OPTIMAL CONTROL AND ENERGY-SAVING ANALYSIS OF COMMON PRESSURE RAIL ARCHITECTURES: HHEA & STEAM

Jacob Siefert and Perry Y. Li
Department of Mechanical Engineering,
University of Minnesota
Minneapolis, Minnesota 55455
Email: {siefe009, lixxx099}@umn.edu

ABSTRACT

In recent years several novel hydraulic architectures have been proposed with the intention of significantly increasing system efficiency. Two of these architectures, Steigerung der Energieeffizienz in der Arbeitshydraulik mobiler Arbeitsmaschinen (STEAM), and the Hybrid Hydraulic-Electric Architecture (HHEA), use a system of multiple common pressure rails (CPRs) to serve the multiple degrees-of-freedom of the machine. The key difference is that STEAM throttles hydraulic power from these rails while HHEA combines electric and hydraulic power to meet actuator demands. As a throttle-less architecture, HHEA is expected to save more energy than STEAM at the expense of added complexity. Therefore, it is useful to quantify this additional energy saving.

Both systems have discrete operational choices corresponding to how the CPRs are utilized for each actuator. It is necessary to determine optimal operation for each of these architectures for analysis and fair comparison. Techniques for optimal operation of the HHEA have been developed previously from the Langrange multiplier method. Applying the same optimal control method to STEAM encountered some technical challenge leading to the optimal control algorithm not being able to satisfy certain constraints. The issue is analyzed and solved by adding noise to the optimization.

Using this proposed algorithm, case studies are performed to compare the energy-saving potentials of STEAM and HHEA for two sizes of excavators and a wheel-loader performing representative duty cycles. The baseline is a standard load-sensing architecture. Results show that STEAM and HHEA can reduce energy consumption between 35-65% and 50-80% respectively.

1 INTRODUCTION

Off-highway mobile machines in construction, agriculture, and turf industries traditionally use hydraulics for power transmission due to unmatched power density. Throttling valves are the primary method of control, providing precise position control at the expense of efficiency. Average efficiency of existing mobile machine transmissions is 21% [1]. Machine efficiency (with engine) is only 7%.

Two novel hydraulic architectures, STEAM (Steigerung der Energieeffizienz in der Arbeitshydraulik mobiler Arbeitsmaschinen) proposed by researchers at RWTH Aachen [2] and the Hybrid Hydraulic-Electric Architecture (HHEA) [3] proposed by our group both utilize common pressure rails (CPRs) to achieve higher efficiencies. STEAM and HHEA use multiple CPRs to reduce/eliminate the need for throttling and are regenerative.

Both STEAM and HHEA can be represented generically by Fig. 1. Note that the electrical buses and batteries are not used for STEAM but are shown for the case of the HHEA. The key difference between STEAM and HHEA is how each of the control modules achieve modulation of the hydraulic power provided by the selected CPRs.

STEAM uses throttling valves (Fig. 2) which limits the possible selected CPR force/torque to be either higher or lower than the drive cycle force depending on the direction of the actuator velocity and load force/torque. For example, if a linear actuator is moving against a resisting load, the selected CPRs must provide...
a force of greater or equal magnitude and opposite in direction to the load. The difference between the CPR force and drive cycle force is throttled away by the infinite position throttling valves.

HHEA uses a hydraulic-electric control module (HECM) to combine the hydraulic power with electrical power to meet the power requirements of the actuator (Fig. 3). The motivation for HHEA is to achieve the benefit of electrification for high power machines without the cost of high power electric machines. This is accomplished by using the CPRs to provide the majority of power hydraulically, and using small electric machines to modulate this power for precise control. This approach is throttle-less (all valves are switching on/off valves) and while component losses are incurred, the majority of modulating manifests as charging/discharging a central battery. It is intended to keep electrical components small by limiting the modulation that they must account for. This is achieved by supplying hydraulic power close to that needed to perform the drive cycle. In comparison, direct electrification using electro-hydraulic actuators requires that all power must be generated by the electrical components. Detailed rationale and other efficiency and control benefits of HHEA are discussed in [3].

