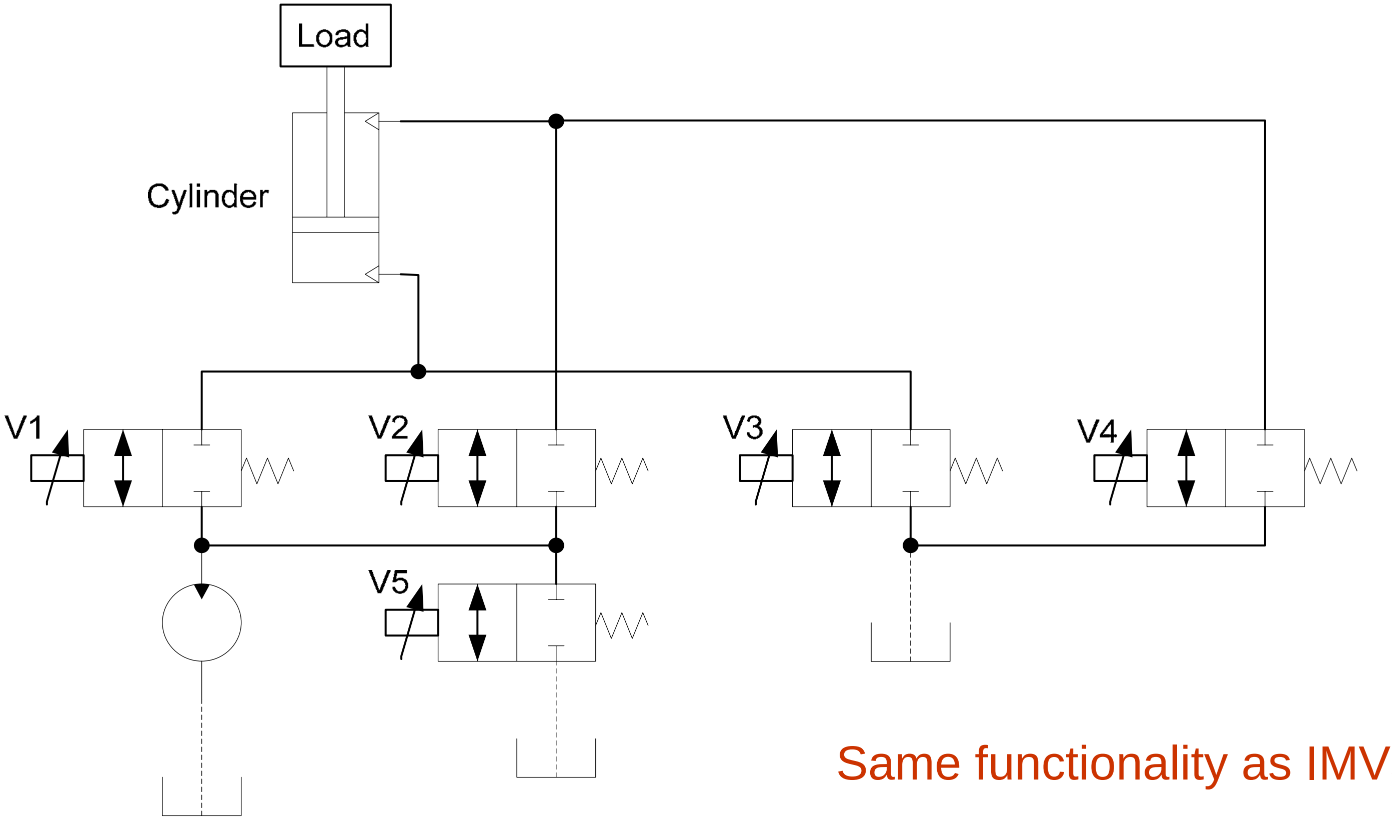
- Four valves

J. Ardema and D. Koehler

Uses four poppet valves to independently control meter-in and meter-out flows

Aardema and Koehler, Caterpillar Inc., "System and method for controlling an independent metering valve", United States Patent 5,947,140, 1999

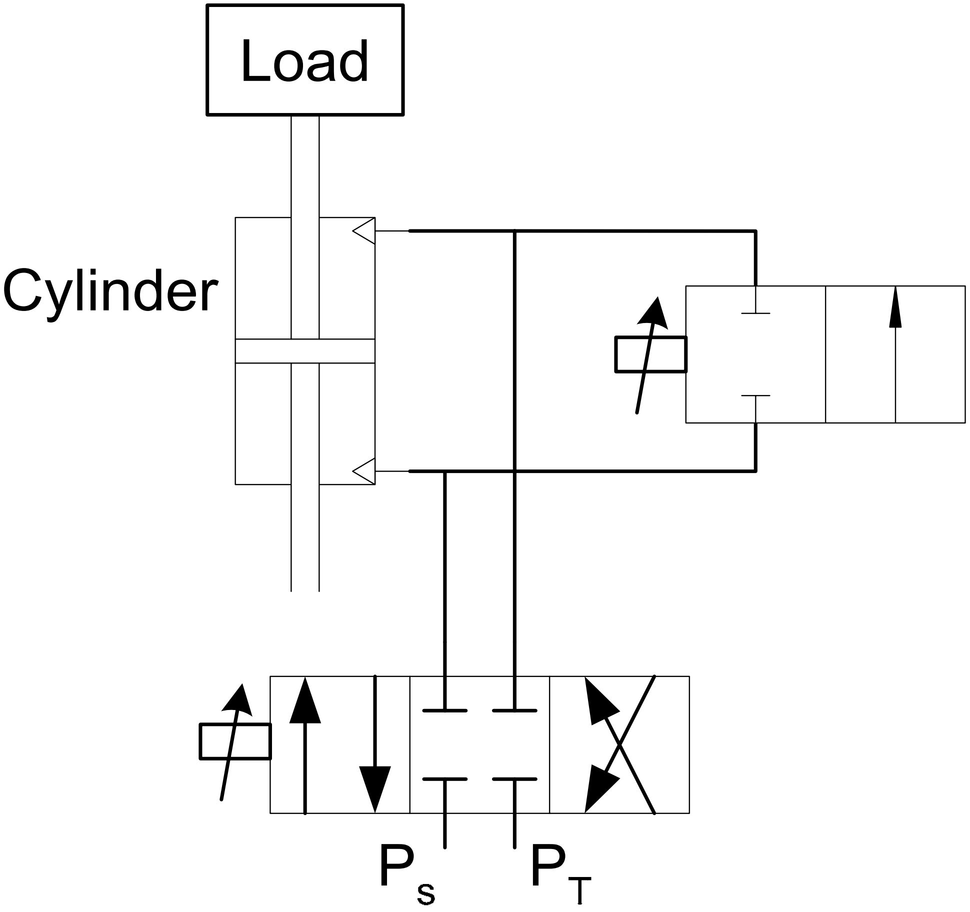
Five-Valve Meter-in and Meter-out



Same functionality as IMVs only

Ruth Book and Carrol E. Goering , "Programmable electrohydraulic valve",
SAE Vol. 1, No. 2, pp28-34, 1999

Use Regeneration Flow



- Regeneration Valve

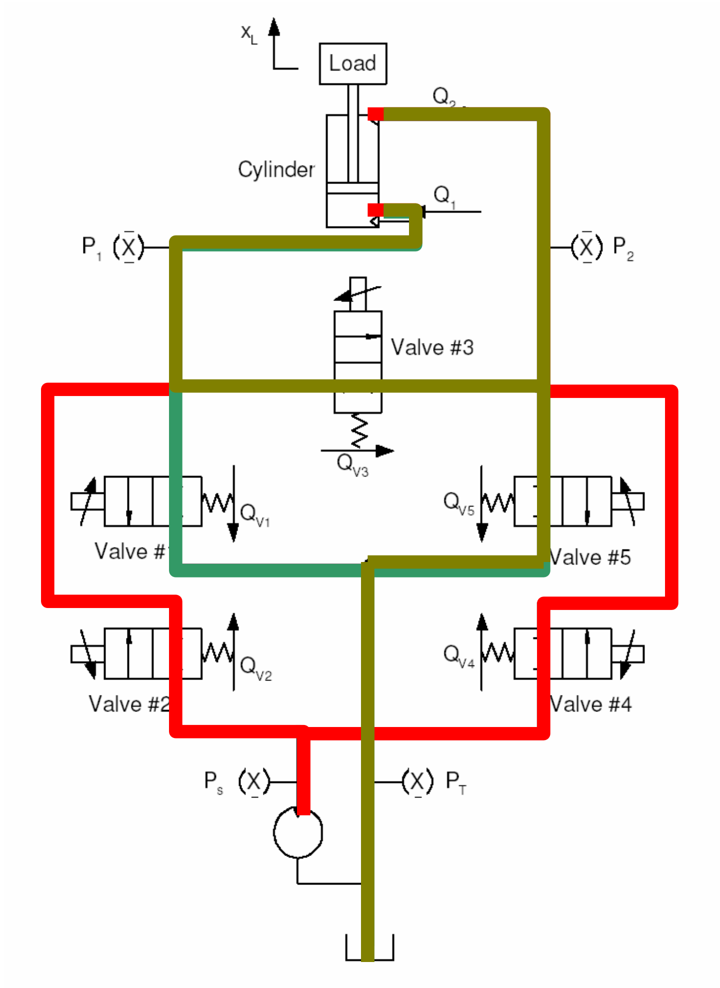
Patented by:

K. Garnjost, 1989.

Uses one additional valve to provide regenerative flow for energy saving but cannot control both chambers independently

Garnjost, K. D., "Energy-conserving regenerative-flow valves for hydraulic servomoters", United States Patent 4,840,111, 1989

Energy Saving Programmable Valves



Purdue Energy Saving Programmable Valves

Developed by:
Bin Yao, 2000

- Take advantages of four valve configuration to control meter-in/meter-out flows independently for precise cylinder positioning
- Use an additional valve to precisely control cross-port flow (or regenerative flow) for energy saving
- Overcome the sandwiched deadband control problem of conventional PDC valves through the use of cheap but fast acting cartridge valves

Programmable Valves Advantages

- Fully decoupled meter-in and meter-out flow
- Fully controlled true cross port regeneration flow
- More flexibility and controllability
- Completely solve/bypass the sandwiched deadband problem of EH systems controlled by closed-center valves
- Virtually eliminate leakage
- Faster response than PDC valves
- Low cost
- Low maintenance cost

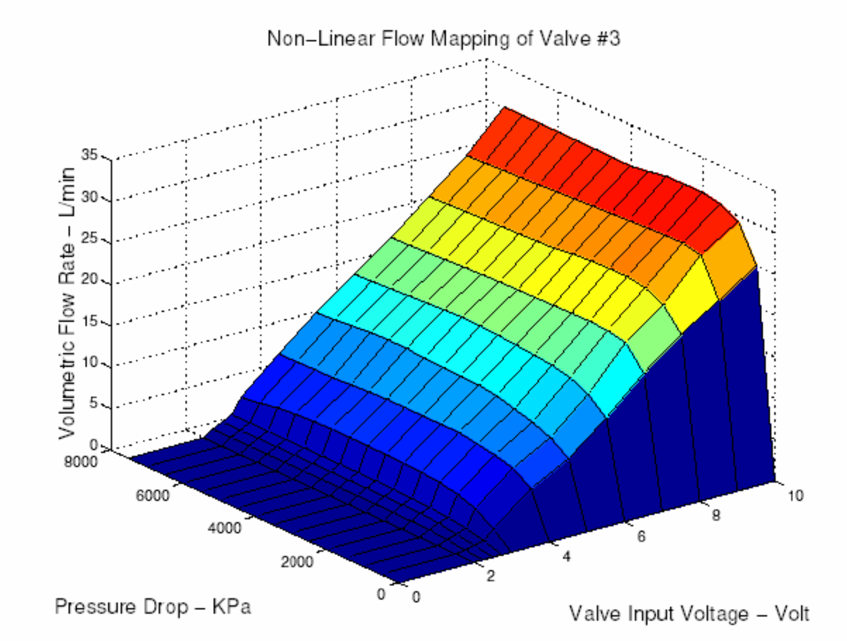
Outline

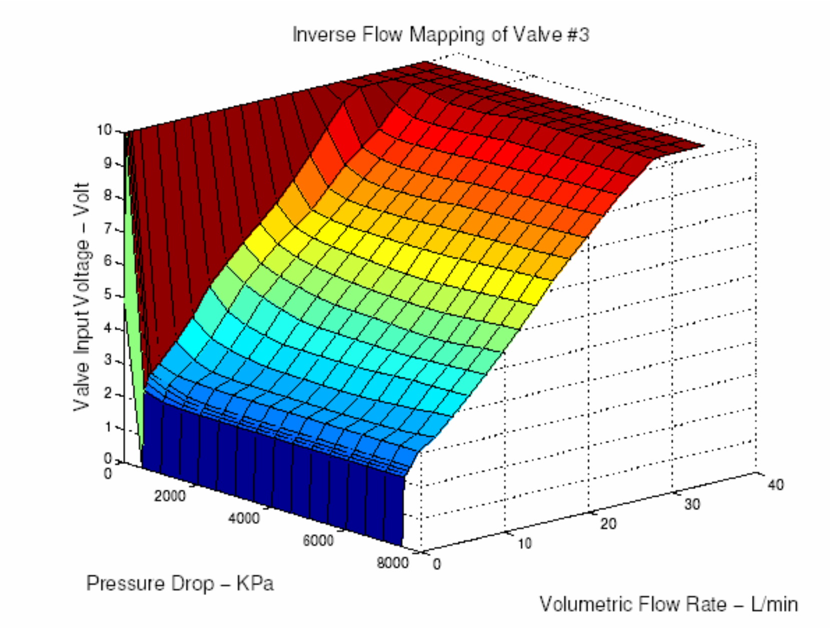
- Development of Programmable Valves
- Control of Programmable Valves
  - Challenges
  - Two-level control system
  - Comparative experimental results
- On-board Modeling of Valve Flow Mapping
- Programmable Valves Bypass Sandwiched Deadband Problem
- Summary

