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A HYBRID HYDRAULIC-ELECTRIC ARCHITECTURE (HHEA) FOR HIGH POWER OFF-ROAD MOBILE MACHINES

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ABSTRACT

Traditionally, off-road mobile machines such as excavators and wheel loaders are primarily powered by hydraulics and throttling valves are used to control their work circuits. In recent years, two general trends are towards more energy efficient systems and electrification. With electrification, both efficiency and control performance can be improved by the elimination of throttling losses and the use of high-bandwidth inverter control. Electrification is generally accomplished with Electro-hydraulic actuators (EHA) but they are limited to lower powered systems due to the high cost of electric machines capable of high power or high torque. This paper presents preliminary results of a new system architecture for off-road vehicles to improve efficiency and control performance. The architecture combines hydraulic power and electric power in such a way that the majority of power is provided hydraulically while electric drives are used to modulate this power. The hybrid hydraulic-electric architecture (HHEA) and its rationale are described. In addition, a case study is presented to illustrate its operation, its potential for energy saving, and its benefits of component downsizing. The case study indicates that compared to a baseline load sensing system, the HHEA has the potential to reduce energy consumption by more than 50%. Furthermore, the torque capability of the electrical components need only be $\sim 28\%$ *of what is required for the direct application of EHA.*

1 INTRODUCTION

Efficiency is an increasingly important consideration for the next generation of mobile machines. Conventional mobile machines use hydraulics as the means for power transmission, and throttling valves as the means for control. The inefficiency due to the hydraulic systems and control does not just increase fuel consumption and harmful emissions, but also necessitates larger overall system, such as engines and heat exchangers, and decreases productivity due to lower achievable speeds. In fact, the average efficiency of such machines today is only 21% [1] with respect to the engine power output. If engine efficiency is also considered, the efficiency will only be 7%.

Another driving force in the next generation of mobile machinery is electrification. Electrification, i.e. the use of electric drives, brings the potential benefits of improved energy conversion efficiency, effective control, flexible routing, high energy density storage, and less noise and leakage. Yet, electric actuation still lags far behind hydraulics in power and force/torque densities, and costs of high power electric drives are still expensive compared to hydraulic equivalents.

In this paper, a new system architecture for combining the merits of electric and hydraulic technologies for mobile machinery with multiple degrees of freedom, traditionally actuated by hydraulics, is described. The architecture is both highly energy efficient and controllable by exploiting the respective strengths of hydraulic actuation (such as power density) and electric actuation (such as controllability, efficiency and energy dense storage in batteries), while minimizing their respective weaknesses.

Here, the word hybrid has dual meanings: i.e. actuation by hydraulics or electric, and also power from prime-mover or from hydraulic or electric energy storages as in hybrid vehicles. The major weaknesses of hydraulic actuation are the relatively low component efficiency and that increasing system efficiency is often accompanied by the decrease in control performance or the increase in system complexity and bulkiness. The primary weakness of electric actuation is that high power and high torque electric machines are expensive, heavy, and bulky, and hence not appropriate for high power mobile machines. The latter limitation is due to the challenge to generate and maintain a large magnetic field to develop high force/torque. In contrast, for large scale systems, hydraulics is one to two orders of magnitude more power dense and torque/force dense than electric actuation.

The rest of the paper is organized as follows. In Section 2, different approaches to improve off-road vehicle efficiencies, hydraulically and electrically are reviewed. Section 3 describes the proposed Hybrid Hydraulic-Electric architecture (HHEA) and its motivation. Section 4 presents a case study comparing the proposed HHEA and a baseline load sensing system. Concluding remarks are contained in Section 5.