Since control is achieved in a throttle-less manner, HHEA efficiency should exceed that of STEAM at cost of additional complexity. Determining the energy saving effects of the HHEA and STEAM with respect to baseline (often load-sensing) architectures is essential to defining this architectural trade-off. Furthermore, to fairly compare the architectures, it is important that they are both operated optimally. A method to determine the optimal operation of the HHEA was presented in [4]. The same technique is applied to STEAM. An alteration to the method was required due to a mathematical grouping of drive cycle points and is solved by adding a small amount of noise to the power loss decisions.

The rest of the paper is organised as follows. Section 2 provides a summary of the architectures and modeling assumptions. Section 3 defines an optimization method to determine optimal operations and details modifications to handle constraint discretization. Section 4 presents results from drive cycles provided by original equipment manufacturers for 5 and 20 ton excavators and a 20 ton wheel-loader. Concluding remarks are made in section 5.

2 System Modeling

Drive cycles are known beforehand and consist of force/torque and velocity trajectories for each actuator of a machine. Optimal operation of STEAM and HHEA is defined as the trajectory of discrete valve positions (does not include proportional valves in STEAM) that minimizes energy use for the drive cycle. Thus the trajectory of discrete valve positions is the decision variable over which the energy use is optimized for a drive cycle. This necessitates a model of operating conditions
and power losses for system components given a drive cycle and a combination of valve positions at a given time.

A static modeling framework is used to capture key component losses during system operation, ignoring pressure and valve dynamics. This allows for an optimization approach that is computationally much less expensive than approaches such as dynamic programming (see e.g. [5] and many others). While dynamic programming can capture more detailed losses, the algorithm must solve each time in sequence which significantly increases computational effort.

2.1 CPR Architecture Decisions

Discrete CPR valve positions determine the selected pressures, \( P_L \) and \( P_H \) for each actuator (Figs. 2 and 3). For HHEA’s linear actuator service, the side of the actuator to which the hydraulic pump/motor is connected is also determined by a discrete directional control valve. There is a finite number of combinations for these discrete valve positions for a given machine. Let the set of all discrete valve position combinations for a given machine be \( \mathcal{D} \) and note that \( \mathcal{D} \) is time-invariant. A decision variable, \( d(t) \), is defined as the trajectory over time of discrete valve position combinations where \( d(t) \in \mathcal{D} \ \forall t \in \mathcal{R} \). Each element of \( \mathcal{D} \) corresponds directly to all positions of selected CPR valves, and directional control valves (specific to HHEA).

A major implication for CPR systems is that each element of \( \mathcal{D} \), corresponds to a hydraulic force/torque \( (F_{DV}/T_{DV}) \) that would be applied to the actuator by the selected pressure rails in the absence of modulation and actuator losses. These are calculated using the ideal actuator equations for linear or rotary actuators as:

\[
F_{DV}(d(t)) = P_L(d(t))A_c - P_H(d(t))A_r
\]

\[
T_{DV}(d(t)) = \frac{D}{2\pi}(P_L(d(t)) - P_H(d(t)))
\]

where \( A_c \) and \( A_r \) are the capside and rodside piston areas for a linear actuator, and \( D \) is the displacement of a rotary actuator. Because the velocities and flow rates are known for linear and rotary actuators respectively, the only way to alter the hydraulic power from the common pressure rails is to select amongst the finite number of \( F_{DV} \) and \( T_{DV} \) options. These forces and torques must then be modulated to meet the demands of the drive cycle.

2.2 HHEA: Hydraulic-Electric Control Modules

The HHEA linear and rotary hydraulic-electric control modules (HECMs) are shown in detail in Fig. 3 for a system with 3 CPRs. The idea of HHEA operation is to select \( F_{DV}/T_{DV} \) to be close in magnitude and opposite in direction of the drive cycle force/torque, \( F/T \). In doing so, the modulation power required by the electrical components to meet actuator demands can be reduced.