Challenges

- Multi-input dual-objective system
- Lack for accurate mathematical model of cartridge valves
- Coordination of the five cartridge valves
- Highly nonlinear hydraulic dynamics
- Large parameter variations
- Uncertain nonlinearities such as external disturbances, flow leakage and seal frictions

Nonlinear Valve Flow Mapping

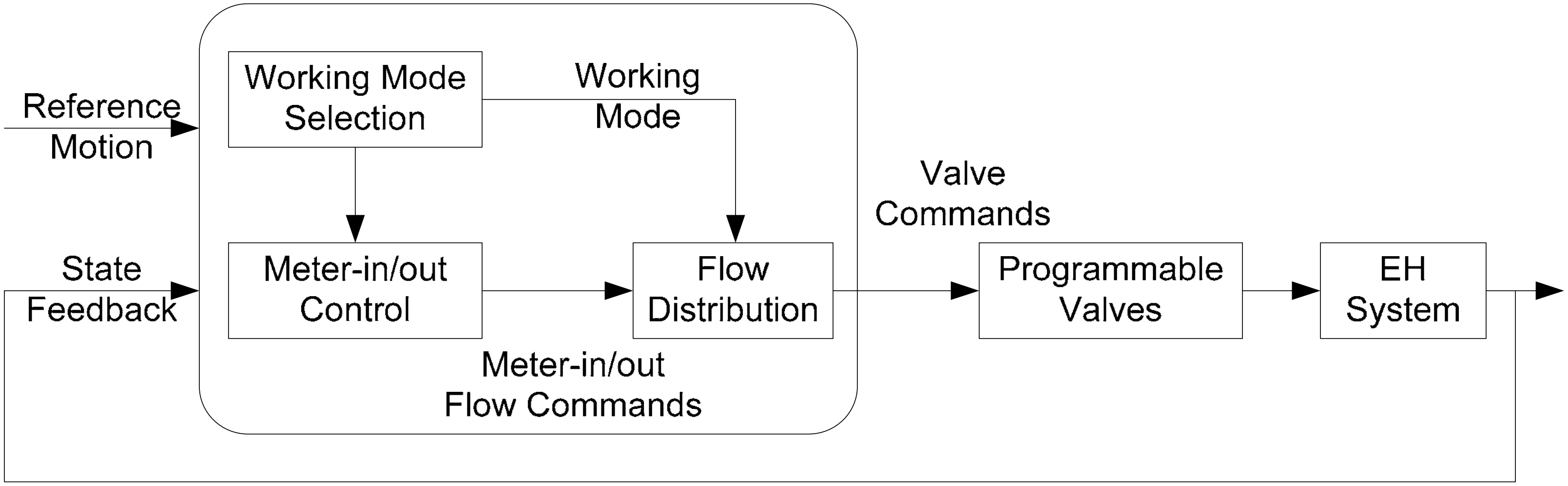

Non–Linear Flow Mapping of Valve #3


Inverse Flow Mapping of Valve #3

$$Q_{vi} = f_{vi}(\Delta P_{vi}, u_{vi})$$

$$u_{vi} = f_{vi}^{-1}(\Delta P_{vi}, Q_{vi})$$

Control of Programmable Valves



Schematic of the two-level Control System

Two-level Control System

- Task level (Working Mode Selection)
  - Proper hydraulic circuitry
  - Optimal valve configuration for maximal energy saving
- Valve level (ARC Control)
  - Nonlinear model based design to take the system nonlinearities into account explicitly
  - Adaptive model compensation to reduce the effects of parametric uncertainties and disturbances
  - Robust feedback to guarantee stability

Working Mode Selection --- Tracking Task

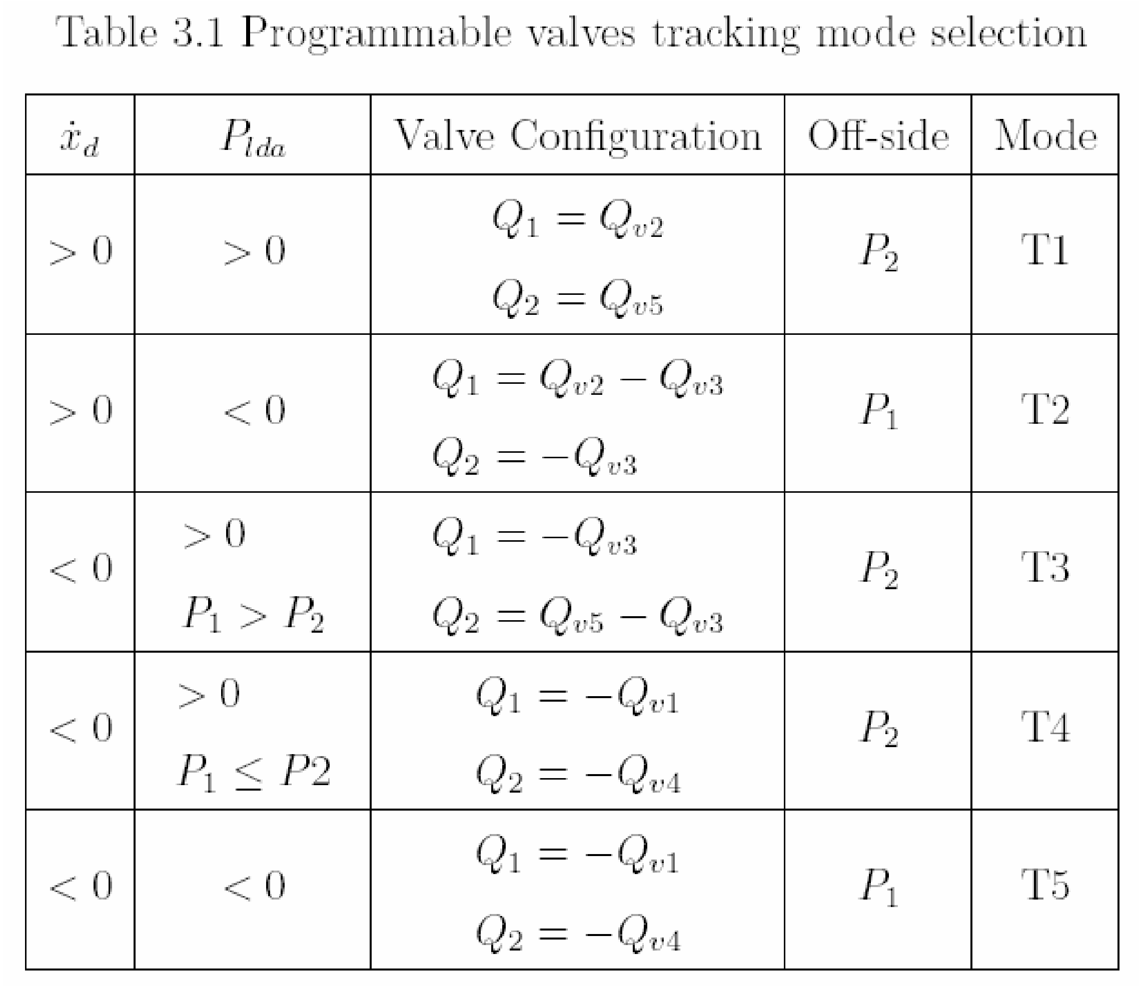


Table 3.1 Programmable valves tracking mode selection

$\dot{x}_d$	P_{lda}	Valve Configuration	Off-side	Mode
> 0	> 0	$Q_1 = Q_{v2}$ $Q_2 = Q_{v5}$	P_2	T1
> 0	< 0	$Q_1 = Q_{v2} - Q_{v3}$ $Q_2 = -Q_{v3}$	P_1	T2
< 0	> 0 $P_1 > P_2$	$Q_1 = -Q_{v3}$ $Q_2 = Q_{v5} - Q_{v3}$	P_2	T3
< 0	> 0 $P_1 \leq P2$	$Q_1 = -Q_{v1}$ $Q_2 = -Q_{v4}$	P_2	T4
< 0	< 0	$Q_1 = -Q_{v1}$ $Q_2 = -Q_{v4}$	P_1	T5

Working Mode Selection --- Regulation Task

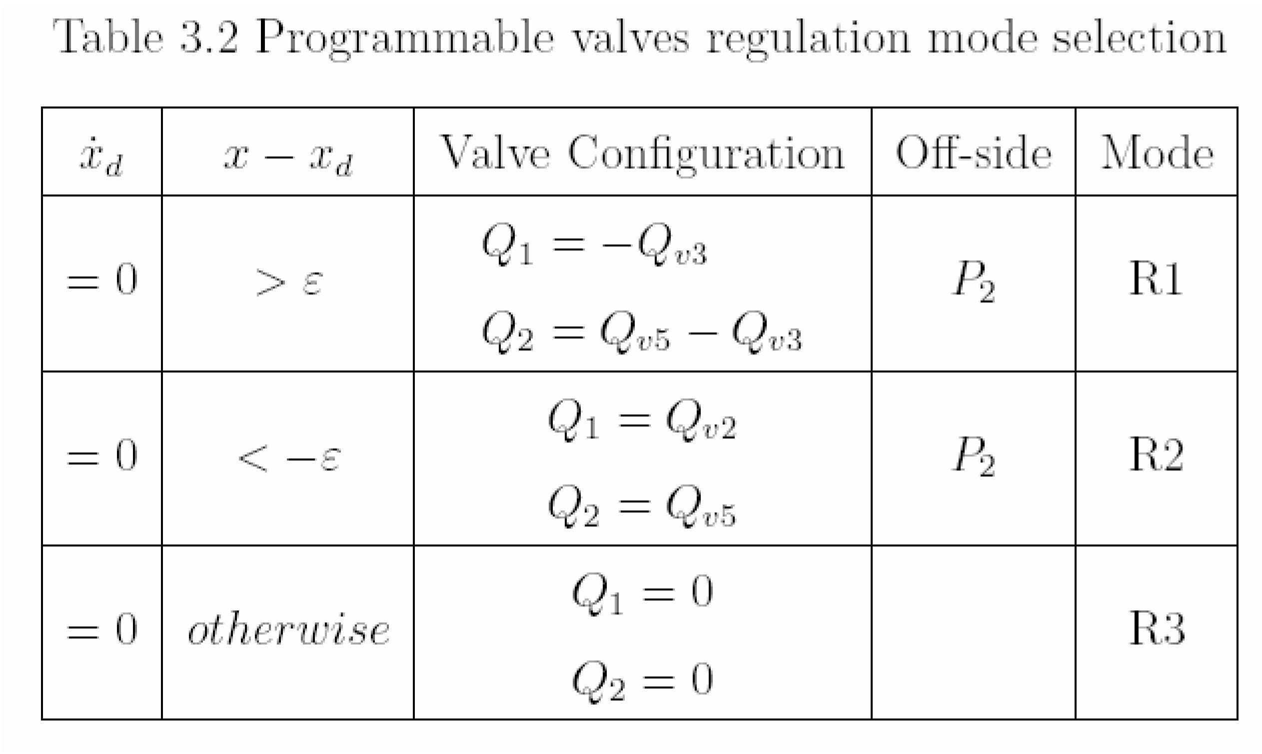
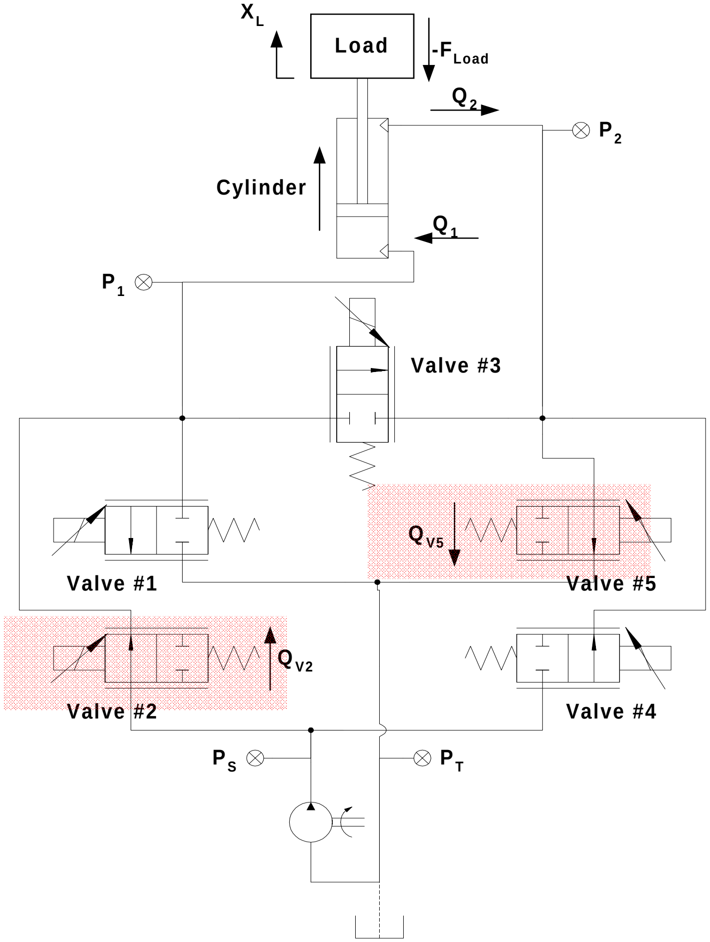