2 BACKGROUND

Conventional mobile machines, such as excavator, skid-steer/wheel loaders, and mowers, have multiple degrees-of-freedom. A state-of-the-art commercially available architecture for a multi degree-of-freedom system is a load-sensing (LS) system in which a pressure compensated pump provides a common pressure at a level that is slightly higher ($\sim$ 14 bar) than the highest pressure requirement of all the services. Throttling valves are then used to drop the pressure to the required pressure of the services. This circuit can be very efficient if all services require nearly the same pressure levels (which is not true of most systems), so that the pressure drops are kept low. However, significant throttling energy losses are incurred in typical systems, where the required instantaneous pressures differ significantly. Moreover, energy from over-running loads is typically not recaptured due to mismatch in pressures.

To improve efficiency over the LS system, it is necessary to

1. avoid using throttling valves as the primary means of control;
2. enable the system to recapture energy from overrunning/regenerative loads;
3. components should be more efficient or be allowed to operate in more efficient regimes–i.e., as efficiencies of hydraulic pumps and motors tend to drop when operating at low displacements, it would be advantageous to avoid operating them at partial displacements;
4. the operation of the engine should not be restricted but be allowed to operate at its most efficient regime.

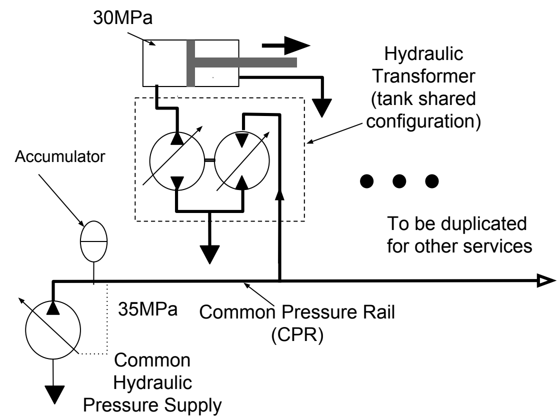

FIGURE 1. A Common Pressure Rail (CPR) with hydraulic transformer architecture.

2.1 Common Pressure Rails (CPR) with Hydraulic Transformers

A potentially efficient approach along these lines is to use a common pressure rail (CPR) supplied by a centralized hydraulic power supply, and for each degree-of-freedom, utilize a hydraulic transformer to conservatively buck or boost the CPR pressure to the required pressure (Fig. 1). This approach is throttle-less and regenerative, and potentially efficient. Moreover, using a centralized source of hydraulic power for all the services is power dense and generally allows the engine to be operated more efficiently or be downsized (for mean instead of peak power). In the past 2 decades, there has been significant research on the Innas Hydraulic transformer which has a rotatable 3-ported port plate [2], and more recently on the various transformer configurations in which a pair of variable displacement pump/motors are coupled together mechanically [3, 4]. Efficiency improvement has indeed been demonstrated using CPR with transformers [5].

Nevertheless, there are also drawbacks to transformers. They are generally not commercially available, bulky, have limited practical transformation ratios (typically < 3). Their efficiencies also decrease at partial loads since the constituent pump/motors tend to be inefficient at low effective displacements.

2.2 Multiple Pressure Rails

Because hydraulic transformers are not readily available, the multiple CPR approach has also been proposed [6]. Instead of using the hydraulic transformer to transform the pressure of a common pressure rail (CPR) to the desired pressure, multiple CPRs are used. The pressure rail with a pressure slightly higher than the desired pressure is selected using switching valves. The

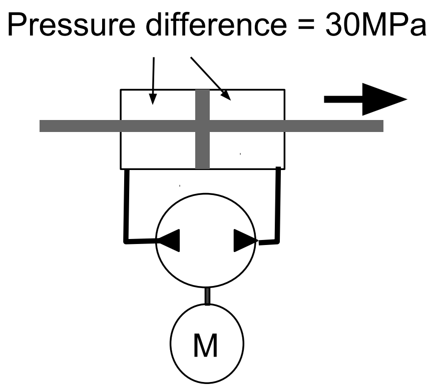

FIGURE 2. An electro-hydraulic actuator setup for an double ended actuator.

inevitable difference between the selected CPR pressure and desired pressure is throttled away. The throttling loss can be minimized with a larger number of CPRs at the expense of complexity and cost.

