Test Bed 1 – Energy Efficient Displacement-Controlled Hydraulic Hybrid Excavator

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Outline

Testbed goals

Achievements up to date on the prototype

Advancements in control development
  
  For hydraulic hybrid
  
  For power management
  
  For pump switching

Measurements results

Conclusions
## Testbed Goals

<table>
<thead>
<tr>
<th>Target</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieve 50% fuel savings</td>
<td>kg of fuel</td>
</tr>
<tr>
<td>Maintain or improve machine productivity</td>
<td>(tons soil / hour)</td>
</tr>
<tr>
<td>50% reduction of rated engine power</td>
<td>kW</td>
</tr>
<tr>
<td>Maintain or improve machine controllability</td>
<td>(expert operator evaluation)</td>
</tr>
<tr>
<td>50% reduction of cooling power</td>
<td>kW</td>
</tr>
</tbody>
</table>
Displacement-Controlled (DC) Actuation

- Energy savings by throttle-less actuation
- Each actuator requires a hydraulic unit
- Motion is achieved through unit displacement
- Energy recovery
Testbed Goals

Implemented on a Bobcat 435 excavator on 2009

LS Hydraulics

DC Hydraulics
## CAT Productivity Test

**90° truck loading cycle**

<table>
<thead>
<tr>
<th>Machine</th>
<th>Soil Loaded (ton)</th>
<th>Fuel Consumed (kg)</th>
<th>Cycle Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard LS</td>
<td>7.55</td>
<td>0.533</td>
<td>12.1</td>
</tr>
<tr>
<td>Prototype DC</td>
<td>7.66</td>
<td>0.321</td>
<td>10.4</td>
</tr>
<tr>
<td>Difference</td>
<td>+1.5%</td>
<td>-39.7%</td>
<td>-14.1%</td>
</tr>
</tbody>
</table>

**~40% Fuel savings**

**~70% Productivity increase**

<table>
<thead>
<tr>
<th>Machine</th>
<th>Fuel Consumption (l/h)</th>
<th>Productivity (t/h)</th>
<th>Efficiency (ton/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard LS</td>
<td>9.36</td>
<td>101.7</td>
<td>10.9</td>
</tr>
<tr>
<td>Prototype DC</td>
<td>6.57</td>
<td>120.9</td>
<td>18.4</td>
</tr>
<tr>
<td>Difference</td>
<td>-29.8%</td>
<td>+18.9%</td>
<td>+69.4%</td>
</tr>
</tbody>
</table>
One of the underestimated benefits of DC technology is less heat generation.

In 2010 a preliminary study of the oil temperatures was conducted using a DC excavator prototype.

Simulations showed possible reduction of required cooling power by \( \approx 50\% \)


Hydraulic Hybrid and DC Actuation

- Stored energy complements engine power
- Sizing study with 256 different designs determined hydraulic components sizes

Parameter | Parameter sizes
---|---
$V_1$ (cc/rev) | 12 18 24 30
$V_2$ (cc/rev) | 20 30 50 70
$V_0$ (L) | 2 5 7 10
$p_{\text{min}}$ (bar) | 100 200 250 350

Secondary-Controlled Hydraulic Hybrid

Formerly focused on constant HP level

MEANINGLESS FOR A HYDRAULIC HYBRID

Pressure Control

Primary unit allows energy storage and transmission to common shaft

Secondary unit controls inertia load dynamics

Speed Control

Velocity feedback

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Hydraulic Hybrid Actuator-Level Control

PI Controller

Adaptive Robust Control

Pressure is considered a disturbance and controlled using a separate PI controller

Robust $H_\infty$ Controller

$\begin{align*}
K_s & \begin{bmatrix} p_{hp \, ref} \\ \dot{\theta}_{ref} \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \\
W_1 & \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} p_{hp \, act} \\ \dot{\theta}_{act} \end{bmatrix}
\end{align*}$


Measurement Results

PI – Cabin Position

H∞ – Cabin Position

ARC – Cabin Position

PI – Cabin Velocity

H∞ – Cabin Velocity

ARC – Cabin Velocity

Cabin Position Error

Cabin Velocity Error

$e_{PI}$ – $e_{H\infty}$ – $e_{ARC}$

$0^\circ$ to $\sim90^\circ$ High Inertia
Measurement Results

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0° to ~180° High Inertia
Measurement Results

Parameter Adaptation

- The parameter related to inertial load ($\theta_1$) is crucial in achieving tracking

- Modifying the load inertia by changing the boom and arm positions is reflected on this parameter

Pressure Tracking

- Pressure tracking with the $H_{\infty}$ controller is greatly improved
ARC controller for cab speed control
Engine power can charge the accumulator and actuate the swing drive. Engine power can be complemented with accumulator energy.