Table 3.2 Programmable valves regulation mode selection

$\dot{x}_d$	$x - x_d$	Valve Configuration	Off-side	Mode
$= 0$	$> \varepsilon$	$Q_1 = -Q_{v3}$ $Q_2 = Q_{v5} - Q_{v3}$	P_2	R1
$= 0$	$< -\varepsilon$	$Q_1 = Q_{v2}$ $Q_2 = Q_{v5}$	P_2	R2
$= 0$	$otherwise$	$Q_1 = 0$ $Q_2 = 0$		R3



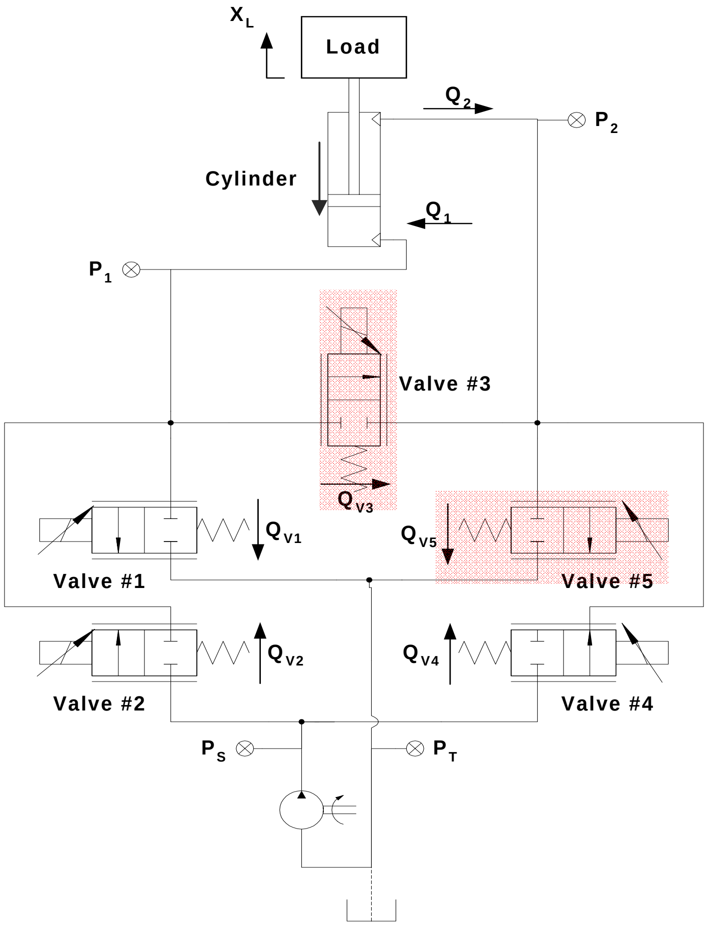
)esired Cylinder
/elocity > 0

)esired Cylinder
-orce >0

Jses Valve #2 and
/alve #5

/laintain P2 as
.ow as Possible

Mode T3



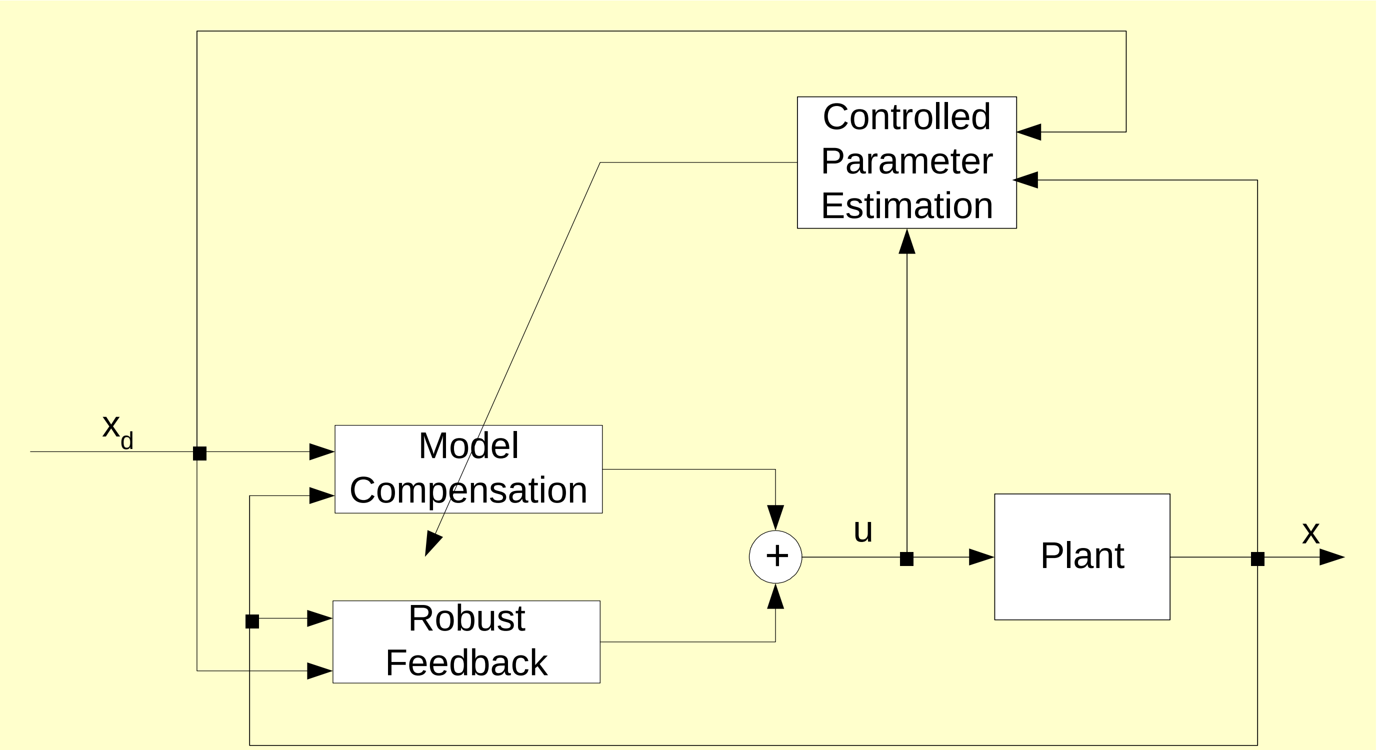
- Desired Cylinder Velocity < 0
- Desired Cylinder Force >0
- P1 >P2

- Uses Valve #3 and Valve #5
- Maintain P2 as Low as Possible

Valve-Level Control --- Adaptive Robust Controller

- Nonlinear model based controller design
- Compensate known nonlinearities and disturbances
- Guarantee stability and prescribed transient performance in the presence of unmodeled uncertainties and external disturbances
- Achieve asymptotic stability in the absence of disturbance

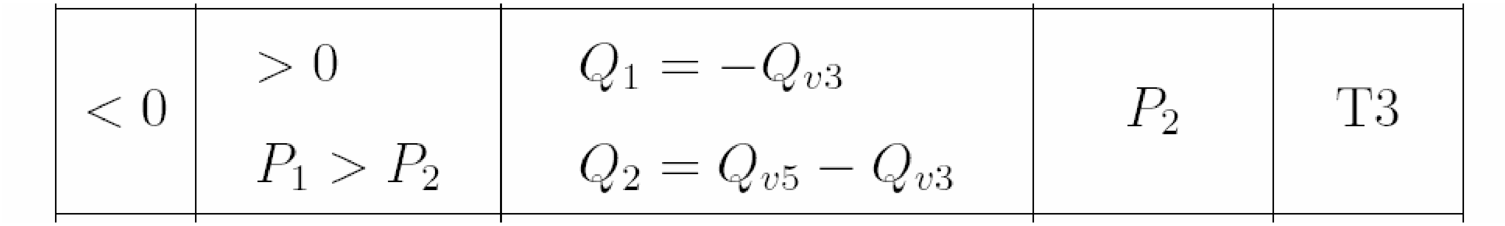
Adaptive Robust Control Structure



Valve-Level Control

- Off-side pressure regulator
  - Maintain the off-side chamber at a constant low pressure
- Working-side motion controller
  - Control the working-side pressure so that the desired trajectory is followed as close as possible
- Flow distribution
  - convert flow commands to valve voltage input signals