This makes it apparent that component operating conditions are dependant on the drive cycle, the time point within the drive cycle, and the selected \( F_{DV}(d(t))/T_{DV}(d(t)) \). Unknown operating conditions are solved using component maps (both hydraulic and electric) and static force/torque balances described at length in [4]. The resulting hydraulic and electric HECM power losses \( (\text{Loss}_{\text{HECM,H}}(t,d(t)) \text{ and } \text{Loss}_{\text{HECM,E}}(t,d(t))) \) and battery power \( (P_{\text{battery},i}(t,d(t))) \) for the \( i \)-th actuator, are defined as functions of time and the decision variable. Losses associated with infeasible decisions or those that cause cavitation are marked as infinite.

The total HECM losses and battery power are found by summation over all \( n_t \) actuators.

\[
\text{Loss}_{\text{HECM}}(t,d(t)) = \sum_{i=1}^{n_t} \text{Loss}_{\text{HECM,H}}(t,d(t)) + \text{Loss}_{\text{HECM,E}}(t,d(t))
\]

\[
P_{\text{battery}}(t,d(t)) = \sum_{i=1}^{n_t} P_{\text{battery},i}(t,d(t))
\]

2.3 STEAM: Throttling Control Modules

The control modules for STEAM are shown in Fig. 2. Similar to an HHEA, STEAM operation attempts to select \( F_{DV}/T_{DV} \) to be close in magnitude and opposite in direction of the drive cycle force/torque, \( F/T \). This limits the throttling loss required to meet the needs of the actuator. In contrast to HECMs, throttling control modules (TCMs) can only reduce power using throttling. Thus selected \( F_{DV}/T_{DV} \) must be chosen such that by only reducing power the drive cycle demands can be met.

In this model, it is assumed that the actuator is always controlled solely by metering out. The calculated throttling losses are independent of the throttling method used (as will be shown in Eqs. (6) and (12)), however the metering out assumption is generous, allowing more decisions to be feasible during regenerative drive cycle scenarios than other metering assumptions such as proportional metering. The TCM losses for both linear and rotary actuators are shown below along with constraints ensuring feasibility of the decision.

2.3.1 Linear TCM Losses As in the HECM for HHEA, the flow rates on either side of the actuator are:

\[
Q_A = xA_{cap}, \quad Q_B = -xA_{rod}
\]
Using the selected pressures, flow rates, and drive cycle, losses are derived by subtracting the output power from the input power of the combination of the actuator and the control module:

\[
Loss_{TCM,i}(t, d(t)) = P_A Q_A + P_B Q_B + F \dot{x} \tag{6}
\]

Using a metering out assumption, it can be shown that valve decisions that result in all linear TCM losses calculated to be positive are feasible with throttling, and any feasible decision results in positive loss for each actuator. The necessary and sufficient condition for feasible valve decision for a linear actuator is:

\[
Loss_{TCM,i}(t, d(t)) \geq 0 \tag{7}
\]

In additional ensuring that the direction of flow is consistent with pressure differentials across throttling valves, it is also necessary to ensure that cavitation does not occur. If a decision is infeasible, the power losses associated with the decision are set to infinity such that it is never chosen. Referencing Fig. 2, these constraints are:

\[
P_R \geq P_B, \quad P_A \geq P_C, \quad \text{if } Q_A \geq 0 \tag{8}
\]

\[
P_C \geq P_A, \quad P_B \geq P_R, \quad \text{if } Q_A \leq A \tag{9}
\]

\[
P_C, P_R \geq P_{cav} \tag{10}
\]

where \(P_{cav}\) is the pressure at which the hydraulic fluid will cavitate. A conservative approach is to set \(P_{cav} = 0\).

### 2.3.2 Rotary TCM Losses

A hydraulic pump/motor map is used to find the required flow, \(Q_A(t)\), and the pressure differential \(\Delta P(t)\) to meet the drive cycle torque and angular velocity. The power losses in the pump/motor and total power losses in the combination of the pump/motor and the control valve are:

\[
Loss_{PM,i}(t) = \Delta P Q_A + T \omega \tag{11}
\]

\[
Loss_{TCM,i}(t, d(t)) = P_A Q_A - P_B Q_B + T \omega \tag{12}
\]

Again, the feasibility of each decision and time must be considered. Similar to (8) - (10) for linear actuators, for rotary actuators assuming metering out, the rail selection for a rotary actuator is feasible if and only if

\[
Loss_{TCM,i}(t, d(t)) \geq Loss_{PM,i}(t) \tag{13}
\]

This relationship makes sense, as it ensures the losses specific to the throttling valves must be positive.

