The digital hydraulic challenge, to switch or not to switch

Dr. Magnus Sethson
Assistant Professor, Senior Lecturer
Division of Fluid and Mechatronic Systems, Linköping University
Sweden
Digital Hydraulics
Switched Controlled Force

Project Update
Cooperative Work with Linköping University

Norrhydro Oy, Finland

Volvo Construction Equipment AB, Sweden

HYDAC GmbH, Germany

**Project Mission:**
To evaluate the Norrhydro multi chamber cylinder technology in a digital hydraulic configuration with focus on applications of Volvo Construction Equipments products using valves from HYDAC. The digital hydraulic technology is originally invented by prof. Matti Linjama at Tampere University in Finland.
Switched Circuits
The Electronic Analogy
\[ \dot{\Theta}(t) = \dot{\Theta}(T(t), H_1[t_n], L_1[t_n], H_2[t_n], L_2[t_n]) \]
\[ \dot{x}(t) = \dot{x}(F(t), H_1[t_n], L_1[t_n], H_2[t_n], L_2[t_n]) \]
Switched Circuits

\[ H_1[t_n] \quad T(t) \quad \dot{\Theta}(t) \quad H_2[t_n] \]

\[ L_1[t_n] \quad \dot{M} \quad L_2[t_n] \]

\[ H_1[t_n] \quad F(t) \quad \dot{x}(t) \quad H_2[t_n] \]

\[ L_1[t_n] \quad \dot{x}(t) \quad L_2[t_n] \]
The supply does not need to be the same!
Multi Chamber Cylinder
Discrete force actuator
Several cylinders can be put in parallel.
The Norrhydro 4 chamber cylinder
The test setup
Valve package
27 valves
4 A chamber
2 B chamber
2 C chamber
1 D chamber
Valve inline orifice configuration

Lift main cylinder & WS10 valves
Orifice diameter configuration

<table>
<thead>
<tr>
<th>Valve number</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<td>1</td>
<td>-</td>
<td>1,5</td>
<td>3</td>
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</tr>
<tr>
<td>4</td>
<td>1,5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Valve inline orifice configuration
3 pressure lines and 4 chambers gives 81 force steps

Force steps

max: 129.9 kN
min: -2.1 kN
Overall system layout
Control

Strategies for force and position control
Control structure
Strategy: \( \min \Delta F \)

\[ u = u_i \text{ such as } \min \left( |F_{ref} - \hat{F}(u_i)| \right) \text{ for } i \in [1..81] \]

- \( u \) : Controller signal
- \( u_i \) : Valve combination index
- \( F_{ref} \) : Estimated force reference
- \( \hat{F}(u_i) \) : Calculated force response
- \( i \) : index in the 81 combination set
Strategy: \( \min \Delta F + F_{\text{penalty}} \)

\[
u = u_i \text{ such as } \min \left( |F_{ref} - \hat{F}(u_i)| + F_p \right) \text{ for } i \in [1..81]
\]

\( u \): Controller signal
\( u_i \): Valve combination index
\( F_{ref} \): Estimated force reference
\( \hat{F}(u_i) \): Calculated force response
\( i \): index in the 81 combination set
\( F_p = 2000N \) if \( u_i \neq u_{\text{previous}} \) otherwise \( 0N \)
Strategy: $\min \Delta F + F_{\text{penalty}} + \text{ Score}$

$$u = u_i \text{ such as min} \left( |F_{\text{ref}} - \hat{F}(u_i)| + F_p \right) \text{ for } i \in [1..81]$$

$u$: Controller signal

$u_i$: Valve combination index

$F_{\text{ref}}$: Estimated force reference

$\hat{F}(u_i)$: Calculated force response

$i$: index in the 81 combination set

$F_p = f(u_i, u_{\text{previous}}, p_H, p_M, p_L)$
Comparison

- **min $\Delta F$**
  - Extensive switching
  - Larger errors

- **min $\Delta F + F_{\text{penalty}}$**
  - Smoother switching
  - Some errors

- **min $\Delta F + F_{\text{penalty}} + \text{Score}$**
  - Some switching
Phase 2

Reevaluating the switching trigger functions and energy harvesting
Human in-the-loop
Example: Velocity matching
Path following

\[ x(t) \]

\[ x_{\text{measure}}(t) \]

\[ x_{\text{ref}}(t) \]
1/ Lagenliga skyddsanordningar ombesörjes av beställaren.
Conclusions

• Digital hydraulics have potential in multi-axis systems.

• The switching strategy is paramount to its energy efficiency and controllability.

• Research is still needed to understand the non pre-filtered applications.