Individual Electro-Hydraulic Drives for Off-Road Vehicles (a DOE supported project)

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Basic idea

Classical centralized architecture

Hydraulic Individualization

- Decentralized valve group independent metering edges
- Separate use of motor and pump

Electrification
Electric – Hydraulic Hybrid architecture

Main features
✓ Self contained individual drives
✓ No fluid throttling
✓ Energy recuperation
✓ Reduced ICE size
✓ Enables smart actuators, operating as modern “plug & play” elements
✓ Zero emission modes

DOE Objective: Lower power consumption of the fluid power system up to 70%
Key components

4-quadrant EH hydraulic unit

Individualized EH system

Technology demonstration
reference vehicle
Off-road construction vehicle: skid-steer loader **Case TV 380**

- **Machine Main Specification**
  - **Engine Type**: Diesel, Turbo – Direct Injection, 4 cylinders
  - **Max power**: 90 hp [67 kW]
  - **Fuel Capacity**: 25.5 gal [96.5 L]
  - **Max Standard flow**: 24.2 gpm [91.5 L/min]
  - **Machine Weight**: 10,207 lb [4630 Kg]
  - **Engine speed**: 1150-2500 rpm

- Two functions (boom, bucket) considered for the technology demonstration
- Machine instrumented for baseline measurements of hydraulic power consumption
- Tests representative of typical machine duty cycle
Reference vehicle

Case TV380

Instrumentation:
- Pressure sensors
- Position sensors
- Flow metering

Cylinders

Lift Cylinder
Tip Cylinder
Bucket

Pump

Boom

Open Center Valves

Hydraulic Couplers

Auxiliary Quick Disconnections

Secondary Auxiliary Quick Disconnections

Gear Pump interface to Tandem Pump

Line 1
Hyd Oil Filter
wl 50psi Bypass

Oil Cooler
wl 75psi Bypass

PR1 PR2 PR3

Instrumentation:
- Pressure sensors
- Position sensors
- Flow metering
Boom test

Pump power [kW]

Raise  Lower

Pressure in chamber [bar]

$F$

$p_2$  $p_1$

high load – low speed

low load – high speed
Open Center System

Boom control

Raise

Lower

High pressure
Low pressure
Open Center System

Raising phase (resistive)

Lowering phase (overrunning)

Area function plot (lowering)

\[ F \]

\[ \Omega_{BT} \]

\[ \Omega_{PA} \]

\[ \Omega_{PT} \]

\[ \dot{\chi} \]

\[ \Omega_{PB} \]

\[ \Omega_{AT} \]

\[ \dot{\chi} \]

Equivalent \[ \Omega \] [mm²]

command current lowering [mA]
Power Demands

Full command, 1000 pounds load

Essential for sizing the EHA
Power Demands

Pump Power

- Raising
- Lowering
- Bucket down
- Bucket up

Pump Power [kW]

Engine Speed [Rpm]
proposed solution
Proposed Architecture

- EHA units are powered by a vehicle DC power distribution network.

- Power electronics convert DC voltage into three-phase AC currents to regulate electric machine torque, and thus pump output.
Proposed Architecture
Working Modes

High pressure
Low pressure

\[ \Delta p > 0 \quad \Rightarrow \quad F = p_1 A - p_2 a \]

\[ Q_{acc} = Q_a (\varphi - 1) \]

\[ Q_{acc} = Q_a (\varphi - 1) \]

\[ F = p_1 A - p_2 a \]

\[ \Delta p \]

\[ F < 0 \]

\[ F > 0 \]
Working Modes

\[ \Delta p \]

\[ F < 0 \quad F > 0 \]

\[ \dot{x} \]
Simulation

Model of the hydraulic system

Model of the mechanism

Boom

Lift Cylinder

Tip Cylinder

Bucket

Bucket

Tip Cylinder

Lift Cylinder

Boom

Model of the hydraulic system

Model of the mechanism
Simulation

A1

A2

B1

B2

BUCKET

TILT CYLINDER

LIFT CYLINDER

ARM1

ARM2
Simulation

Displacement tracking

Load data from tests

\[ \eta_{vol} \times \eta_{hm} \]
Simulation
Results: boom cycle

Power Comparison (close-loop)
Average EngRpm: 1320Rpm

For the proposed system:
- results based on simulation
- regenerates energy when lowering
Results: boom cycle

