Hydraulic Flywheel Accumulator for Mobile Energy Storage

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Outline

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   III. Research Goals and Progress

II. Modeling
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   III. Kinetic Losses

III. Prototype and Experimental Setup

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OVERVIEW
Why Hybridize a Powertrain?

- Recapture kinetic energy otherwise dissipated as heat during braking events
- Downsize engine and run at peak efficiency point without compromising vehicle performance
- With “plug-in” capability, utilize cleaner energy sources for vehicle propulsion
# Hydraulic vs. Electric Powertrain

<table>
<thead>
<tr>
<th>Component</th>
<th>Hydraulic Powertrain</th>
<th>Electric Powertrain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component Weight</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Component Cost</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>ESS Lifetime</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>ESS Power Density</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td><strong>ESS Energy Storage Density</strong></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
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Li-Ion Battery Energy Density: 432 $\frac{kJ}{kg}$  
Hydraulic Accumulator Energy Density: 6 $\frac{kJ}{kg}$
Pressure vs. SOC

In a traditional accumulator, pressure varies with state-of-charge.

\[ E = P_{\text{charge}} V_{\text{charge}} \ln \left( \frac{V_{\text{charge}}}{V_{\text{gas}}} \right) \]
Flywheel-Accumulator Concept

- Rotating Pressure Vessel
- Piston Separates Compressed Gas and Oil
- Torque is applied at the gas side
- Two Energy Storage Domains:
  - Hydro-Pneumatic
  - Rotating Kinetic

\[ E = E_{pneumatic} + E_{kinetic} = P_{charge} V_{charge} \ln \left( \frac{P_{max}}{P_{charge}} \right) + \frac{1}{2} I_{max} \omega_{max}^2 \]
Analyzing Fluid Pressure

\[
P(r) = \frac{\rho \omega^2 r^2}{2} + P_s
\]

PS = P_{charge} \left( \frac{V_{\text{charge}}}{V_{\text{gas}}} \right) - \frac{1}{4} \rho \omega^2 r_i^2

Influences on System Pressure:

- Adding Oil Increases Pressure
- Increasing Angular Velocity Decreases Pressure
Flywheel-Accumulator Concept

- Pressure rises as flywheel kinetic energy is extracted
- More pneumatic energy is stored for the same system pressure.
- Less kinetic energy is required to maintain pressure.
- Potential for higher efficiency than a spatially separated combination of flywheel and accumulator

\[ P(r) = \frac{\rho \omega^2 r^2}{2} + P_s \]

\[ P_s = P_{\text{charge}} \left( \frac{V_{\text{charge}}}{V_{\text{gas}}} \right) - \frac{1}{4} \rho \omega^2 r_i^2 \]
Research Goals

• Specify physically feasible design
• Model performance and optimize design parameters to maximize energy capacity and efficiency
• **Build and test medium energy prototype**
• Refine model and for higher energy levels.
MODELING
Architecture

Steel liner with circumferential composite filament winding
- Composite provides high hoop strength
- Liner ensures piston sealing and alleviates radial tensile stresses in composite

![Diagram of Steel liner with circumferential composite filament winding]
Architecture

- Axial and radial ports in the axle facilitate transport of oil
- The axle, housing, and end caps are radially unconstrained to one another
- Retainers and radial pins provide axial and tangential constraints between components
Hydraulic Losses

• Axle Port Losses

\[ \Delta P = \frac{1}{2} \rho_o u^2 \left( \frac{f L}{D} + k \right) \]

• HSRU Leakage

\[ \dot{W}_l = P_s \dot{V}_l = \frac{P_s^2 \pi d_s c_s^3}{12 \mu l_s} \]
Kinetic Losses

• Bearing losses
  \[ W_b = 2 \omega T_b = \frac{\mu_b(m + m_o) \omega^3 r_{ecc} d_{b,i}}{2} \]

• Aerodynamic drag
  \[ W_a = C_m \rho_{ch} \omega^3 r_o^5 \]

• HSRU Viscous Dissipation
  \[ W_{vh} = \mu \left( \frac{\partial w}{\partial y} \right)^2 = \frac{\mu \pi d_s^3 l_s \omega^2}{4 c_s} \]