Swing drive braking energy can be stored and accumulated.

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Hydraulic Hybrid Power Management Control

Feedforward approach

\[ E_{e \max \@ \min \text{bsfc}} - E_{DC} \geq 0 \]
- Primary unit charges accumulator
- Upper limit must be imposed on \( E_A \)
\[
\beta_p = \left( \frac{E_{e \max \@ \min \text{bsfc}} - E_{DC}}{E_{DC \max} - E_{e \text{ downsized max}}} \right) \left( S_A(E_A) \right)
\]
Uses available energy to charge accumulator
Sets an upper limit on the amount of stored energy

\[ E_{e \max \@ \min \text{bsfc}} - E_{DC} < 0 \]
- Accumulator is discharged to compliment engine
- Lower limit must be imposed on \( E_A \)
\[
\beta_p = \left( \frac{E_{e \max \@ \min \text{bsfc}} - E_{DC}}{E_{e \text{ downsized max}}} \right) \left( 1 - S_A(E_A) \right)
\]
Uses stored energy to compliment engine
Sets a lower limit on the amount of available stored energy
Engine Power Management Control

Instantaneous optimization approach

\[
\min(J) = \min\left(\text{bsfc}(n_e, M_e) + k_Q \sum_{i=1}^{n} Q_{DC \text{ err}, i} + J_c\right)
\]

where

\[
\text{bsfc}(n_e, M_e) = \text{measured engine bsfc}
\]

\[
k_Q = \text{performance gain}
\]

\[
Q_{DC \text{ err}} = \begin{cases} 0 & |Q_{DC, \text{ desired}}| \leq |Q_p, \text{ current}| \\ |Q_{DC, \text{ desired}}| - |Q_p, \text{ current}| & |Q_{DC, \text{ desired}}| > |Q_p, \text{ current}| \end{cases}
\]

\[
J_c = \text{penalizing factor}
\]

Scalable engine map

Golden search

For any given torque load, the minimum fuel consumption is at relatively low speeds
Power Management Simulation Results

Maximum simulated engine power is 55%

- Aggressive truck-loading cycle from CAT measurements

55% Downsized engine max power is 20 kW
Power Management Measurement Results

Maximum allowable engine power is 55%

- Measurements were performed with full-sized engine

Engine operation is maintained below maximum allowed power
DC Actuation with Pump Switching

- Fewer pumps than actuators
- Cost-effective solution to multi-actuator systems
- Lower parasitic losses
- Combined pumps flows


Challenges were identified and control strategies were developed for a multi-actuator test rig

Actuator and supervisory-level controllers are necessary

DC Actuation with Pump Switching
Actuator-Level Measurement Results

Without Control

With Control

Pump Switching Measurement Results

Without Control
Pressure and motion transients are observed (evident by noise)

With Control
No pressure or motion transients are observed
Pump Switching Priority-Based Supervisory

- Focus on the proposed architecture
- Compare the proposed architecture with the stock excavator (LS system)

Supervisory Controller Measurements

Trench-digging cycle - BUCKET
Supervisory Controller Measurements

Trench-digging cycle - SWING
Conclusions

• Precision motion controls for secondary-controlled hydraulic hybrid drives under large and rapidly-changing inertial and dynamic loads were investigated, synthesized and implemented

• Effective and generalized power management schemes were developed and tested for both the hydraulic hybrid and the engine in the excavator prototype

• Actuator-level controls were developed for DC machines with pump switching leading to smooth switching transitions on the testbed

• Supervisory-level algorithms were researched and validated through measurements for DC machines with pump switching

• The above mentioned control strategies exploit the benefits of DC machines with hydraulic hybrids and pump switching while achieving conventional operability
Future Work

• Advanced control algorithms such as learning schemes that can exploit the hydraulic hybrid architecture can be formulated to further optimize fuel savings

• Actuator-level controls for pump switching can be improved by means of feedback making them robust against changes in the plant parameters

• Advanced supervisory controls can be developed for pump switching to supersede operator commands based on operating trends or desired performance
Thank you!

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