Energy Saving

\[ \eta = \frac{E_{\text{ref}}}{E_{\text{EHA}}} \times 100\% \]

Remarks

✓ Closed vs open circuit architecture

✓ Independence on load

\[ \eta = \frac{E_{\text{ref}}}{E_{\text{EHA}}} \times 100\% \]
Results: boom/bucket cycle

Power Comparison (close-loop)
Average EngRpm: 2448 Rpm  \( \eta = 79\% \)

- Measured Pump Power [kW]
- Evaluated EHA Power [kW]

Time [s]

- Raise boom
- Bucket down
- Buc up

Energy Saving

- Engine Speed [Rpm]
EH unit
Model Integration

**HYGESim** *(HYdraulic GEar machines Simulator)*

- **Geometrical Module**
  - Flexible geometry from CAD
  - Asymmetric teeth
  - Cycloidal-involute Profile
  - Helical Gears

- **Fluid-Dynamic Module**
  - Analysis of Main Flow
  - Effect of Porting grooves
  - Aeration and Cavitation

- **Lateral Gap Module**
  - Fluid Structure and Thermal Interaction

- **Micro-Motion Module**
  - Evaluation of Gears’ Micro-Motion

- **Journal Bearing Module**
  - Fluid Structure Interaction

- **Loading Module**
  - Evaluation of Instantaneous Radial Forces and Torque

- **Noise FEM/BEM Module**
  - Fluid-Borne Noise
  - Structure-Borne Noise
  - Air-Borne Noise

**CAD Drawings**

*HYGESim* is a hydraulic gear machines simulator that integrates various modules for comprehensive analysis of gear systems.
Model Integration

Operating Conditions

Winding Configuration

Magnetic Material Characterization

Vehicle power requirements; EHA requirements; manufacturability constraints; ...

Electric Drive Optimization

Geometry Candidate

Create feasible geometry

Electric Analysis

Leakage and magnetizing inductances, Ohmic resistance, proximity effect, ...

Control

Select current commands, winding and semiconductor losses, ...

Magnetic Analysis

Core losses, torque, ...

Set of optimal design solutions

Electric drive performance

Mechanical output
Objective functions

1. Minimize Cycle Power
2. Minimize EH Volume
3. Minimize Flow Ripple
4. Minimize Torque Ripple

Optimization

Problem Definition

Design Goals → Parametrize Problem → Generate Design → Calculate Performance → Adjust Parameters

Optimize for Problem

$x_{cyl}$ → $t_{raise}$ → $t_{lower}$
Optimization

Minimize Volume:

\[ \begin{align*}
\theta_1 & \quad X_1 \\
\theta_P & \quad X_3 \\
\theta_3 & \\
\end{align*} \]

\( \eta_{\text{EHA}} \)

- Nominal
- Peak

\( \Delta p \) [bar]

\( \omega \) [rpm]
Arrangement
Arrangement
Arrangement
Conclusion
Remaining challenges

O1. EH unit
- Design integration including alternative cooling solutions
- Performance evaluation internal gear vs external gear design
- Identification of tolerances and fabrication process
- EH Testing and verification of performance

O2. EH module
- Space limitation on the demo vehicle for applications
- Simultaneous actuation of multiple actuators
- Prototype implementation and testing

O3. Technology Demonstration
- Supervisory controller for energy management
- Zero emission mode of operation
- Integration of energy generator and power electronics
- Performance measurements