### 2.4 STEAM & HHEA: CPR and Main Pump Modeling

A fixed displacement main pump is mounted directly to the engine, which spins at constant velocity in many off-road machines such as excavators. The output of the main pump is connected to each of the CPRs in a time-multiplexed manner, apportioning flow to meet each CPR demand. CPR demand is defined as the net flow of a CPR toward the actuators. With an additional directional control valve (not shown in Fig. 1) the main pump can both provide or absorb flow from a CPR.

As shown in Fig. 1, each CPR has an associated accumulator to help maintain near-constant pressure in the rail. A key assumption is that the accumulators are large enough to accommodate transient flow in the opposite direction from that of the net CPR flow. This allows the flow between the main pump and each CPR to be unidirectional. For example, the net flow of one CPR may be towards the actuators (or the main pump) but the accumulator may at times absorb transient return flow (or flow towards the actuators). The ability for the accumulator to store and reuse energy is an important mechanism for energy saving by avoiding energy re-circulation and associated losses through the main pump. Using these assumptions, it is assumed that accumulator losses are insignificant and are intentionally neglected.

The main pump loss associated with the i-th CPR is generated using the following procedure.

1. Assume a direction of net flow, \(V_{R,i}\). This can be found by integrating the flow use of the i-th rail, \(Q_{R,i}\).

\[
V_{R,i} := \int_{t_0}^{t_f} Q_{R,i}(t, d(t)) dt \tag{14}
\]

2. Using a pump/motor efficiency map (analytical, experimental, etc.) to determine a loss per volume constant, \(l_{MP,i}\).

\[
l_{MP,i} = \begin{cases} l_{MP,i}^P & \text{if } V_{R,i} \geq 0 \\ l_{MP,i}^M & \text{if } V_{R,i} < 0 \end{cases} \tag{15}\]

3. The i-th rail main pump energy loss can then be calculated as:

\[
EMP_i = l_{MP,i} V_{R,i} \tag{16}
\]

The total main pump energy loss of the system is then the sum of the main pump energy loss associated with each rail.

\[
EMP = \sum_{i=1}^{nR} EMP_i \tag{17}
\]

Thus the main pump losses are dependent only on the net flow of each rail, not the instantaneous flows. Note that the first rail is
not included in Eq. (17). It is assumed that the main pump losses associated with the tank CPR are negligible \( l_{MP_1} = 0 \).

3 OPERATION OPTIMIZATION

3.1 STEAM Optimization Problem Statement

Optimal operation for HHEA and STEAM is defined as the trajectory of discrete valve positions that minimizes the system energy loss for a given drive cycle. Optimal operation for HHEA also must meet a battery constraint such that the battery ends at the same charge it began with. This ensures the operation is repeatable and not dependent on starting charge. The battery is assumed to be large enough to always provide or store electrical energy.

The HHEA operation optimization was developed previously and is described in [4] in detail. The STEAM operation optimization problem is very similar. This section and the following sections will detail the STEAM optimization problem, a difficulty that arises when applying the approach in [4] to the STEAM case, and the resolution of this difficulty.

