Design of a Lightweight, Portable Hydraulic Power Supply

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Project Objectives

• Develop an analytical model to aid in the system level design of a minimal-weight portable hydraulic power supply

• Develop design guidelines for optimal component integration techniques
Motivation

- October 2015 CCEFP Strategic Research Plan (SRP) identifies excessive weight and size as a barrier for new portable applications, and particularly for new human-scale applications
Methods for Minimizing Weight

• Optimal Component Selection Using Computer Modeling
  – Battery, motor, pump parameter selection

• Component Integration
  – Packaging techniques
  – 3D Printing

https://www.asme.org/engineering-topics/articles/manufacturing-processing/spotlight-tim-simpson-penn-state-cimp3d
3D Printing

Boston Dynamic: Atlas

Child Hydraulic Ankle-Foot Orthosis: 3D Printed Titanium Version

Hydraulic Ankle-Foot Orthosis

Untethered, hydraulic power supply

Hydraulic actuators

Brushless DC Motor

Axial piston pump

Gearbox

Lithium polymer battery
Power Supply Configuration

DC Motor → Axial Piston Pump → Hydraulic Manifold

Lithium Ion Battery

http://www.maxonmotorusa.com/
Circuit Selection

Electro-hydraulic actuator (EHA)

Throttling valve configuration
Motor and Pump Selection Procedure

**Basic Procedure**  
- Does not consider operation efficiency

![Diagram of Basic Procedure]

**Optimized Procedure**  
- Considers operation efficiency

![Diagram of Optimized Procedure]
Motor Modeling

No-load Losses

- **Core losses (magnetic losses/iron losses):** alternating magnetic flux produces hysteresis losses and eddy current losses in the stator and rotor cores, magnets, and other motor components

\[
P_c = \frac{\pi^2}{6} V_c B^2 f^2 a^2 \sigma = K_c V_c B^2 f^2 \quad K_c = \frac{\pi^2 a^2 \sigma}{6}
\]

where

- \(V_c\) is the volume of magnetic core in unit of \(m^3\)
- \(a\) is the lamination thickness in unit of \(m\)
- \(B\) is the peak flux density

- **Mechanical losses:** including bearing friction

\[
T_v = 10^{-7} f_0 (\nu_o n)^{2/3} D_m^3 
\]

- \(T_v\) is the bearing friction torque in unit of N\(\cdot\)m
- \(f_0\) is the bearing friction factor
- \(\nu_o n\) is the angular velocity of the rotor in rad\(\cdot\)s

**Load Losses**

- **Resistive losses (copper losses):** losses in the windings

\[
P_c = I^2 R
\]

Mechanical Design of Electric Motors: Wei Tong
Motor Modeling: Maximum Power

\[ \eta = \frac{P_{out}}{P_{in}} \]

At Steady-State:
\[ P_{in} = P_{out} + Q_{out} \]
\[ Q_{out} = P_{in} (1 - \eta) \]

\[ T_{winding} = [P_{in} \times (1 - \eta) \times \sum R_{total}] + T_{surrounding} \]

\[ Q_{flow} \]

\[ R_{contact} \]
\[ \frac{L}{kA} \]
\[ \frac{1}{hA} \]
Motor Model: Validation

http://www.maxonmotorusa.com/
Battery + Motor Configuration Case Study

70W

- 0.140 kg
- R = 0.608 Ohm
- Kt = 0.036 Nm/A

100W

- 0.390 kg
- R = 1.01 Ohm
- Kt = 0.091 Nm/A

- 3600 run time
- Picked 4 steady-state operating points
- Calculated overall system weight, battery + motor

http://www.maxonmotorusa.com/
Motor Case Study: Results

Motor+Battery Weight Comparison

<table>
<thead>
<tr>
<th>Torque</th>
<th>System Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05 Nm, 300 rad/sec</td>
<td>0.2</td>
</tr>
<tr>
<td>0.28 Nm, 200 rad/sec</td>
<td>0.8</td>
</tr>
<tr>
<td>0.39 Nm, 150 rad/sec</td>
<td>1.0</td>
</tr>
<tr>
<td>0.5 Nm, 100 rad/sec</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Increasing torque
Large vs. Small Motor

- Copper Losses: \( P_c = I^2 R \)
- Resistivity: \( R = \frac{\rho L}{A} \)

