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

Dual-Valve Meter-in and Meter-out

- Two valves:
  
  Patented by:
  
  J. Ardema, 1996

  Uses two directional control valves to meter flows

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

Five-Valve Meter-in and Meter-out

Same functionality as IMVs only

Use Regeneration Flow

- Regeneration Valve

Patented by:

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

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

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

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

<table>
<thead>
<tr>
<th>$\dot{x}_d$</th>
<th>$P_{ide}$</th>
<th>Valve Configuration</th>
<th>Off-side</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; 0$</td>
<td>$&gt; 0$</td>
<td>$Q_1 = Q_{v2}$</td>
<td>$P_2$</td>
<td>T1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_2 = Q_{v5}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt; 0$</td>
<td>$&lt; 0$</td>
<td>$Q_1 = Q_{v2} - Q_{v3}$</td>
<td>$P_1$</td>
<td>T2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_2 = -Q_{v3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; 0$</td>
<td>$&gt; 0$</td>
<td>$Q_1 = -Q_{v3}$</td>
<td>$P_2$</td>
<td>T3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_2 = Q_{v5} - Q_{v3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; 0$</td>
<td>$P_1 &gt; P_2$</td>
<td>$Q_1 = -Q_{v1}$</td>
<td>$P_2$</td>
<td>T4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_2 = -Q_{v4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; 0$</td>
<td>$P_1 \leq P_2$</td>
<td>$Q_1 = -Q_{v1}$</td>
<td>$P_2$</td>
<td>T5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_2 = -Q_{v4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; 0$</td>
<td>$&lt; 0$</td>
<td>$Q_1 = -Q_{v1}$</td>
<td>$P_1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_2 = -Q_{v4}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Working Mode Selection --- Regulation Task

Table 3.2 Programmable valves regulation mode selection

<table>
<thead>
<tr>
<th>( \dot{x}_d )</th>
<th>( x - x_d )</th>
<th>Valve Configuration</th>
<th>Off-side</th>
<th>Mode</th>
</tr>
</thead>
</table>
| = 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   |
Desired Cylinder Velocity > 0
Desired Cylinder Force > 0
Uses Valve #2 and Valve #5
Maintain P2 as Low 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

\[ x_d \rightarrow \text{Model Compensation} \rightarrow \text{Robust Feedback} \rightarrow + \rightarrow \text{Plant} \rightarrow u \rightarrow \text{Controlled Parameter Estimation} \rightarrow x \]
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

<table>
<thead>
<tr>
<th>&lt; 0</th>
<th>&gt; 0</th>
<th>$Q_1 = -Q_{v3}$</th>
<th>$P_2$</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_1 &gt; P_2$</td>
<td>$Q_2 = Q_{v5} - Q_{v3}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$Q_{v1} = 0$

$Q_{v2} = 0$

$Q_{v4} = 0$

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

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

<table>
<thead>
<tr>
<th></th>
<th>$|e|_1$</th>
<th>$|e|_2$</th>
<th>$|e|_\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDC</td>
<td>0.0030</td>
<td>0.0046</td>
<td>0.0146</td>
</tr>
<tr>
<td>Srv</td>
<td>0.0014</td>
<td>0.0018</td>
<td>0.0051</td>
</tr>
<tr>
<td>Prog</td>
<td>0.0007</td>
<td>0.0010</td>
<td>0.0036</td>
</tr>
</tbody>
</table>
Comparison of Cylinder Force

Cylinder Load Force Comparison

- PDC Valve
- Servo Valve
- Programmable Valves

Force (kN) vs. Time (sec)
Comparison of Cylinder Pressures
Comparison of Energy Usage, Constant Supply Pressure Ps=1000psi

32.4 KJ
32.7 KJ
21.3 KJ

34% less than PDC
35% less than Servo
Comparison of Energy Usage

\[ Ps = \text{Working Pressure} + 500\text{KPa} \]

- 20.9 KJ
- 19.3 KJ
- 6.4 KJ

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

  - Accurate
  - Off-board test, time consuming, additional calibration equipments, not suitable for industrial application

  - Ready to use
  - Inaccurate, large modeling error exists, system performance compromised

  - Accuracy & easy implementation
Modeling of Cartridge Valve Flow Mapping

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

\[ Q = k_q u \sqrt{\Delta P} \]