2.3 Displacement Control

Displacement control is another hydraulic approach to improve efficiency [7]. This requires, for each service, one variable displacement pump to be driven, on a common shaft, by the engine. By avoiding throttling, generating power only as needed, and recuperating energy from overrunning load, this approach is potentially efficient. The drawbacks are that the variable displacement pump/motors can suffer from low efficiency at partial loads when they need to operate at low displacements. Control performance is a potential issue due to fluid compressibility in the long fluid lines and the limited bandwidth to control the pump/motor displacement, especially at low rotational speeds.

2.4 Electro-hydraulic actuators - EHA

An electrical approach to improving efficiency is to utilize an electro-hydraulic actuator (EHA) setup in which an electric motor is used to drive a fixed or variable displacement hydraulic pump/motor to control the flow rate to a single actuator (Fig. 2). Besides being throttle-less, regenerative, and efficient, it also has good control performance.

High efficiency is due to high energy conversion efficiency of the electric drives (combination of power inverters and electric motor/generators can have over 95% efficiency) and the fact that the hydraulic pump/motor can be a fixed displacement unit. Indeed efficiency of 80-95% over a broad operating range providing 29% energy saving has been demonstrated with EHA (see e.g. [8]). High control performance stems from the ability to adjust the torque virtually instantaneously, so as to control the speed of the hydraulic pump and to precisely control the flow in and out of the hydraulic actuator.

However, because all power is provided electrically, high power electric drives, which are prohibitive in cost and size, are needed. Therefore, the EHA approach is currently only practical for low power machines.

Although each of the above hydraulic-only and electric-only approaches would be more efficient than the current state-of-the-art load-sensing (LS) approach that uses throttling control, their adoption are prevented by their respective drawbacks. The paper proposes an alternate architecture to leverage the comparative advantages of electric and hydraulic technologies for mobile machinery with multiple degrees-of-freedom in order to attain the goal of dramatically improving efficiency.

3 HYBRID HYDRAULIC-ELECTRIC ARCHITECTURE (HHEA)

The motivation is to achieve throttle-less and regenerative flow control using electric drives while the majority of the system power is provided hydraulically from a set of multiple common pressure rails. This will allow the benefit of electrification to be realized without requiring large electric machines.

To accomplish this goal, the HHEA illustrated in Fig. 3 is proposed. Each degree-of-freedom of the mobile machine is controlled by a hydraulic-electric control module (HECM) that combines hydraulic power from a set of common pressure-rails (CPRs) and electric power from a D.C. bus to produce precisely controlled hydraulic pressure/flow to drive linear and rotary hydraulic actuators. The architecture is augmented with energy storages in hydraulic accumulators on the CPRs and in electric batteries on the D.C. bus. The CPR pressures can be constant (simpler) or varying (more versatile). Whereas Fig. 3 shows 3 pressure rails at tank, medium and high pressures, the architecture can easily be extended to accommodate any number of pressure rails.

Each HECM (Fig. 3 bottom) is a combination of an electric motor/generator (permanent magnet AC synchronous motor) and a fixed displacement hydraulic pump/motor[1]. The HECM pump/motor is in series with the selected CPRs and the actuator. With this topology, flow to the actuator can be precisely controlled by controlling the HECM pump/motor. Moreover, the HECM needs only produce the difference between the desired pressure at the actuator and the pressure of the selected CPR. For rotary actuators, the HECM can be simplified as the pump/motor and electric drive can be directly coupled to the load (see right hand circuit in Fig. 3). This offers a more direct (and hence, more efficient) path of actuating and recuperating energy from the rotational degree-of-freedom.

[1] Variable displacement units would provide additional freedom for control at the expense of cost and complexity.