Flow distribution



< 0	> 0 $P_1 > P_2$	$Q_1 = -Q_{v3}$ $Q_2 = Q_{v5} - Q_{v3}$	P_2	T3

⇨

$$Q_{v1} = 0$$

$$Q_{v2} = 0$$

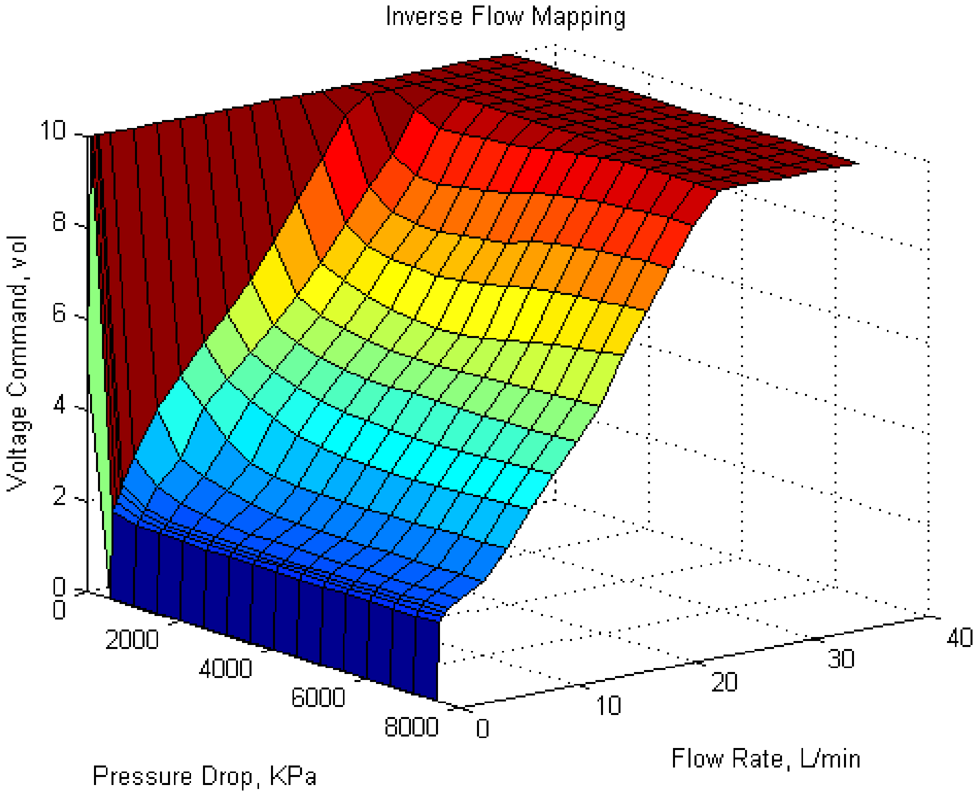
$$Q_{v4} = 0$$

$$Q_{v3} = -Q_{1md}$$

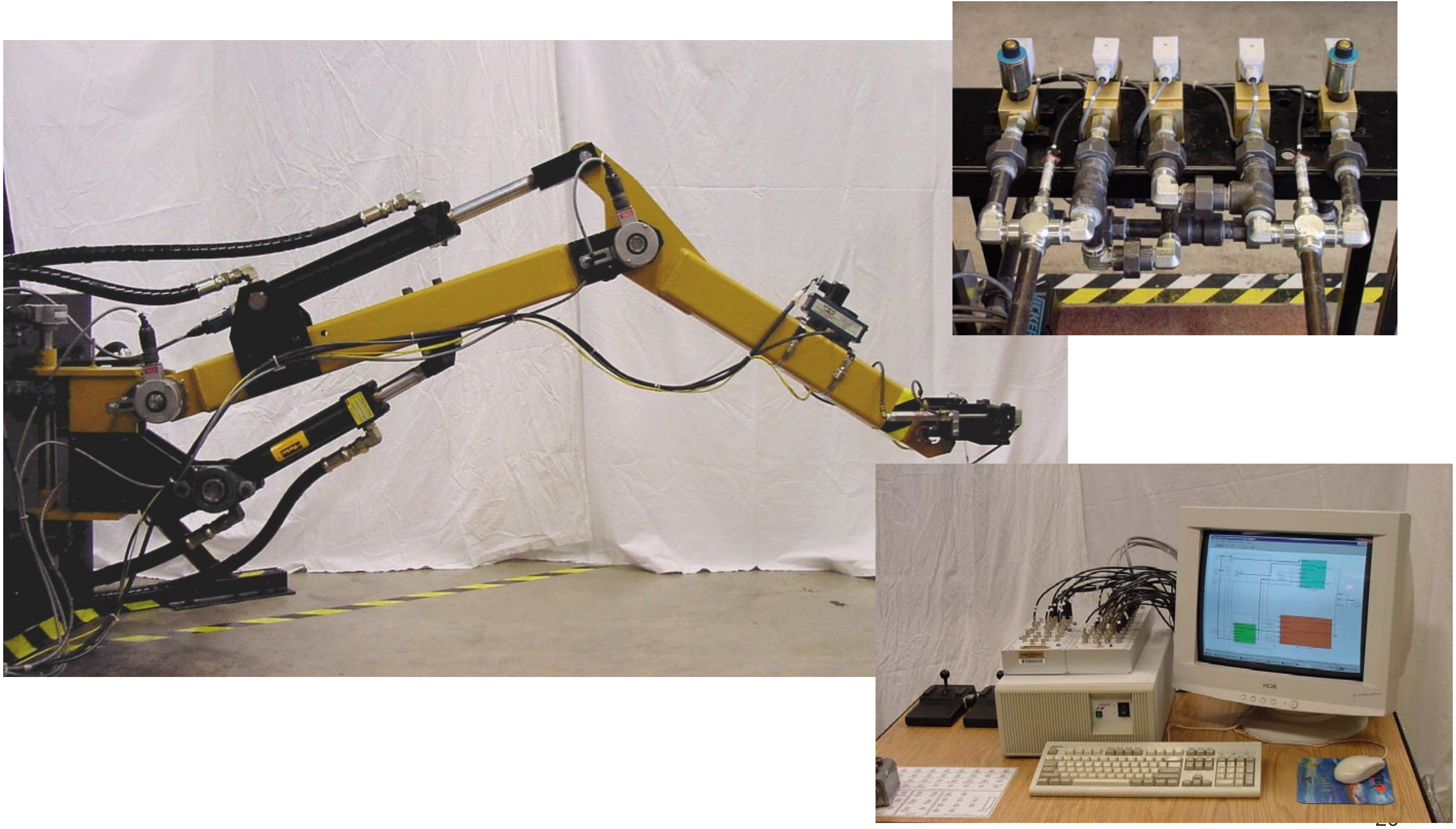
$$Q_{v5} = Q_{2md} + Q_{v3} = Q_{2md} - Q_{1md}$$