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

\[ \frac{V_1(x)}{βe} \dot{p}_1 = -A_1 \dot{x} + Q_1(u_1, ΔP_1) \]

\[ Q_{vi} = f(u_{vi}, ΔP_{vi}) \]

Known Control Signal

Measurable
On-board Modeling of Cartridge Valve Flow Mapping

\[ Q(u, \Delta P) = \bar{Q}(u, \Delta P) + \Delta, \quad \bar{Q} = \varphi_N^T(u, \Delta P) \cdot w_N \]

- 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 \( \theta_{\beta_e} = \frac{1}{\beta_e} \)

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

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

\[
A_1 \dot{x} = \phi_{new}^T \cdot \theta_{new} + \Delta
\]
Why localized estimation?

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

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

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

Invertibility
Localized Basis

\[ Q(u, \Delta P) \big|_{(u, \Delta P) \in I_{ij}} = Q(\tilde{u}_i, \Delta \tilde{P}_j) + \frac{\partial Q}{\partial u} \big|_{(\tilde{u}_i, \Delta \tilde{P}_j)} \tilde{u} + \frac{\partial Q}{\partial \Delta P} \big|_{(\tilde{u}_i, \Delta \tilde{P}_j)} \tilde{P} \]
\[ + \frac{1}{2} \frac{\partial^2 Q}{\partial u^2} \big|_{(\tilde{u}_i, \Delta \tilde{P}_j)} \tilde{u}^2 + \frac{1}{2} \frac{\partial^2 Q}{\partial \Delta P^2} \big|_{(\tilde{u}_i, \Delta \tilde{P}_j)} \tilde{P}^2 + \frac{1}{2} \frac{\partial^2 Q}{\partial u \partial \Delta P} \big|_{(\tilde{u}_i, \Delta \tilde{P}_j)} \tilde{u} \tilde{P} + \Delta \]

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

\[ \tilde{Q}(u, \Delta P) \big|_{(u, \Delta P) \in I_{ij}} = \varphi_{ij}^T \cdot \theta_{ij} \]

\[ \tilde{Q}(u, \Delta P) = \sum_{j=1}^{N_y} \sum_{i=1}^{N_x} \varphi_{ij}^T \cdot \theta_{ij} \]
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
- \( \Phi_{ij}^T \Phi_{ij} \) is not invertible

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

- 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

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

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

\[ \frac{1}{t} \]

\[ 0 \]

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 \( P^+ + P^- = \text{Identity} \).
Automated On-board Modelling of Valve Flow Mapping

\[ A_1 \dot{x} = \phi_{new}^T \cdot \theta_{new} + \Delta \]

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

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

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

\[ A_1 \dot{x}_f = \varphi_{newf}^T \cdot \theta_{new} + \Delta_f \]
On-line Estimation

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

### TABLE I
**Estimated Flow Mapping vs. True Value**

<table>
<thead>
<tr>
<th>Pressure Drop (MPa)</th>
<th>4v</th>
<th>5v</th>
<th>6v</th>
<th>7v</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5MPa</td>
<td>7.35</td>
<td>12.02</td>
<td>17.79</td>
<td>22.96</td>
</tr>
<tr>
<td></td>
<td>8.00</td>
<td>11.83</td>
<td>17.57</td>
<td>22.60</td>
</tr>
<tr>
<td>5MPa</td>
<td>8.20</td>
<td>12.44</td>
<td>17.37</td>
<td>22.62</td>
</tr>
<tr>
<td></td>
<td>8.00</td>
<td>12.22</td>
<td>17.18</td>
<td>21.95</td>
</tr>
<tr>
<td>5.5MPa</td>
<td>7.98</td>
<td>12.02</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>7.97</td>
<td>12.00</td>
<td>16.39</td>
<td>20.61</td>
</tr>
</tbody>
</table>

Blocks and Locations of Simulation Data

- Estimated
- Calibrated
Off-line Estimation

\[ Q(u, \Delta P) \big|_{u=u_i} = Q_i(\Delta P), \quad i = 1, 2, \ldots, Nx \]
Comparison of Different Flow Mappings

Comparative Tracking Results with Different Flow Mappings

Desired Motion Trajectory

Tracking Error – rad

Time – sec
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EH system controlled by a closed-center valve
What is sandwiched deadband 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.
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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.
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References


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