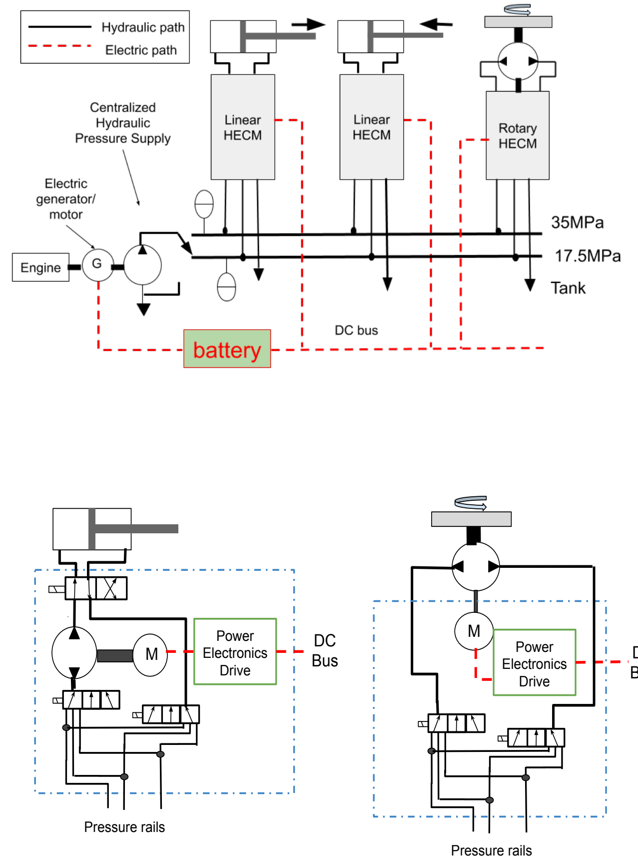

FIGURE 3. Top: The hybrid hydraulic-electric architecture (HHEA) with 3 services and 3 pressure rails at 0 MPa, 17.5 MPa, and 35 MPa. The electric generator/motor at the engine is optional. Bottom: Linear and rotary Hydraulic-Electric Control Modules (HECMs).

A set of switching valves and a directional control valve are used to select which CPRs are connected to HECM and which actuator port is connected to the pump/motor. For example, in order to produce a desired pressure of 30 MPa, the HECM can select the 35 MPa pressure rail, whereas for the desired pressure of 5 MPa, the tank pressure line may be connected. In both cases, the electrical machine needs only buck or boost 5 MPa.

By controlling the electric motor/generator via efficient power electronic converters, the flow to the hydraulic cylinder or the speed of the rotary service can be controlled precisely and responsively. However, the torque required of the electric generator/motor, which is proportional to the pressure across the pump/motor, needs only be responsible for the difference between the selected CPR pressure and the required pressure of the cylinder/rotary load. If there are n CPRs (including tank), there are potentially $2n^2$ options (may not be unique) of connecting the HECM with the load and supply. Thus, by choosing the pair of pressure-rails/return that most closely provide the desired pressure differential across the cylinder chambers, the torque and power requirements of the electric motor/generator will be significantly reduced. Note that the electric drive can either increase (boost) or decrease (buck) pressure from the selected CPR. This is in contrast with the multiple pressure rail with throttling valves approach where the throttling valves must dissipate energy. Even with only 2 CPRs (including return), the torque (and hence, size) required of the electric drive is reduced by 50%, compared to a purely electrically driven conventional EHA without hydraulic assist (Fig. 2). With three or four CPRs, the electric drive can be reduced by 75% and 83% (i.e. $(2n-3)/(2(n-1))$) respectively, etc. if the pressure levels of the rails are uniformly distributed. Further reduction can be achieved if the pressure levels are optimized.

The CPRs can be efficiently and compactly supplied by a single centralized hydraulic power supply. The outlet of the fixed displacement pump can be alternately connected to the rails or unloaded. This enables the pump to always operate efficiently at full displacement. To avoid frequent switching of the supply pump, or large variations in the pressure levels of the pressure rails, accumulators with sufficient capacities can be installed to each rail. Accumulators also allow for efficient regeneration to occur without first motoring the power supply, thus avoiding the associated conversion losses.