Flow distribution

- Inverse flow mapping to convert flow commands to valve voltages input signals

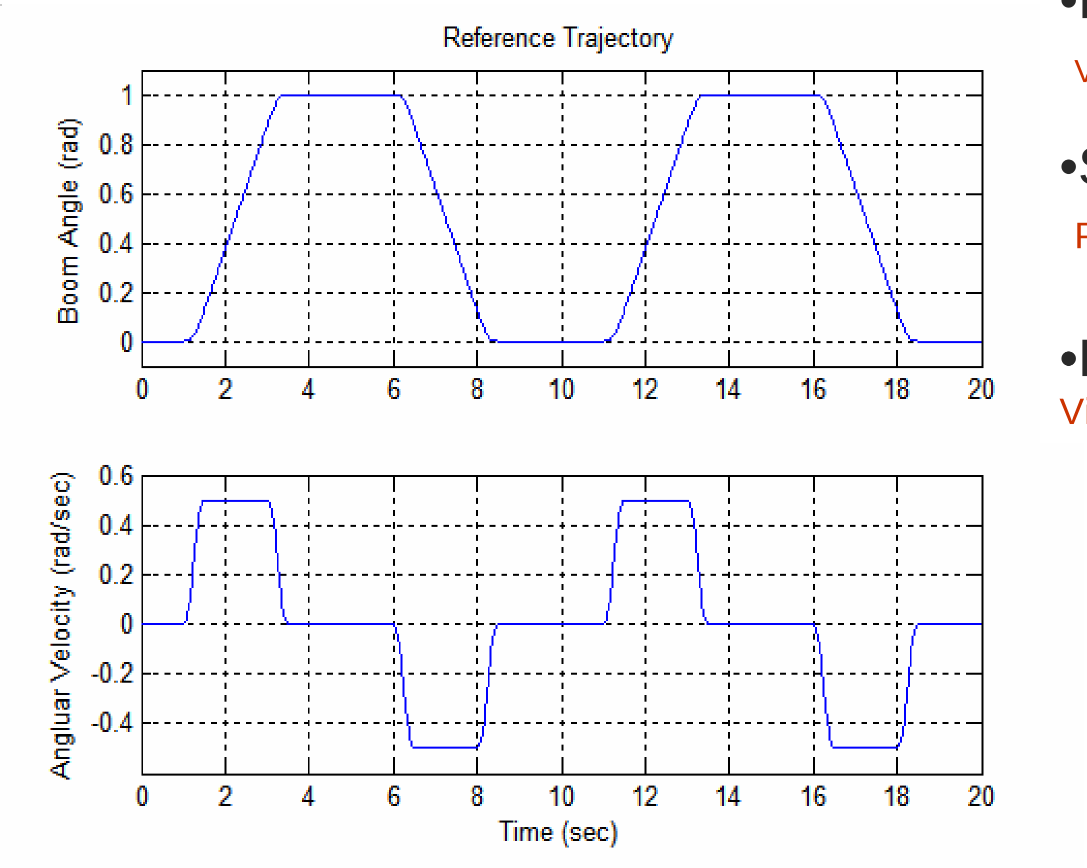


Experimental Setup



Smooth Working Mode Switching

Comparative Experiment



- •PDC valve

  Vickers KBFDG4V-5-2C50N-Z-PE7-H7-10

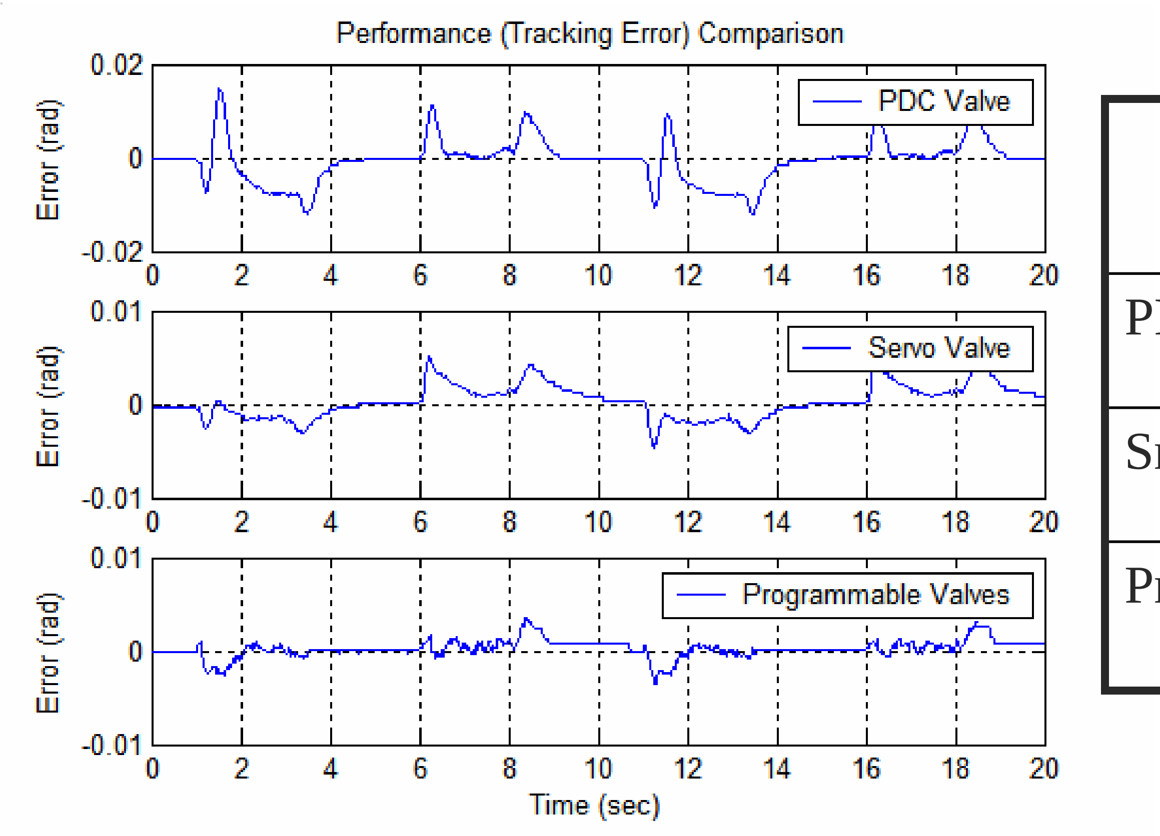
- •Servo valve

  Parker BD760AAAN10

- •Programmable valves

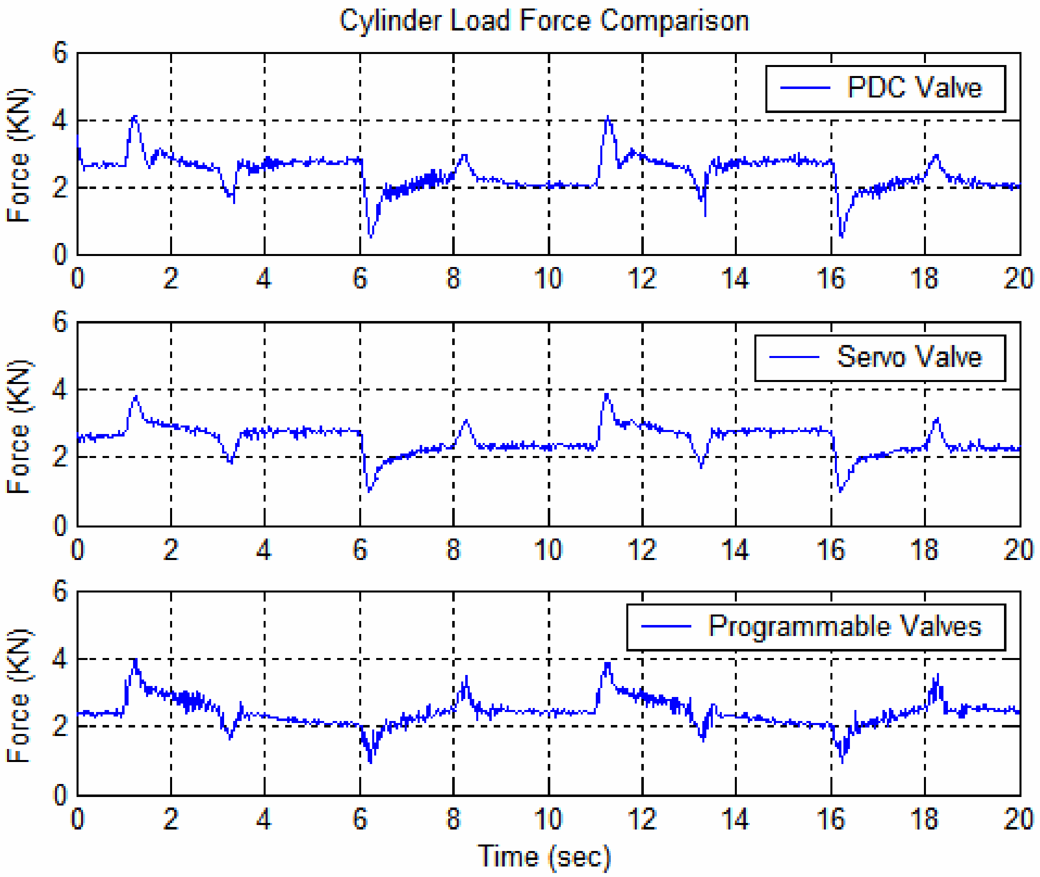
  Vickers EPV10-A-8H-12D-U-10

Comparison of Performance

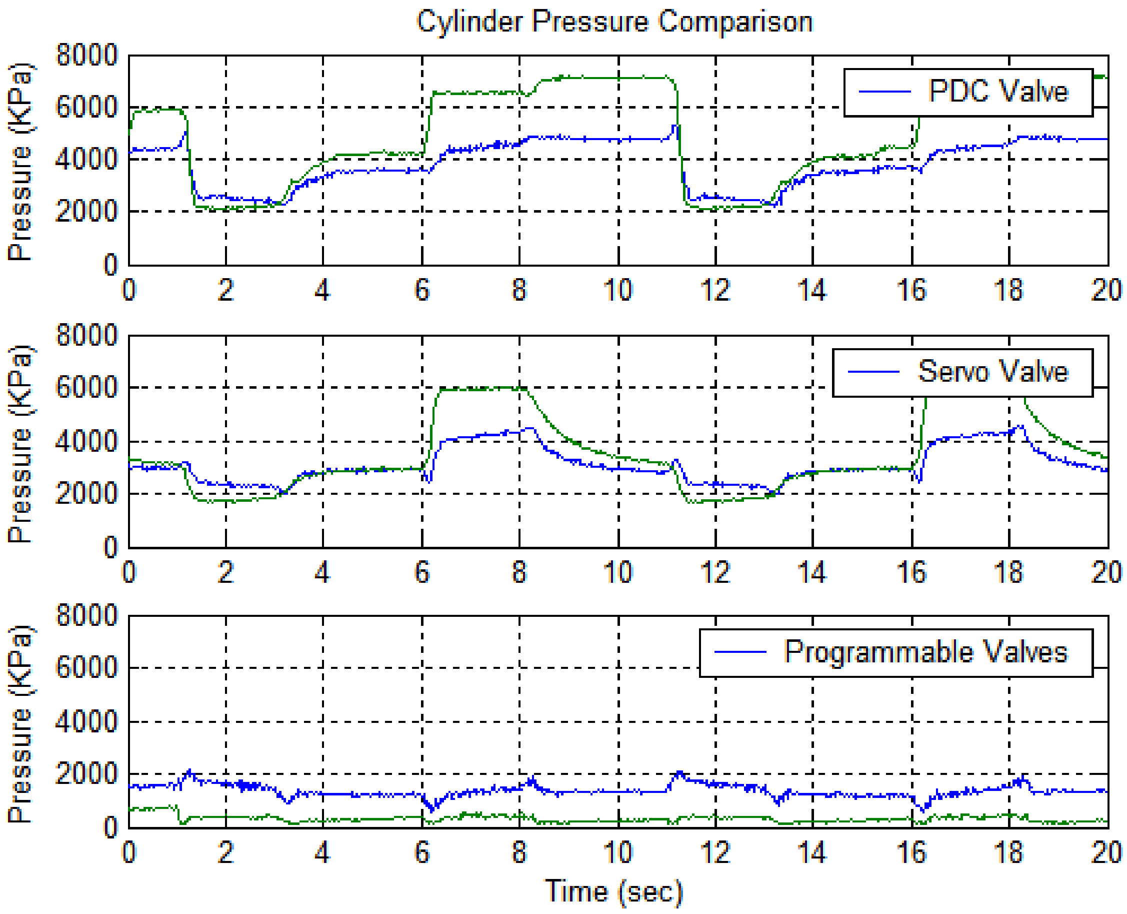


	$\|e\|_1$	$\|e\|_2$	$\|e\|_\infty$
PDC	0.0030	0.0046	0.0146
Srv	0.0014	0.0018	0.0051
Prog	0.0007	0.0010	0.0036

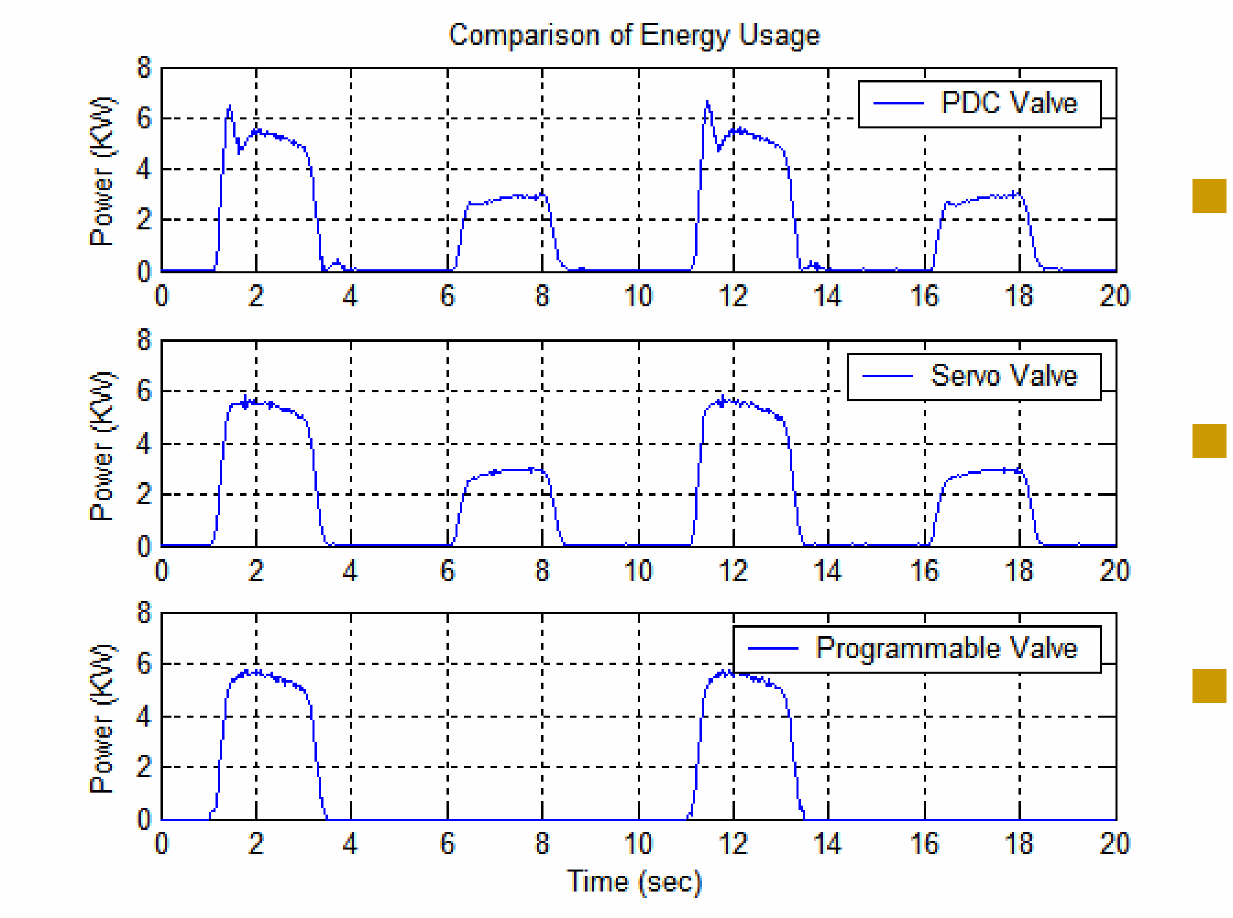
Comparison of Cylinder Force



Comparison of Cylinder Pressures



Comparison of Energy Usage, Constant Supply Pressure Ps=1000psi

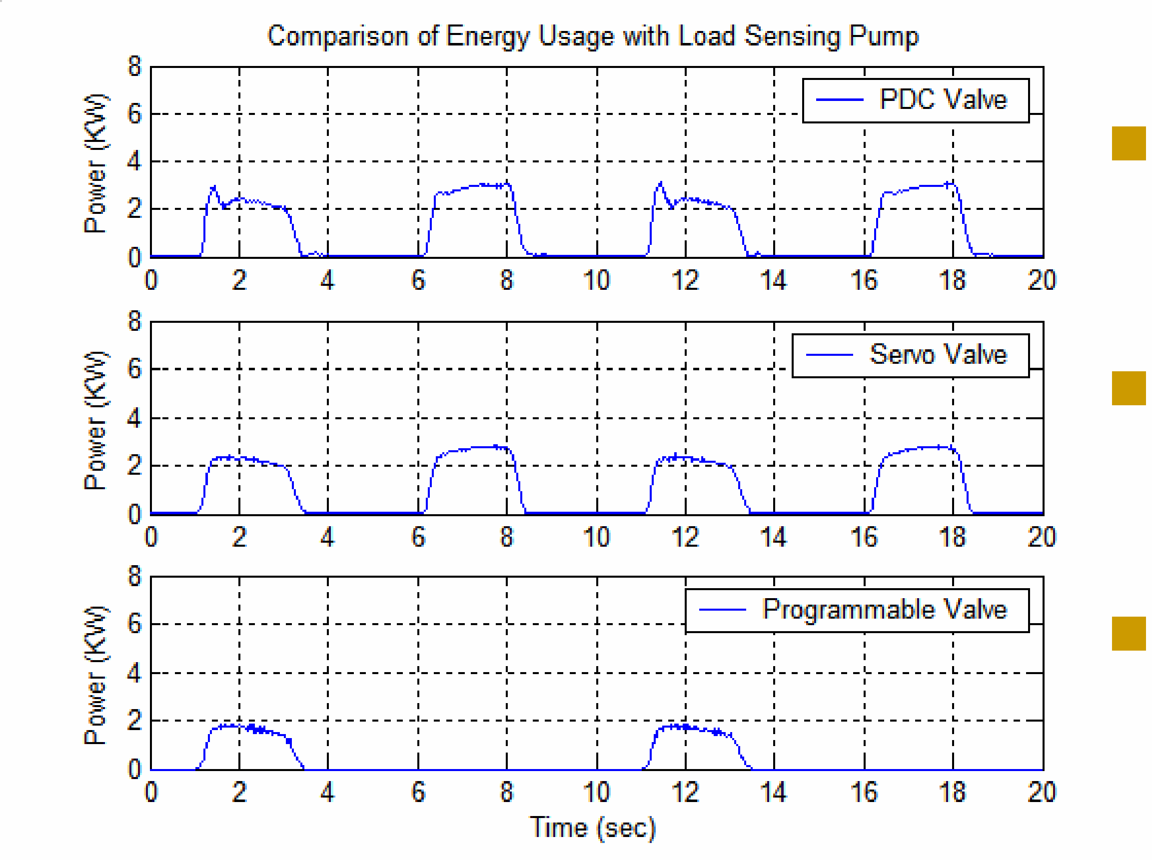


- 32.4 KJ
- 32.7KJ
- 21.3KJ

  34% less than PDC

  35% less than Servo

Comparison of Energy Usage
Ps=Working Pressure + 500KPa



- 20.9 KJ
- 19.3KJ
- 6.4KJ

  69% less than PDC

  67% less than Servo

Outline

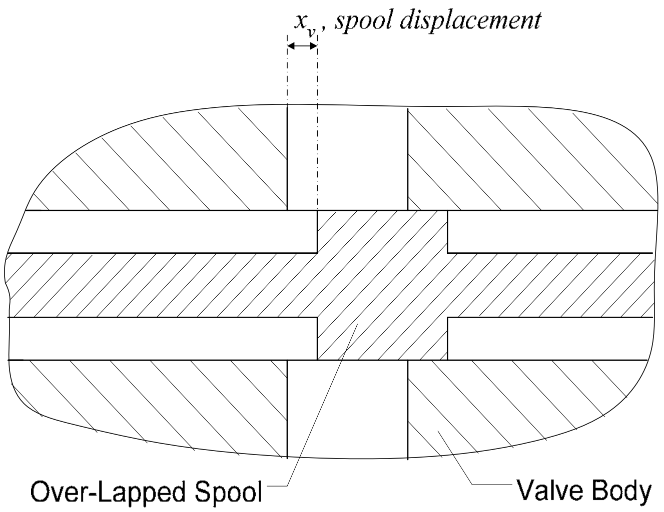
- Development of Programmable Valves
- Control of Programmable Valves
- On-board Modeling of Valve Flow Mapping
  - Problem formulation
  - Localized basis functions and smooth blending
  - On-board modeling
  - Comparative experimental results
- Programmable Valves Bypass Sandwiched Deadband Problem
- Summary

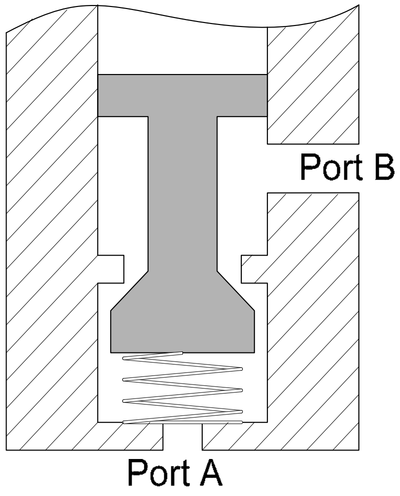
Cartridge Valve Flow Mapping

- Individually calibrated flow mapping (2002-2003)
  - Accurate
  - Off-board test, time consuming, additional calibration equipments, not suitable for industrial application
- Manufacture supplied flow mapping (2004)
  - Ready to use
  - Inaccurate, large modeling error exists, system performance compromised
- Automated on-board modeling of cartridge valve flow mapping (2004-2005)
  - Accuracy & easy implementation

Modeling of Cartridge Valve Flow Mapping

$$Q(u,\Delta P) = C_d A_v\big(x_v(u,\Delta P)\big)\sqrt{\frac{2}{\rho}}\sqrt{\Delta P}$$





$$Q = k_q u\sqrt{\Delta P}$$

Unknown nonlinear function $Q(u,\Delta P)$

On-board Modeling of Cartridge Valve Flow Mapping --- Observer Approach

Flow Rate Observer based on Cylinder Pressure Dynamics

$$\frac{V_1(x)}{\beta_e}\dot{P}_1 = -A_1\dot{x} + Q_1(u_1, \Delta P_1)$$

$$Q_{vi} = f(u_{vi}, \Delta P_{vi})$$

Known Control Signal

Measurable

On-board Modeling of Cartridge Valve Flow Mapping

$$Q(u,\Delta P) = \bar{Q}(u,\Delta P) + \Delta, \qquad \bar{Q} = \varphi_N^T(u,\Delta P)\cdot w_N$$