The STEAM optimization problem begins as an unconstrained minimization of the system energy loss, \( E_{total} \), over all possible decision trajectories, \( d(\cdot) \)

\[
\min_{d(\cdot)} E_{total}(d(\cdot)) \quad (18)
\]

where \( E_{total}(d(\cdot)) \) is defined as follows:

\[
E_{total}(d(\cdot)) = \int_0^T \left[ \frac{Loss_{TCM,i}(t,d(t))}{TCM \ Energy \ Loss} + \frac{E_{MP}(d(\cdot))}{Main \ Pump \ Energy \ Loss} \right] dt \quad (19)
\]

The main pump energy loss can be re-written and brought inside the integral.

\[
E_{total}(d(\cdot)) = \int_0^T \left[ Loss_{TCM,i}(t,d(t)) + \sum_{i=2}^{n_R} l_{MP,i} Q_R,i(t,d(t)) \right] dt \quad (20)
\]

The optimization problem (18) can be re-written with the minimization brought inside the integral as:

\[
\int_0^T \min_{d(t)} \left[ Loss_{TCM,i}(t,d(t)) + \sum_{i=2}^{n_R} l_{MP,i} Q_R,i(t,d(t)) \right] dt \quad (21)
\]

This significantly reduces computational time since the decisions at each time can be solved simultaneously.

3.2 Modified Langrange Multiplier Method Overview

Unfortunately, the direction of net CPR flow use is not known a-priori since they are functions of the decision variable over which the function is minimized. This means the exact form of \( l_{MP,i} \) in (15) is unknown. To handle this, [4] proposes that all possible combinations of net rail flow directions be considered. CPR flow inequality constraints are added to ensure consistency with the assumed net flow direction. Each of these optimizations is a sub-problem to the original optimization problem (Eq.(21)). To solve the original problem, all sub-problems are solved and results are compared. The sub-problems are formulated by creating a variable, \( s_i \), that corresponds to the sign of the net rail flows (and thus the assumed form of \( l_{MP,i} \)) of each CPR.

\[
l_{MP,i} = \begin{cases} \frac{P_{MP,i}}{\lambda_{MP,i}} & \text{if } s_i = 1 \\ \frac{P_{MP,i}}{\lambda_{MP,i}} & \text{if } s_i = -1 \end{cases} \quad (22)
\]

Each sub-problem is constructed as follows:

\[
\min_{d(\cdot)} E_{total}(d(\cdot)) \quad (23)
\]

\[
s_i Q_R,i \geq 0 \forall i \quad (24)
\]

Using the Lagrange multiplier method, each sub-problem is solved by constructing the dual problem of each sub-problem:

\[
\max_{\lambda \geq 0} \int_0^T \min_{d(t)} \left[ Loss_{TCM,i}(t,d(t)) + \sum_{i=2}^{n_R} (l_{MP,i} + \lambda_i s_i) Q_R,i(t,d(t)) \right] dt \quad (25)
\]

By considering the complementary slackness conditions, each sub-problem dual can be broken into sub-sub-problems in which each inequality constraint is considered to be active, or inactive. Active constraints are solved by constraining net CPR flow to 0, while inactive constraints are ignored. Sub-sub-problems are constructed as follows:

\[
\max_{\lambda_i \forall i \in \Psi} \int_0^T \min_{d(t)} \left[ Loss_{TCM,i}(t,d(t)) + \sum_{i=2}^{n_R} l_{MP,i} Q_R,i(t,d(t)) \right. \\
+ \left. \sum_{i \in \Psi} \lambda_i s_i Q_R,i(t,d(t)) \right] dt \quad (26)
\]

where \( \Psi \) is the defined as the set of rail indices for which constraints are active. All possible sub-sub-problems for all sub-problems are solved and compared to find the solution of a the
primal problem. The enumeration of all sub-sub-problems is achieved by considering three possibilities for net rail flow for each CPR:

\[ V_{R,i} > 0 \rightarrow \lambda_{MP,i} = \lambda_{MP}^R, \quad i \notin \Psi \quad (27) \]
\[ V_{R,i} < 0 \rightarrow \lambda_{MP,i} = \lambda_{MP}^L, \quad i \notin \Psi \quad (28) \]
\[ V_{R,i} = 0 \rightarrow \lambda_{MP,i} = 0, \quad i \in \Psi \quad (29) \]

The maximum number of sub-sub-problems is \(3^{n-1}\) which is found by considering all combinations of net CPR flow directions across all rails. The number of sub-sub-problems can be reduced significantly by considering whether the sub-sub-problem is feasible or a repeat. For example, for a drive cycle that performs net work on the environment, at least one CPR must be assumed to be positive.