The proposed architecture combines electrical actuation and hydraulic actuation in a complementary manner to simultaneously improve efficiency, performance and compactness. As pointed out earlier, previous approaches have focused on the power source as exclusively hydraulic or electric. By combining them, the limitation of each actuation approach can be avoided.

The HECM can be viewed as:

1. an EHA with hydraulic assist - thus reducing the size of the electric motor and drive; or
2. an input shared hydraulic transformer with one of hydraulic pump/motors replaced by an electric motor. This is expected to improve efficiency (with the use of fixed displacement pump/motor) and control performance (with electric drive for high bandwidth control); or
3. a power steering valve with an electric motor controlling the steering.

The proposed architecture is throttle-less and regenerative. It is highly modular and applicable to a wide range of machines, including excavators, wheel- and skid steer- loaders, and mowers, etc.

The power density and efficiency advantages of the HECM can become even greater if the hydraulic pump/motor and the electric motor/generator are intentionally integrated tightly and designed to operate at high speeds. This will have the potential of reducing mechanical friction through fewer bearings and elimination of shaft seals; reducing energy conversion losses through reducing the number of energy conversion stages; improved power density of the electric motor and motor drive electronics enabled by hydraulic cooling of the electric components, and improved control response by reducing the rotational inertia of the integrated electric-hydraulic machine.

In summary, the proposed hybrid hydraulic-electric architecture has these features:

1. hydraulics as the majority means of power transmission
2. a centralized hydraulic power supply feeds the pressure rails
3. engine operates in efficient regimes and can be downsized
4. throttling is not used for control
5. precise control of hydraulic power via the electric power-inverter and the electric-drive
6. reduced size of the electric drives (motor/generator and inverter) compared with systems with only electric actuation
7. use of fixed displacement hydraulic pump/motors ensures high hydraulic efficiency,
8. can recuperate regenerative energy either electrically or hydraulically
9. flexibility of storing energy either in hydraulic accumulators or electric batteries
10. highly modular and applicable to many platforms.

4 CASE STUDY

To illustrate the potentials for the HHEA, load sensing and HHEA simulations were conducted for the work circuit of a construction machine with representative duty cycle data provided by an OEM. The duty cycle consists of two actuators extending and retracting at different times, and with portions of the cycle being overrunning.

The peak forces, velocities and power for each actuator for the duty cycle are given in Table 1. The peak and corner powers (max. speed $\times$ max. force) correspond roughly to the power requirements of the electric machines in conventional EHAs with variable or fixed displacement pump/motors respectively.

TABLE 1. Force, speed and power requirements of duty cycle.

Actuator	Peak force (kN)	Peak speed (m/s)	Peak power (kW)	Corner power (kW)
1	1062	0.62	103	658
2	581	0.52	97	302

4.1 Baseline: Load sensing

As a baseline, the energy consumption for the system if a load sensing system is used is first evaluated. Here, a 401cc common load sensing pump at 1800 RPM supplies flows to both actuators at a pressure dictated by the higher pressure requirement of the two actuators and a 13.8bar (200 psi) pressure margin. The main pump does not supply flow to actuators when they experience overrunning loads. The efficiency map of LS pump is obtained by scaling the efficiency map of a 107cc axial piston pump described in [9] and is shown in Fig. 4. In the scaling process, it is assumed that the efficiency map with respect to the fractional displacement ($\in [-1,1]$) is unchanged. The scaling of the load sensing pump was determined based on the flow requirements to the actuators such that the peak flow requirement would be met at full displacement for the assumed engine speed. This also tends to maximize efficiency by driving all operating points to higher fractional displacements.