- Huge number of basis functions and weighting factors
- Limited experimental data
- Dynamic flow rate unavailable

Cylinder Dynamics Based Estimation

Cylinder dynamics: $\frac{V_1(x)}{\beta_e}\dot{P}_1 = -A_1\dot{x} + Q_1(u_1, \Delta P_1)$

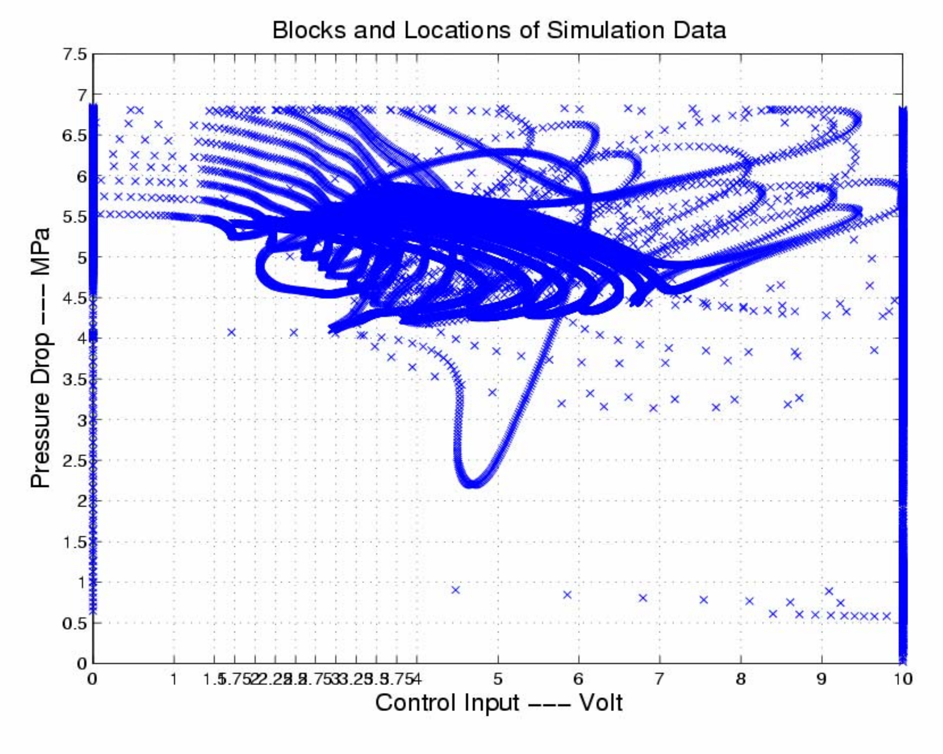
Define $\theta_{\beta_e} = \frac{1}{\beta_e}$

➡ $A_1\dot{x} = -V_1(x)\dot{P}_1 \cdot \theta_{\beta_e} + \varphi_N(u_1, \Delta P_1)^T \cdot \theta + \Delta$

Defining $\varphi_{new}^T = [-V_1(x)\dot{P}_1 \quad \varphi_N(u_1, \Delta P_1)^T]$ $\theta_{new}^T = [\theta_{\beta_e} \quad \theta^T]$

➡ $A_1\dot{x} = \varphi_{new}^T \cdot \theta_{new} + \Delta$

Why localized estimation?



$$[Q] = \Phi \cdot \theta + [\Delta]$$

$$\hat{\theta} = \Phi^{+} \cdot [Q]$$

$$\tilde{\theta} = \Phi^{+}[\Delta] = \left(\Phi^{T}\Phi\right)^{-1}\Phi^{T}[\Delta]$$

Invertibility

Localized Basis

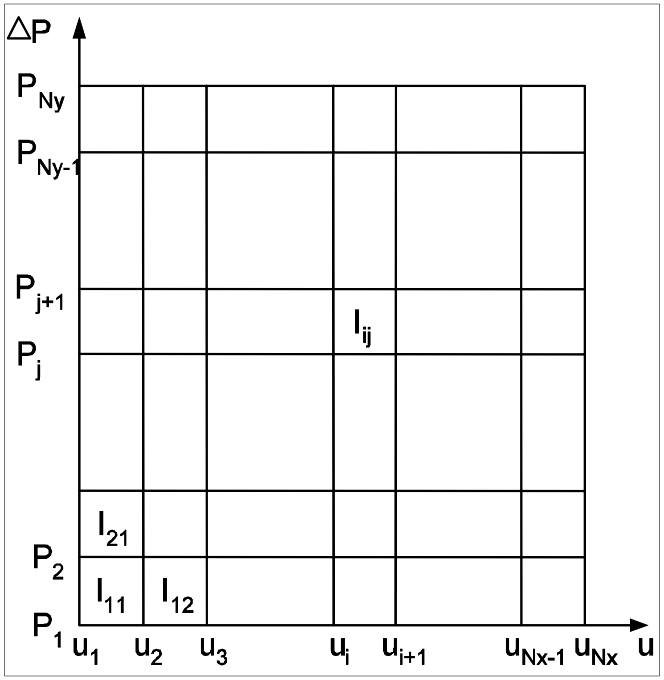
$$Q(u,\Delta P)|_{(u,\Delta P)\in I_{ij}} = Q(\bar{u}_i,\Delta\bar{P}_j) + \frac{\partial Q}{\partial u}|_{(\bar{u}_i,\Delta\bar{P}_j)}\tilde{u} + \frac{\partial Q}{\partial \Delta P}|_{(\bar{u}_i,\Delta\bar{P}_j)}\tilde{P}$$

$$+\frac{1}{2}\frac{\partial^2 Q}{\partial u^2}|_{(\bar{u}_i,\Delta\bar{P}_j)}\tilde{u}^2 + \frac{1}{2}\frac{\partial^2 Q}{\partial \Delta P^2}|_{(\bar{u}_i,\Delta\bar{P}_j)}\tilde{P}^2 + \frac{1}{2}\frac{\partial^2 Q}{\partial u\partial \Delta P}|_{(\bar{u}_i,\Delta\bar{P}_j)}\tilde{u}\tilde{P} + \Delta$$

$$\varphi_{ij}^T = \begin{cases} [1,\ \tilde{u},\ \tilde{P},\ \tilde{u}^2,\ \tilde{P}^2,\ \tilde{u}\tilde{P}] & (u,\Delta P)\in I_{ij} \\ [0,\ 0,\ 0,\ 0,\ 0,\ 0] & \text{otherwise.} \end{cases}$$

$$\bar{Q}(u,\Delta P)|_{(u,\Delta P)\in I_{ij}} = \varphi_{ij}^T \cdot \theta_{ij}$$

$$\bar{Q}(u,\Delta P) = \Sigma_{j=1}^{N_y}\,\Sigma_{i=1}^{N_x}\,\varphi_{ij}^T \cdot \theta_{ij}$$



Localized Estimation

$$[Q(u,\Delta P)]|_{(u,\Delta P)\in I_{ij}} = \Phi_{ij}\cdot\theta_{ij} + [\Delta]$$

$\Phi_{ij}^T\Phi_{ij}$ is invertible

$$\hat{\theta}_{ij} = (\Phi_{ij}^T\Phi_{ij})^{-1}\Phi_{ij}^T\cdot[Q(u,\Delta P)]|_{(u,\Delta P)\in I_{ij}}$$

$\Phi_{ij}^T\Phi_{ij}$ is not invertible

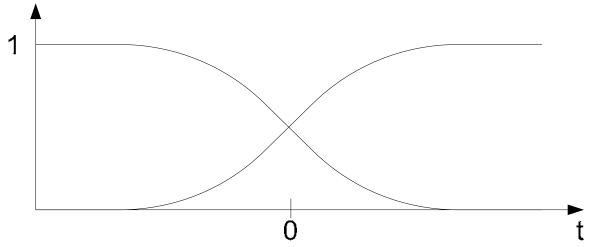
Extrapolation

- PE condition is easily satisfied in small local region rather than globally
- Estimation error can be controlled by checking the condition number instead of invertibility
- Discontinuity may happen at the block borders

Smooth Blending

$$P^+ f(t) = \beta(t)[\beta(t)f(t) + \beta(-t)f(-t)]$$
$$P^- f(t) = \beta(-t)[\beta(-t)f(t) - \beta(t)f(-t)]$$

$$\beta(t) = \begin{cases} 0 & \text{if } t < -1 \\ 1 & \text{if } t > 1 \end{cases} \text{ and } \beta^2(t) + \beta^2(-t) = 1 \quad \forall t \in [-1, 1]$$



Theorem 1: (Coifman and Meyer) The operators P^+ and P^- are orthogonal projectors respectively on W^+ and W^-. The spaces W^+ and W^- are orthogonal and $P^+ + P^- = Identity$.

Automated On-board Modelling of Valve Flow Mapping

$$A_1\dot{x} = \varphi_{new}^T \cdot \theta_{new} + \Delta$$

$$\theta_{new}^T = [\theta_{\beta_e} \quad \tilde{\theta}^T]$$

$$\varphi_{new}^T = [-V_1(x)\dot{P}_1 \quad \varphi_N(u_1, \Delta P_1)^T]$$

$$H_f(s) = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$$

$$A_1\dot{x}_f = \varphi_{new\,f}^T \cdot \theta_{new} + \Delta_f$$

On-line Estimation

On-line, Swiped sinusoidal trajectory, 0.1Hz~0.5Hz over 80sec.