3.3 Constraint Discretization Phenomena

Another method to solve each of the sub-sub-problems (26) is to find all combinations of active Lagrange multipliers (\(\lambda_i, \forall i \in \Psi\)) for which solutions of the inner optimization of (26), \(d(\cdot)\), satisfy active constraints. These solution trajectories are used to calculate and compare the energy losses incurred, \(E_{total}(d(\cdot))\). This is done in practice by evaluating the inner minimization of (26), also called the dual function for a given set of active Lagrange multipliers. The associated decision trajectory, \(d(\cdot)(\lambda_i, \forall i \in \Psi)\), is used to evaluate the net flow to each CPR associated with an active constraint. In this manner, the active CPR constraints, \(V_{R,i} \in \Psi(\lambda_i, \forall i \in \Psi)\), are shown to be functions of active Lagrange multipliers.

Implementing this technique with discrete data often results in some constraint error, however a range near the active constraint is often tolerable. To meet this constraint precisely, the constraint function evaluated with the optimal decision \(d^*(\lambda, t)\) for a choice of Lagrange multipliers \(\lambda\) be:

\[ V_{R,i}(\lambda) := \int_0^{t_f} Q_{R,i}^r(t) d^*(\lambda, t) dt \quad (30) \]

where \(i \in \Psi\) and \(\lambda\) consists of all \(\lambda_j, \forall j \in \Psi\) (Lagrange multipliers for all active constraints), and \(d^*(\lambda, t)\) is the optimal decision of the inner optimization (26) with the choice of \(\lambda\). In general, \(V_{R,i}(\lambda)\) should be a continuous function for the constraint to be satisfied. Unfortunately, \(V_{R,i}(\lambda)\) for STEAM were found to be a discontinuous function of the active Lagrange multipliers with discrete values, making it unlikely that a given tolerance of an active constraint could be met. This is illustrated in Fig. 4 in the no-noise case.

This is caused by a mathematical grouping of drive cycle operating points. Large sets of drive cycle points evaluate to exactly the same cost for multiple decisions at certain values of \(\lambda\). This is a result of the simplified STEAM modeling detailed in section 2 and can be shown rigorously by solving for the value of \(\lambda\) for which any two operating decisions are equal for an arbitrary drive cycle condition. An interpretation is that as an infinitesimal change in the Lagrange multipliers over one of these values, an entire set of points will change from one operating decision to another, together, leading to a discrete finite change in the constraint values. This grouping of drive cycle points causes the large discrete jumps in the active constraints function (30).

To prevent group switching and constraint discretization, it is proposed that a small amount of random noise be added to the cost function for each time and operating decision. The result is that the value of \(\lambda\) for which two operating conditions cost functions are equal will be different and dependent on the drive cycle point. This allows drive cycle points to switch decisions one at a time. By having drive cycle points switch decisions one at a time, the constraint can be met as long as the sub-sub-problem is feasible. Figure 4 demonstrates the discrete constraint phenomena (without noise added) and how adding noise to the cost function prevents large discontinuities in the constraint. For simplicity, only a single active rail constraint, \(V_{R,2}(\lambda_2) = 0\), is illustrated.

![FIGURE 4. Constraint Discretization Phenomena: The constraint without the noise power loss shows large changes in the constraint](Image)

Adding noise will result in a sub-optimal results since the cost function is slightly perturbed. This means additional energy
loss will be incurred. The goal is to bound the maximum value of the additional energy loss to ensure the solution is within an acceptable tolerance of the optimal value. This is done by making the following definitions and assumptions.

1. The added noise power loss is defined as \( X(t, d(t)) \)
2. \( X(t, d(t)) \sim U(-M,M) \). \( U(-M,M) \) defines the uniform distribution between \(-M\) and \(M\).
3. Assume every decision is incorrect. That means another set of decisions will 1) meet all sub-sub-problem constraints and 2) will result in lower power losses at every drive cycle point.
4. Assume every decision incurs the maximum additional power loss.