If \( L \) is doubled, \( P_c \) is cut in half

\[
\begin{align*}
R &= 0.608 \text{ Ohm} \\
K_t &= 0.036 \text{ Nm/A} \\
P_c &= 13.7^2 \times 0.608 = 114 \text{ W} \\
R &= 1.01 \text{ Ohm} \\
K_t &= 0.091 \text{ Nm/A} \\
P_c &= 5.7^2 \times 1.01 = 33 \text{ W}
\end{align*}
\]

http://www.maxonmotorusa.com/
Axial-Piston Pump Modeling

Required torque w/o friction

\[ T_{pp} = \frac{P \cdot A_{p} \cdot R_{p} \cdot \tan \alpha \cdot z}{\pi} \]

Viscous friction loss, pistons and cylinder block

\[ T_{lup} = \frac{\mu \cdot \pi \cdot d_{p} \cdot (R_{p} \cdot \tan \alpha)^2 \cdot (l_{F} + R_{p} \cdot \tan \alpha) \cdot w \cdot z}{2 \cdot h_{p}} + \frac{d_{p} \cdot h_{p} \cdot R_{p} \cdot \tan \alpha \cdot P \cdot z}{2} \]

Coulomb friction, pistons and cylinder block

\[ T_{lp} = \left[ B + \frac{A \cdot b - a \cdot B}{b \cdot \sqrt{a^2 - b^2}} \right] c \cdot A_{p} \cdot P \cdot R_{p} \cdot \tan \alpha \cdot \frac{z}{\pi} \]

Viscous friction, slippers and swash plate

\[ T_{ls} = \frac{z \cdot \mu \cdot w \cdot R_{p} \cdot \pi \cdot (r_{So}^2 - r_{Si}^2) \cdot R_{p}}{h_{s}} \]

Viscous friction, valve plate and cylinder block

\[ T_{lv} = \frac{\mu \cdot \pi \cdot w \cdot (r_{v4}^2 - r_{v3}^2 + r_{v2}^2 - r_{v1}^2)}{2 \cdot h_{v}} \]

Axial-Piston Pump Modeling

Flowrate w/o leakage

\[ Q_{vp} = w \cdot A_p \cdot R_p \cdot \tan \alpha \cdot \frac{z}{\pi} \]

Leakage between pistons and cylinder block

\[ Q_{lp} = \frac{\pi \cdot d_p \cdot h_p^3 \cdot z \cdot P}{24 \cdot \mu \cdot \sqrt{(l_F + R_p \cdot \tan \alpha)^2 - (R_p \cdot \tan \alpha)^2}} + \frac{d_p \cdot h_p \cdot w \cdot R_p \cdot \tan \alpha \cdot z}{2} \]

Leakage between valve plate and cylinder block

\[ Q_{lv} = \frac{h_v^3 \cdot \lambda_v \cdot z \cdot P}{24 \cdot \mu \cdot l_v} + \frac{h_v \cdot (b_{v1} + b_{v2}) \cdot R_p \cdot w \cdot z}{4} \]

Axial-Piston Pump Model: Validation

- Model compared to Takako miniature axial-piston pump line performance

0.4 cc/rev Pump Comparison, 200 rad/sec

Efficiency (%) vs. Pressure (Mpa)

Combined System Model

Inputs
- Desired Run Time
- Desired Flowrate
- Desired Output Pressure

Iterative Component Variables
- Motor Sizing
- Pump Sizing
- Swashplate Angle

Output
Motor size, pump size, swashplate angle to achieve minimum system weight
Fixed Pump, Variable Motor Size

>155 W required, 155 W for minimum system weight

>155 W required, 245 W for minimum system weight
Fixed Motor Size, Variable Pump Parameters
0.5 hour run time, 10 Mpa, 10 cc/sec

285W Motor, 1.48 kg

193W Motor, 1.16 kg

124W Motor, 1.24 kg

95W Motor, 0.84 kg
8 hour run time, 10 Mpa, 10 cc/sec

285W Motor, 8.11 kg

193W Motor, 7.23 kg

124W Motor, 7.97 kg

95W Motor, 8.04 kg
Uses for the Program

• Can be used to provide an exact custom solution for a minimum-weight power supply

• Could be used to help guide selection of off-the-shelf components
  – Fix pump and select optimal motor size
  – Fix motor to select optimal pump size
Next Steps

• Expand from steady-state to a quasi-static analysis
• Eventually consider dynamic operation
• Create test stand to validate system modeling and explore optimized integration techniques
Conclusions

• Required system pressure, flowrate, and runtime are what drive an optimized design

• A system that is optimized for one set of desired outputs will likely not be a minimum-weight solution for another set of outputs
Questions?