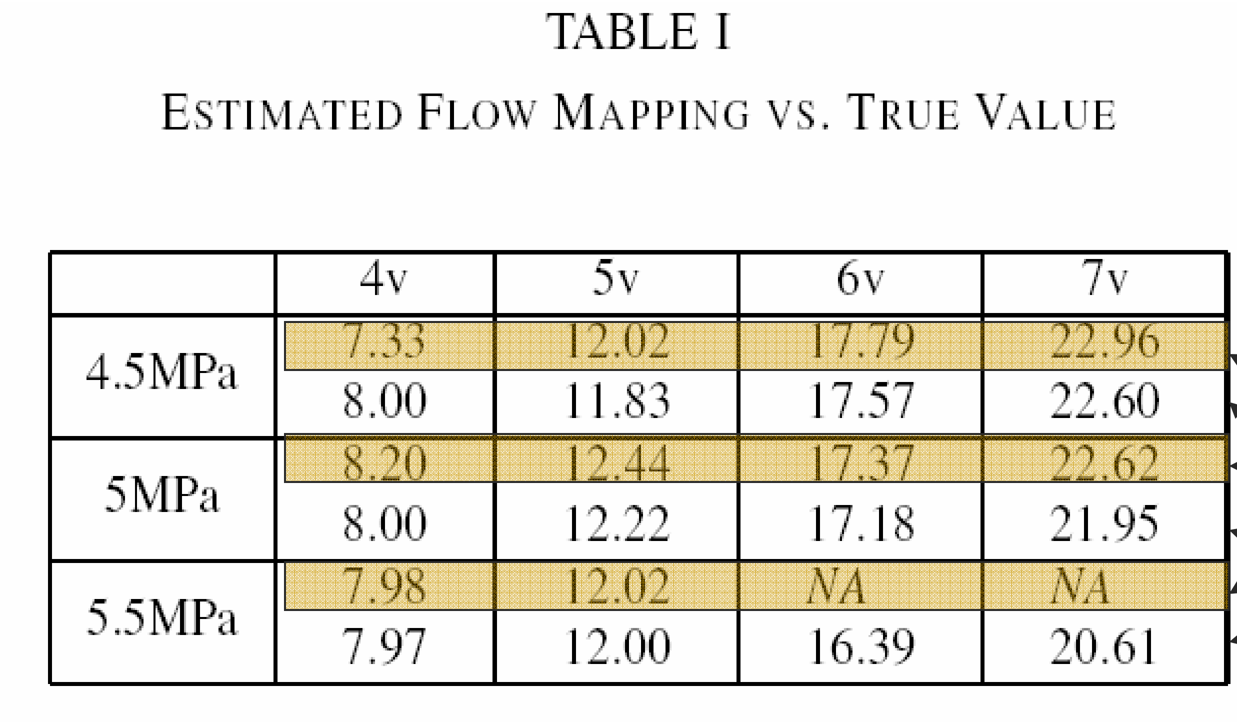


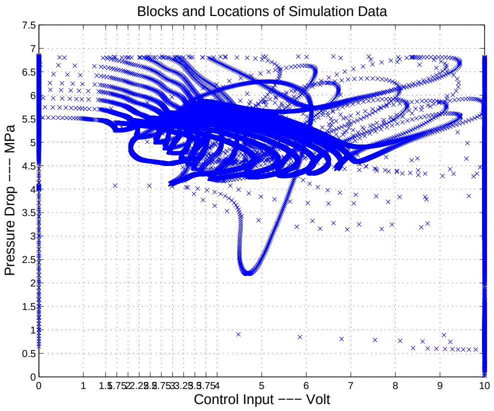
TABLE I

ESTIMATED FLOW MAPPING VS. TRUE VALUE

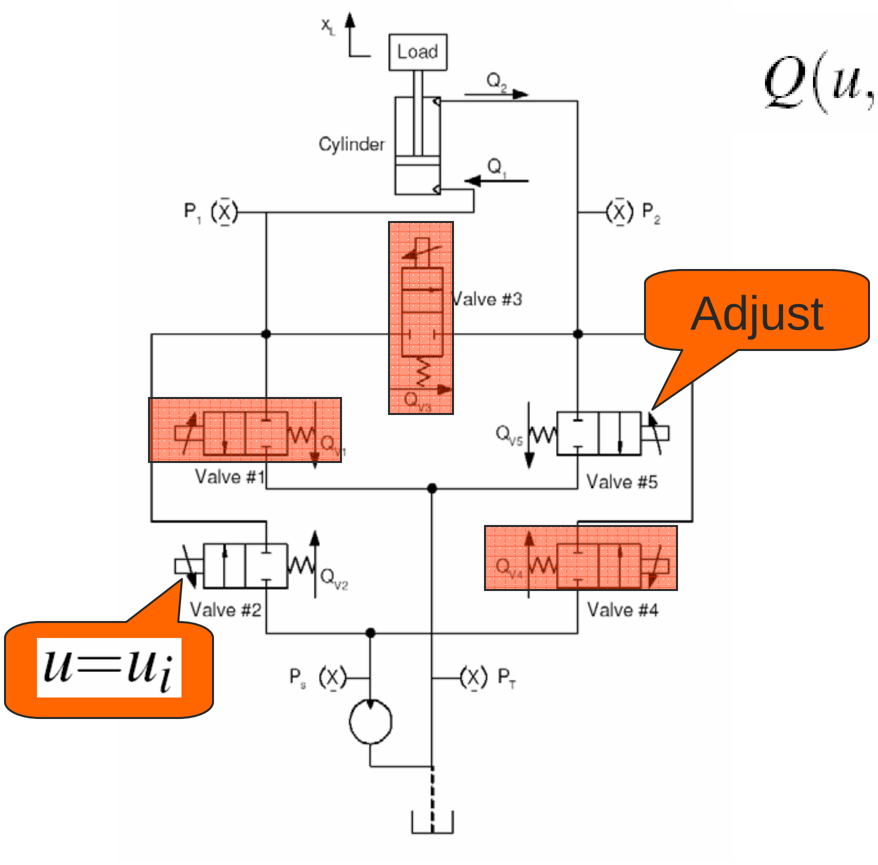
	4v	5v	6v	7v
4.5MPa	7.33	12.02	17.79	22.96
	8.00	11.83	17.57	22.60
5MPa	8.20	12.44	17.37	22.62
	8.00	12.22	17.18	21.95
5.5MPa	7.98	12.02	NA	NA
	7.97	12.00	16.39	20.61

Estimated

Calibrated



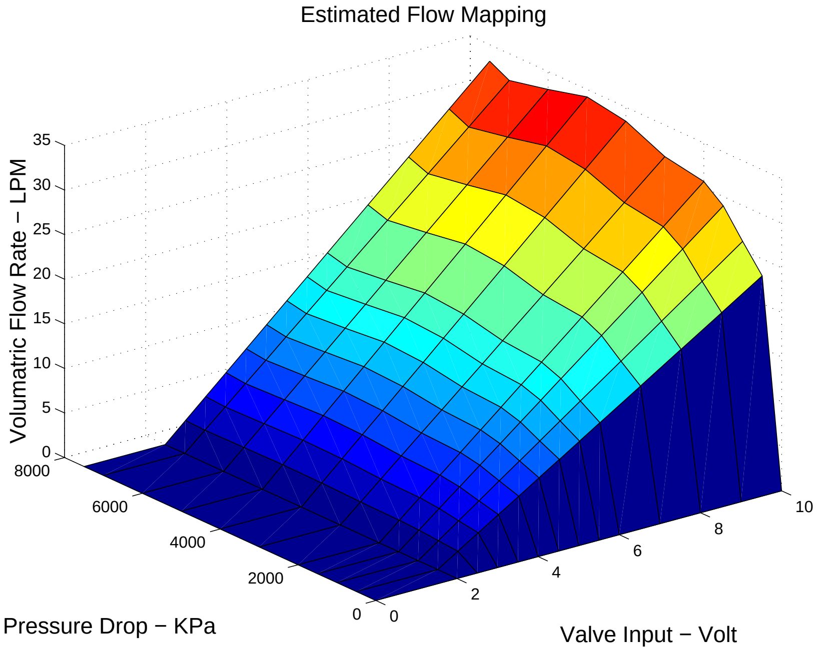
Off-line Estimation



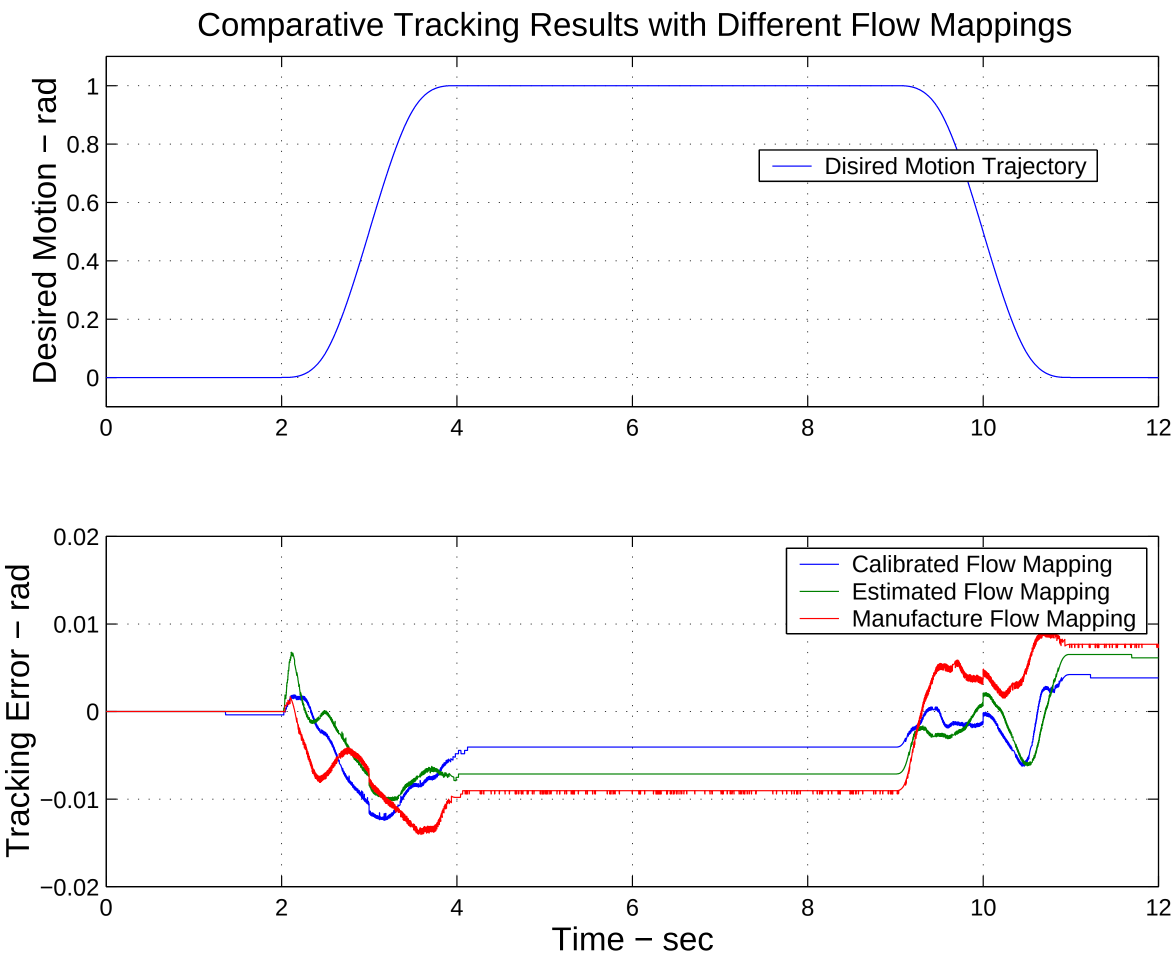
Adjust

$u=u_i$

$$Q(u,\Delta P)\big|_{u=u_i} = Q_i(\Delta P), \quad i=1,2,\dots,Nx$$


Estimated Flow Mapping

Comparison of Different Flow Mappings



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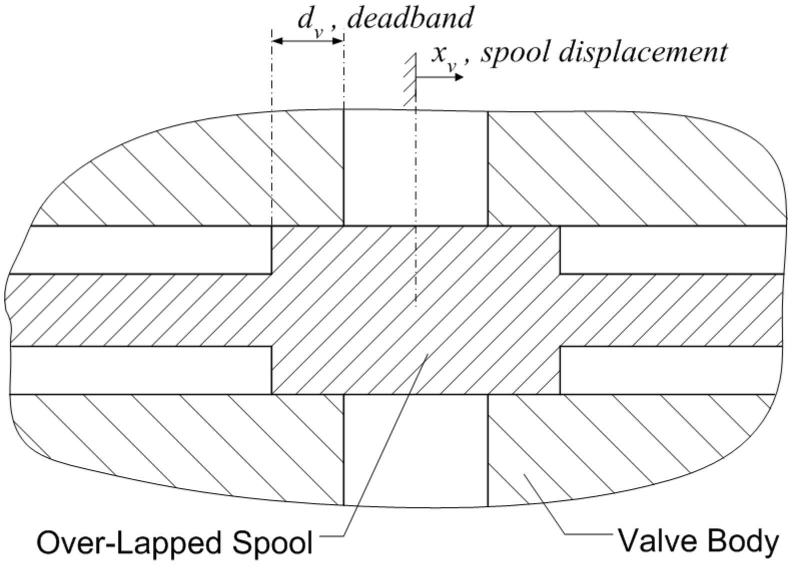
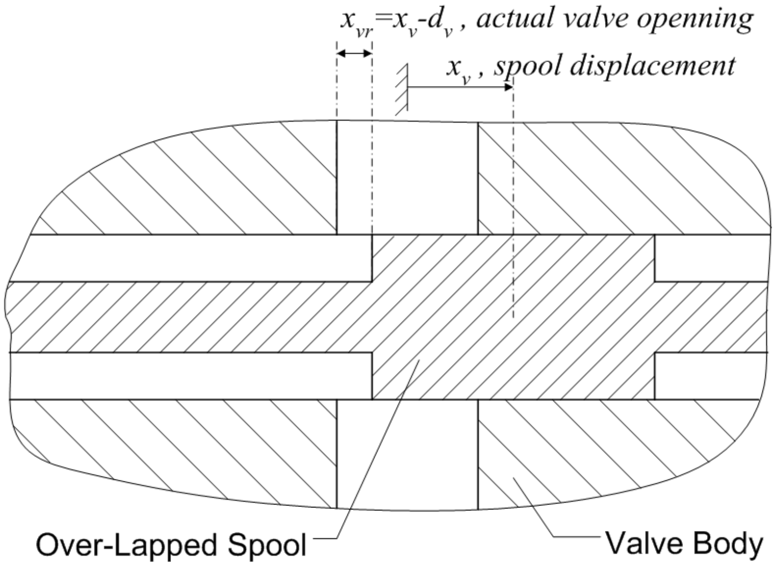
EH system controlled by a closed-center valve