The maximum additional power loss is simply equal to \(2M\) since the incorrect decision cost could be decreased by \(M\) and the correct decision cost could be increased by \(M\). Thus the maximum additional energy loss due to adding noise, \(E_{noise}\), can be calculated as follows:

\[
E_{noise} = \int_0^{t_f} 2M \, dt \tag{31}
\]

Any amount of noise will numerically differentiate the points. Therefore the magnitude of noise can be small to tightly bound the maximum addition energy loss. It should be noted that making the noise small will result in smaller ranges of Lagrange multipliers that meet the constraints.

Constraint discretization also occurs for HHEA rotary actuators, however, this phenomenon was masked by linear actuators since machine operation is typically optimized for operation across all actuators. Systems with linear actuators had sufficient flexibility for the battery and flow constraints of a sub-sub-problem to be met.

4 MACHINE APPLICATIONS AND ENERGY RESULTS

This section details the results from an energy analysis produced using the optimization methods in Section 3 for 3 machines: a 5-ton excavator, a 20-ton excavator, and a 20-ton wheel loader performing representative duty cycles supplied by OEMs. Three architectures, a) load sensing (baseline), b) STEAM and c) HHEA are compared. In particular, given the added complexity of HHEA, we wish to determine the efficiency benefit of HHEA compared to STEAM.

First, key assumptions are provided for each machine and architecture.

Load Sensing Assumptions

1. Main Pump: The main pump for each machine was sized to provide the maximum flow rate required by the actuators across all drive cycles and times when operating at full fractional displacement. It is assumed that the main pump operates at a constant velocity of 2000 rpm.
2. System Pressure: First the required minimum pressure for each actuator was determined for every time. The system pressure was then found by adding a pressure margin of 10 MPa.
3. Minimum Back-side Pressure: By throttling out, the side of each actuator returning flow is pressurized (5 bar). This is often done for control purposes and was only applied to the excavators after comparing model results to analysis of experimental data provided by the OEMs.
4. Regeneration: If the back-side pressure of an actuator is larger than the system pressure, the return flow is directed to offset the main pump flow rate. Regeneration is considered for both actuators of the wheel loader while for both excavators, regeneration is only allowed for the boom and arm actuators.

HHEA Assumptions

1. Linear HECM Hydraulic P/Ms: Displacement sized such that the maximum flow can be provided at 5000 rpm. The same hydraulic pump/motor map is used for all actuators and scaled to displacements by assuming mechanical and volumetric efficiencies remain constant for the angular velocity and pressure domain.
2. CPR Placement: The maximum CPR level was determined by the peak force/torque demands across all actuators. CPR levels were spaced uniformly between 0 (tank) and the maximum CPR level.

STEAM Assumptions

1. CPR Placement: For a given number of pressure rails, the CPR placements are the same as for the HHEA.

For the cap to rod area ratios in the machines examined, uniform rail spacing can be shown to be optimal. For STEAM uniform rail placement limits the maximum possible throttling loss while for HHEA the maximum electrical modulation is minimized.

For all three architectures, the hydraulic pump/motor maps used in the assumptions above are scaled from an analytical model for an axial-piston pump in [6], and are shown in Figure 5. For HHEA, the electrical motor/gen map in Fig. 6 was generated by modeling a 3.2 kW machine using the PLECs software.

4.1 Detailed Architecture Comparison: 5-Ton Excavator Case Study

To demonstrate the difference between each architecture a case study is performed on a 5-ton excavator performing a trenching drive cycle.

Energy Definitions:
1. Positive Work: The amount of work the machine does on the environment.
2. Regenerative Potential: The amount of work the environment does on the machine.
3. Throttling Loss: Total energy throttled for control. This term also includes rotary actuator losses. For HHEA, this term is changed to be called HECM Losses.
4. Main Pump Losses: Total energy loss due to inefficiencies of the main pump.
5. Input Energy: The net work required by the output shaft of the engine to drive the main pump.

The regenerative work and input energy represent how energy enters the system, while the others represent how energy exits the system.