• Pump/Motor losses
  – Use modified McCandlish and Dorey model
  – Assume one set of loss coefficients provides roughly accurate loss estimates for a range of PM sizes

• Spin-Up Losses
Optimization Method

- Multi-Objective Genetic Optimization

<table>
<thead>
<tr>
<th>Geometric</th>
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</thead>
<tbody>
<tr>
<td>Housing inner radius</td>
<td>$r_i$ [cm]</td>
</tr>
<tr>
<td>Housing outer radius</td>
<td>$r_o$ [cm]</td>
</tr>
<tr>
<td>Housing length</td>
<td>$l_h$ [cm]</td>
</tr>
<tr>
<td>Housing liner thickness</td>
<td>$th_l$ [mm]</td>
</tr>
<tr>
<td>Axle port diameter</td>
<td>$d_i$ [mm]</td>
</tr>
<tr>
<td>HSRU seal clearance</td>
<td>$c_s$ [$\mu$m]</td>
</tr>
<tr>
<td>HSRU seal length</td>
<td>$l_s$ [mm]</td>
</tr>
</tbody>
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<table>
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<tr>
<th>Operational</th>
<th></th>
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<tbody>
<tr>
<td>Maximum angular velocity</td>
<td>$\omega_{\text{max}}$ [rad/s]</td>
</tr>
<tr>
<td>Charge pressure</td>
<td>$P_c$ [MPa]</td>
</tr>
</tbody>
</table>

Energy density

$$u_d = \frac{E_d}{m + m_{PM,s}}$$

Drive cycle efficiency

$$\eta = 1 - \frac{W_{\text{loss}}}{\int_t |\dot{W}_t| \, dt + W_{\text{loss}}}$$
Selection of a Prototype Design

- Heavy solutions incur high rolling resistance
- Very energy-dense solutions incur high losses
- Minimize $W_{dc}$ and $E_d$

System mass, $m_{sys} = 39.3$ kg
Energy density, $u_d = 8.77$ kJ/kg
Energy capacity, $E_d = 81.8$ W-h
Mass, excluding PMs = 32.3 kg
Capacity ratio, $R_c = 76.3$
Housing safety factor = 7.35
Storage PM displacement, $D = 0.63$ cc/rev
Packaging volume (approx.) = 48.6 liters
Drive cycle losses, $W_{loss} = 79.2$ kJ
Drive cycle efficiency, $\eta = 86.8\%$
Usage ratio, $R_u = 1.97$
Pressure fraction, $f_{pressure} = 48.0\% (+26.8\%/-21.2\%)$

Diagram shows a graph with $E_d$ (W-h) on the y-axis and $u_d$ (kJ/kg) on the x-axis. The graph includes points indicating Accumulator-like and Flywheel-like performance with respective efficiency ($\eta$) values.
PROTOTYPE AND EXPERIMENTAL SETUP
Prototype Components
Chamber and Drive Section
PRELIMINARY
EXPERIMENTAL RESULTS
Flywheel Mechanical Efficiency

Motor Mechanical Efficiency

\[ \eta_{m,m} = \frac{T_{flywheel}}{T_{ideal}} = \frac{I_{design} \alpha_{flywheel}}{T_{ideal}} \]

Pump Mechanical Efficiency

\[ \eta_{m,p} = \frac{T_{ideal}}{T_{fw}} = \frac{T_{ideal}}{I_{design} \alpha_{flywheel}} \]
Hydraulic Pump/Motor Volumetric Efficiency

\[ \eta_v = \frac{\dot{V}_a}{\dot{V}_i} \]

\[ \eta_v = \frac{\dot{V}_i}{\dot{V}_a} \]
Rotary Union Leakage

\[ W_i = \frac{p_s^2 \pi d_s c_s^3}{12 \mu ol_s} \]
Future Work

• Explore loss mechanisms at higher flywheel speeds
• Explore the effect of fluid spin-up on HFA performance
• Implement the HFA prototype in a simulated drive cycle
• Use validated models to explore benefits of scale
Thank You