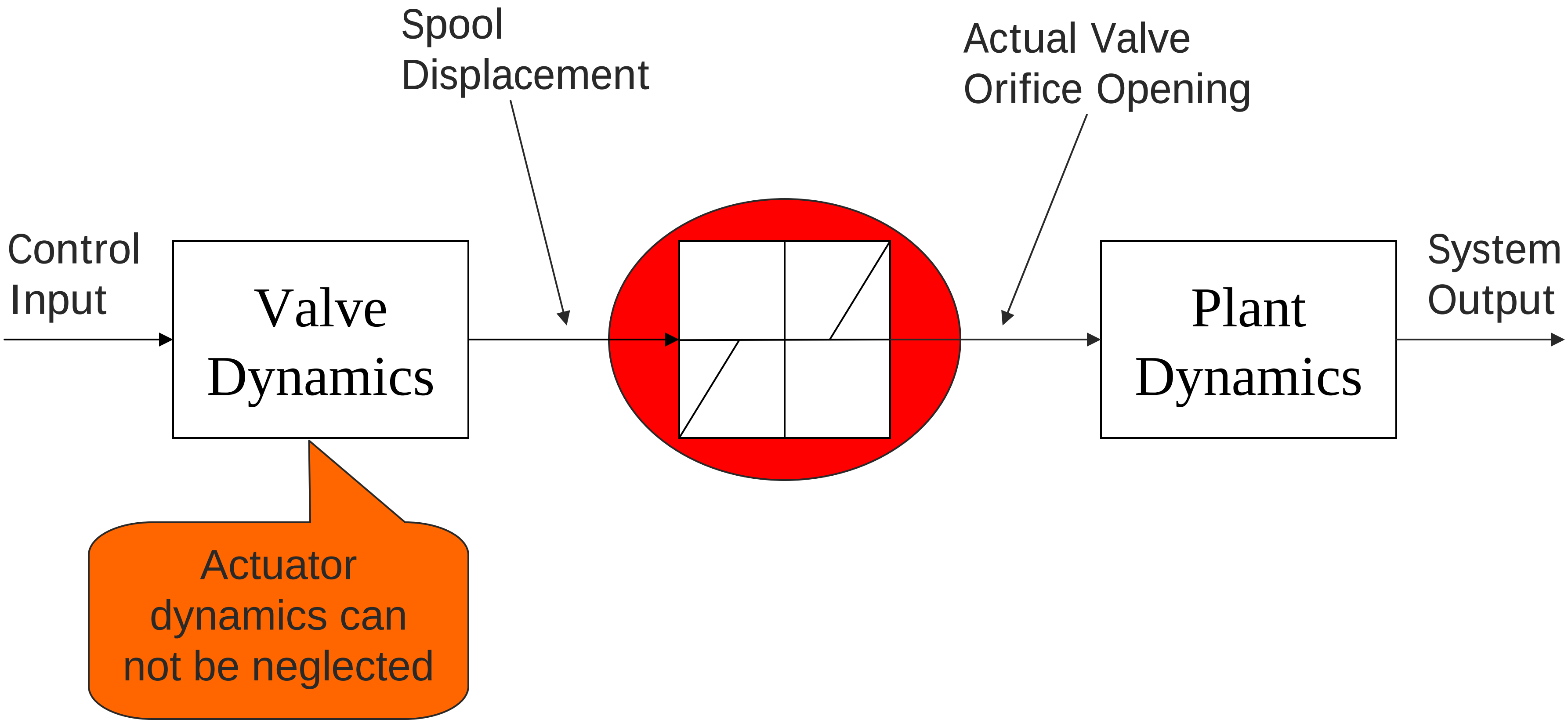


Spool in Neutral Position



Spool in Positive Displacement

What is sandwiched deadband


Spool Displacement

Actual Valve Orifice Opening

Control Input

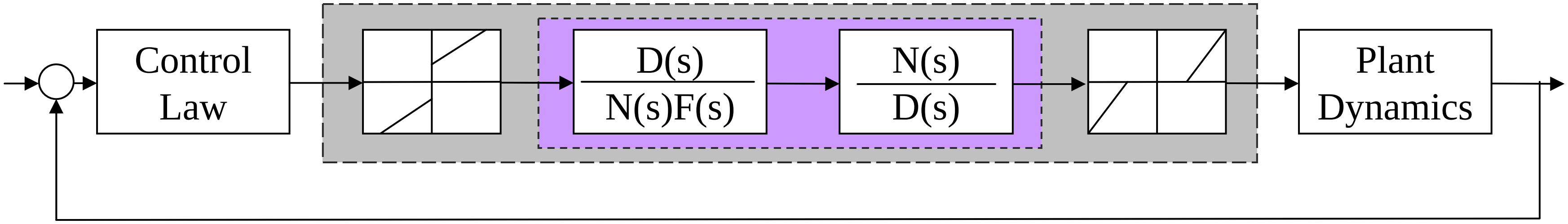
Valve Dynamics

Plant Dynamics

System Output

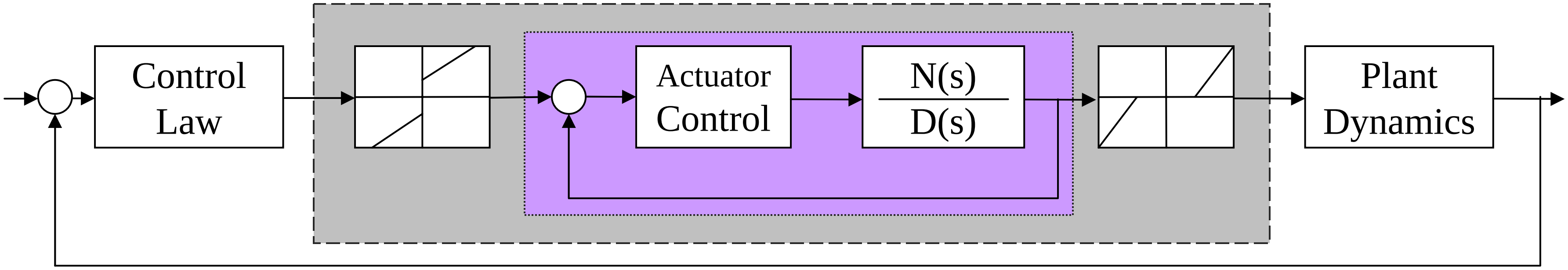
Actuator dynamics can not be neglected

SD is hard to deal with --- Feedforward Compensation



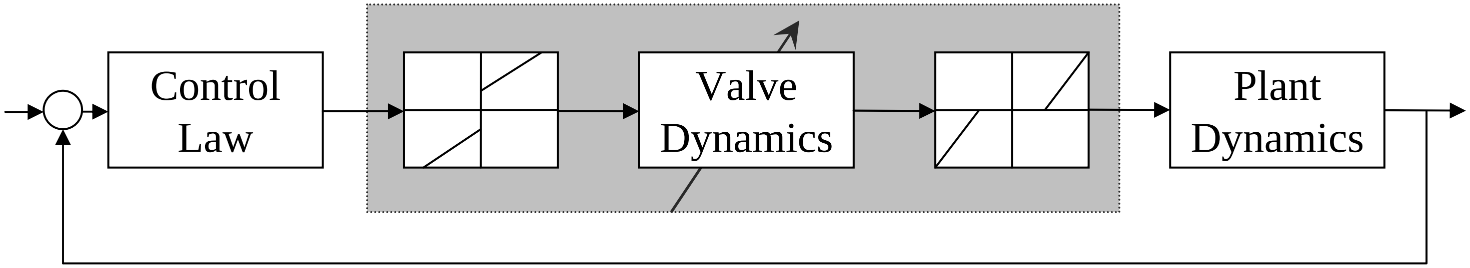
- Use feed-forward controller to increase the actuator dynamics so that it is sufficiently high to be neglected
- Used the inverse deadband function to compensate the nonlinear deadband
- Depends on the accuracy of the valve dynamics, can only achieve limited improvements in practice due to the unavoidable uncertainties in the valve model

SD is hard to deal with --- Feedback Compensation



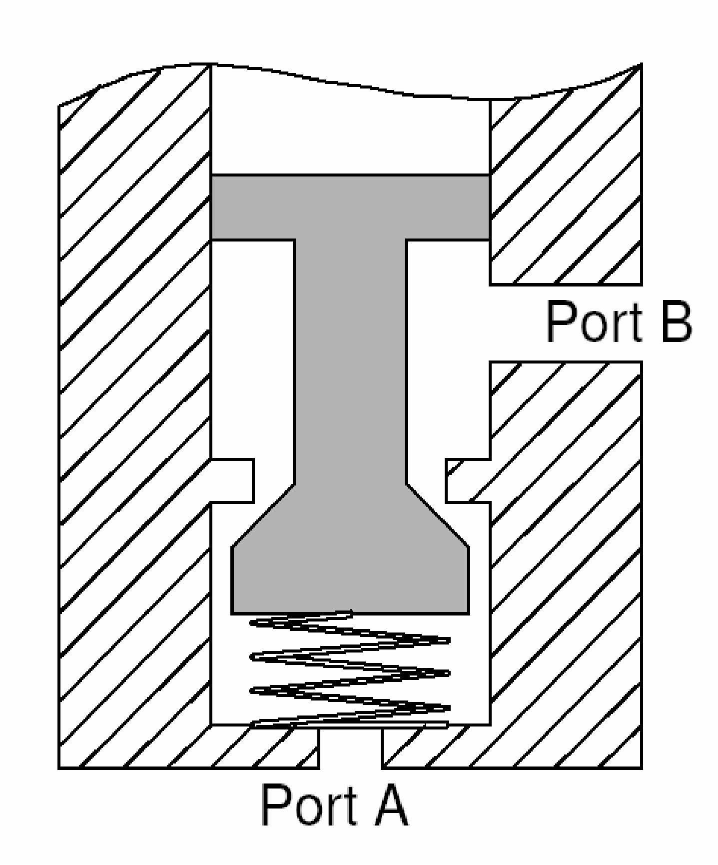
- Use local high gain feedback control to attenuate the deadband
- Require actuator output/state feedback. Significantly increases system cost.
- Sometimes actuator output/state signals are too noisy to help increasing the bandwidth significantly.

SD simple solution --- Direct Compensation



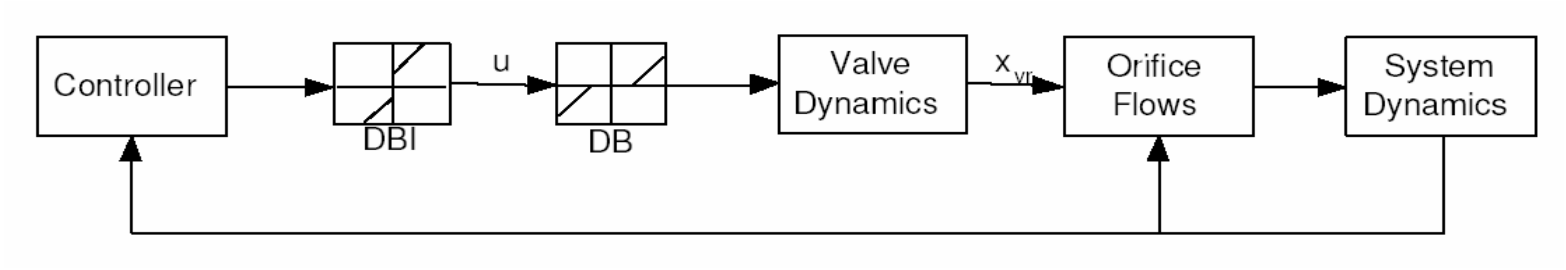
- Simply neglect valve (spool) dynamics
- Economical, easy to implement
- Limit cycle may happen if closed loop bandwidth is not low enough
- Closed loop system is usually conservative, i.e., bandwidth is limited quite low in order to safely neglect valve dynamics

Deadband of poppet-type cartridge valves



- The input signal has to be large enough to overcome the spring force and static friction.

Deadband Compensation of Poppet Valve



- Input deadband is easier to compensate
- Cartridge valve dynamics is much more faster than PDC valves.

Outline

- Development of Programmable Valves
- Control of Programmable Valves
- On-board Modeling of Valve Flow Mapping
- Programmable Valves Bypass Sandwiched Deadband Problem
- Summary

Conclusions

- Eliminate the mechanical linkage between the meter-in and meter-out orifices and enable accurately using the cross port regeneration flow for a controlled motion.
- Energy saving can be achieved without sacrificing precision motion performance.
- The two-level control system successfully control the system to achieve the dual objectives.
- Sandwiched deadband in EH systems can be bypassed by the programmable valves.
- Promising alternatives of conventional four-way valves in precision motion control.

Acknowledgement

- Formal Students:

  Dr. Song Liu
  Chris Deboer

- Past Caterpillar Collaborators:

  John Litherland
  Doug Koehler
  J. Ardema

Acknowledgements

Sponsors:

National Science Foundation

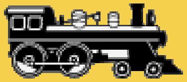
CAREER Grant CMS-9734345

Regular Grant CMS-0220179

Purdue Electro-Hydraulic Research Center

Valve Donations by:

VICKERS



References

Bin Yao and C. Deboer, “**Energy-saving adaptive robust motion control of single-rod hydraulic cylinders with programmable valves**”, the *American Control Conference*, pp4819-4824, Alaska, May, 2002

S. Liu and Bin Yao, “**Energy-saving control of single-rod hydraulic cylinders with programmable valves and improved working mode selection**”, the *SAE Transactions – Journal of Commercial Vehicle,* SAE 2002-01-1343, pp51-61, 2002

S. Liu and Bin Yao, "**Programmable Valves: a Solution to Bypass Deadband Problem of Electro-Hydraulic System**", the *American Control Conference*, pp4438-4443, Boston, 2004.

Liu and Bin Yao, "**Characterization and Attenuation of of Sandwiched Deadband Problem of Electro-Hydraulic Systems Controlled by Closed-Center Valves using Describing Function Analysis**", the *ASME International Mechanical Engineers Congress and Exposition (IMECE)*, IMECE2004-60946, pp1-8, 2004

S. Liu and Bin Yao, **"Adaptive Robust Control of Programmable Valves with Manufacture Supplied Flow Mapping Only**", the *IEEE Conference on Decision and Control,* pp1117-1122, 2004.

References

S. Liu and Bin Yao, "**Automated Modelling of Cartridge Valve Flow Mapping**", the *IEEE/ASME Conference on Advanced Intelligent Mechatronics (AIM'05)*, pp789-794, Monterey, California, 2005.

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