Energy-efficient servohydraulics using a fast reacting variable supply pressure

Can Du, Andrew Plummer, Nigel Johnston

Centre for Power Transmission and Motion Control
University of Bath, UK

www.bath.ac.uk/ptmc
Aim

Hydraulic power supply for mobile servohydraulic systems

Requirements:
• Energy efficient
• Good dynamic response
• Light weight
Introduction

Load prediction: Estimate the minimum $P_s$ (to give maximum valve opening and avoid cavitation)

VPVC system (variable pressure valve-controlled)

A low inertia brushless servo motor and fixed displacement axial piston pump
Outline

• **VPVC Control Algorithm**
  Feed forward
  Feedback

• **Test Rig and Test Information**

• **Simulated and Experimental Results**
  FPVC (fixed supply pressure valve-controlled)
  VPVC (variable supply pressure valve-controlled)

• **Conclusions**
Control Algorithm

1. Calculate the $P_S$ required when valve fully open.
2. Calculate the $P_S$ required avoiding cavitation. (Calculate spool positions)
3. Do the above for two joints: $P_{SO1}, P_{SO2}, P_{SC1}, P_{SC2}$
4. Choose the actuator with largest $P_S$ to be master actuator (MA).
   - Its $P_S$ is the $P_S$ of whole system.
   - Keep its spool position demand (fully open or calculated spool positions)
5. Use the $P_S$ determined last step to calculate the spool position of the other actuator.
6. Use the determined $P_S$ and flow rate requirements to calculate the speed of motor.
Pressure and motor speed feedforward

\[ \Delta P_{\text{valve}} 1 = P_S - P_A \]
\[ \Delta P_{\text{valve}} 2 = P_B - P_R \]

\[ Q_1 = K_V \cdot \sqrt{\Delta P_{\text{valve}} 1} \]
\[ Q_2 = K_V \cdot \sqrt{\Delta P_{\text{valve}} 2} \]

\[ P_A A_1 - P_B A_2 = F \]

\[ P_{SO} = \frac{(A_1^3 + A_2^3) \cdot \nu^2}{A_1 K_V^2} + \frac{F + A_2 P_R}{A_1} \]

\[ \frac{d}{dt} \left( \frac{P_S}{K} \right) + \sum_{j=1}^{2} Q_{aj} \]
\[ \hat{\omega}_m = \frac{D_P}{D_P} \]
The required force for a given motion is derived, which incorporates inertia and weight related terms.

**Feed forward:**
From motion demand to both joints:
- Force prediction
- Minimum $P_s$ (aim for one valve fully open but also avoid cavitation)
- Calculate required flows
- Motor speed and spool positions.
Feedback

Use measured cylinder positions to be feedback signals.

1. Motor speed feedback control

\[ \ddot{\omega}_m = \ddot{\omega}_m + (K_{P,M} + \frac{K_{I,M}}{s})(\ddot{y}_{MA} - y_{MA}) \text{sgn}(\ddot{x}_{MA}) \]

2. Spool positions feedback control

\[ \ddot{x}_j = \ddot{x}_j + (K_{P,S} + \frac{K_{I,S}}{s})(\ddot{y}_j - y_j) \]
Test system

- Robotic Arm
- Tank
- Manifold Block
- 1 Kg Mass
- Motor
- Valves
- Pump
Test system

- Baldor Brushless AC motor BSM63N-375AF: 2.09 Nm continuous, 8.36 Nm peak, 10000 rpm maximum speed;
- Takako micro axial piston pump TFH-315: 3.14 cc/rev, max operating pressure 210 bar, 3000 rpm maximum speed.
- Moog Direct Drive valves D633-R02K01M0NSM2: 5 L/min over 35 bar single path pressure drop.
- Unequal area actuators: 2.01 cm²/1.23 cm²
# Test conditions

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Shoulder Demand</th>
<th>Elbow Demand</th>
<th>FPVC Simulation Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(Amp_1 = 20^\circ \omega_1 = 3 \text{ rad/s})</td>
<td>(Amp_2 = 20^\circ \omega_2 = 4 \text{ rad/s})</td>
<td>(P_S = 39 \text{ bar,}) Max spool opening is 20%</td>
</tr>
<tr>
<td>2</td>
<td>(Amp_1 = 20^\circ \omega_1 = 4 \text{ rad/s})</td>
<td>(Amp_2 = 20^\circ \omega_2 = 5 \text{ rad/s})</td>
<td>(P_S = 39 \text{ bar,}) Max spool opening is 35%</td>
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<tr>
<td>3</td>
<td>(Amp_1 = 30^\circ \omega_1 = 4 \text{ rad/s})</td>
<td>(Amp_2 = 30^\circ \omega_2 = 5 \text{ rad/s})</td>
<td>(P_S = 39 \text{ bar,}) Max spool opening is 50%</td>
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<tr>
<td>4</td>
<td>(Amp_1 = 20^\circ \omega_1 = 7 \text{ rad/s})</td>
<td>(Amp_2 = 30^\circ \omega_2 = 6 \text{ rad/s})</td>
<td>(P_S = 39 \text{ bar,}) Max spool opening is 75%</td>
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<tr>
<td>5</td>
<td>(Amp_1 = 30^\circ \omega_1 = 7 \text{ rad/s})</td>
<td>(Amp_2 = 30^\circ \omega_2 = 7 \text{ rad/s})</td>
<td>(P_S = 39 \text{ bar,}) Max spool opening is 98%</td>
</tr>
</tbody>
</table>
Fixed pressure results (test 4)
Fixed pressure results (test 4)
VPVC Results

Graphs showing:
- Shoulder position / degree
- Elbow position / degree
- Supply pressure / Bar

Different lines represent:
- Demand
- Simulated
- Experimental
VPVC Results
Power-consumption Comparison

- Power Consumption Comparison

- Power (W):
  - FPVC Sim
  - FPVC Exp
  - VPVC Sim
  - VPVC Exp
  - Saving

- Saving:
  - 73.62%
  - 67.45%
  - 45.47%
  - 33.86%
  - 17.42%
Robustness and on-line parameter estimation

<table>
<thead>
<tr>
<th>COMPARISON OF CONTROLLERS</th>
<th>Predicted Mass - 1.673kg</th>
<th>Online RLS Mass</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Max error</td>
<td>Av. Error</td>
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<tr>
<td>0kg</td>
<td>Shoulder</td>
<td>12.00</td>
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<tr>
<td></td>
<td>Elbow</td>
<td>12.52</td>
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<tr>
<td>1.039kg</td>
<td>Shoulder</td>
<td>6.04</td>
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<tr>
<td></td>
<td>Elbow</td>
<td>5.51</td>
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<tr>
<td>1.673kg</td>
<td>Shoulder</td>
<td>4.23</td>
</tr>
<tr>
<td></td>
<td>Elbow</td>
<td>4.34</td>
</tr>
</tbody>
</table>

Errors in degrees
Conclusions

• VPVC is an efficient control method for a multi-axis hydraulic actuation system compared with a traditional fixed supply pressure system.
• The dynamic performance of VPVC is good as well, but this is reliant on a highly responsive servomotor.
• Responsiveness also requires force prediction; adaptive force prediction has been demonstrated but only with a load consisting of a variable mass.