The baseline load-sensing results are shown in Figure 7. Notice that 50% of the energy is lost through throttling, another 18% is lost in the main pump, and regenerative energy is hardly recovered.

STEAM results with 3 common pressure rails (CPRs) are shown in Figure 8. As expected, STEAM significantly reduces throttling losses and main pump losses since each actuator can select a CPR force/torque close to what is required. This is not the case in load-sensing as the system pressure is set by the most demanding actuator. Additional reductions in main pump losses are realized by decoupling the main pump from the actuators. This allows the main pump to operate at fixed displacement avoiding poor efficiency of variable displacement pumps at low fractional displacement.

The HHEA results also with 3 CPRs are shown in Figure 9. As the HHEA is a throttle-less architecture, there are no throttling losses. However, losses associated with HECM components are associated with controlling the actuator, just as throttling losses are for load-sensing and STEAM. The HECM losses are...
significantly lower than the throttling losses from load-sensing and STEAM. This is not unexpected since primary control of actuators using an HECM is achieved by storing and using electrical energy from the battery versus solely by throttling. A small yet significant reduction is main pump losses is also observed. This is related to the decrease in input energy, since the net input energy must be provided by the main pump. These energy saving trends hold across all machines and drive cycles studied.

4.2 General Energy Saving Results

Top Graphs in figures 10-12 show the input energy results for STEAM and HHEA for varying numbers of CPRs for all 3 machines - 5ton and 22ton excavators, and the 20ton wheel loader. Input energy is normalized and shown as a percentage of the load-sensing baseline for each drive cycle.

Both the STEAM and HHEA outperform the baseline load-sensing architecture with exception of the 2-CPR STEAM 5-Tonne Excavator. A 2-CPR STEAM excavator would be expected to use more energy than a load-sensing system because the load-sensing system is already a 2-CPR system with the ability to control the pressure setting of the high pressure rail.

As expected, HHEA outperforms STEAM, however the degree to which this is true depends on the number of CPRs. STEAM performance approaches that of HHEA for large numbers of CPRs. This means the benefit of HHEA compared to STEAM at low numbers of CPRs is higher than that at low numbers of CPRs.

Furthermore HHEA performance is relatively stable with varying numbers of CPRs. This is because HHEA is a throttle-less architecture. The price of reducing the number of CPRs for HHEA can be seen in the increase in the required torque required by each HECM. The bottom graphs in figures 10-12 show the torque requirement of the electric machines for each degree-of-freedom with increasing number of pressure rails. This torque is normalized by the torque requirement if the degree-of-freedom is directly electrified using an electro-hydraulic actuator (EHA). As the number of CPRs increase, the electric machine torque (and by extension power) requirement in the HECM modules of the HHEA machines are significantly reduced. For example, for all 3 machines, with only 4 CPRs, the electric machines can be downsized to below 20% of the EHA case for all the linear degrees of freedom. The electric machines for the swing (rotary) degree-of-freedom can be further downsized if the placement of the pressure rails are optimized instead of placed uniformly.

5 CONCLUSION

A method to model and optimize STEAM architecture performance was presented, building off of a previous method presented for the HHEA in [4]. An addendum to successfully meet the rail constraints of sub-sub-problems with bounded optimality was described. The method was then applied to two sizes of excavators and a wheel-loader for many drive cycles.

Results show that HHEA outperforms STEAM which in turn outperforms the baseline load-sensing architecture. With 3 CPRs, HHEA reduce energy consumption over STEAM by additional 40%. The difference in performance is reduced as the number of CPRs increase. As the rationale for HHEA is that with sufficient number of CPRs, the size and cost of the electrical components will be reduced. A key result therefore is the trade off between the benefit of HHEA over STEAM input en-
energy and the torque/power requirements of the HECMs, and is expected to be machine and duty cycle dependent.

The results demonstrate the relative performance of each architecture, and demonstrate key trade-offs. System design would require coupling these results with other design factors such as cost to choose amongst various architectures.

ACKNOWLEDGEMENTS

This material is based upon work supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) under grant: DE-0008384.

REFERENCES