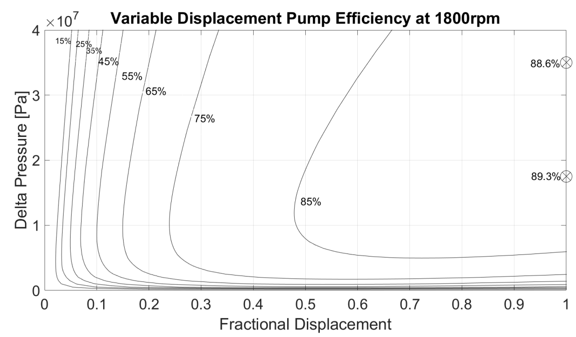

FIGURE 4. Efficiency maps of the hydraulic pump/motor at 1800 RPM used in this study.

The energy consumption, and energy losses due to throttling and LS pump inefficiencies are shown in Fig. 5. The ratio of positive actuator work (i.e. $F \cdot \dot{x} > 0$) to energy consumption is

$$\eta_{LS} = \frac{\text{Positive work}}{\text{Input Work}} = 41.3\%.$$

The majority of the losses is contributed by the LS pump whose mean efficiency is $\approx 60\%$. If it is allowed to operate at variable speed, its operating efficiency can be improved to avoid operating at low fractional displacements. Throttling is the second largest contributor to loss. Here, more than half of the throttling loss is associated with dissipating the wasted overrunning load. Recuperating this energy can potentially increase the efficiency by 17%.

4.2 HHEA

For the HHEA, we choose a set of 3 uniformly distributed pressure rails at 0 MPa, 17.5 MPa, and 35 MPa. The pressure rails are assumed to be fed by one common fixed displacement pump/motor that connects to the rails sequentially to maintain the desired pressures of the rails. For simplicity, the accumulator on

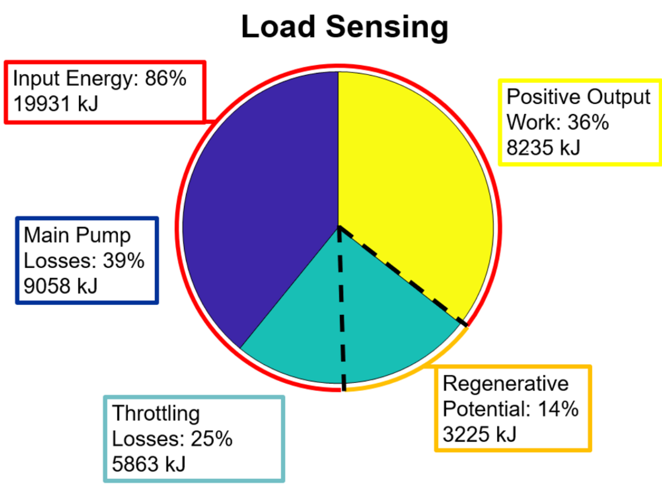

FIGURE 5. Energy use in the load sensing system.

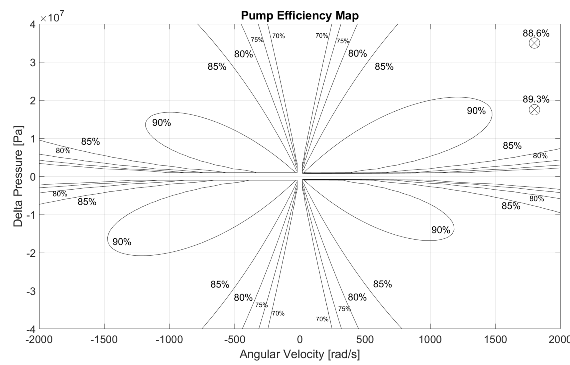

FIGURE 6. Efficiency map of the HECM pump/motor operating at full displacement.

each rail is assumed to be large enough so that switching between rails is not unrealistically rapid.

Each HECM is assumed to consist of a 107cc hydraulic pump/motor and an electric motor. The size of the hydraulic pump/motor is part of an ongoing optimization with a desired peak angular velocity from 3000-15000 RPM. The 107cc sizing results in a peak angular velocity of 6000 RPM. The electric motor and drive are assumed to have a combined efficiency of 90%. Each HECM is connected to two pressure rails P_{R1} and P_{R2}, selected in real time from the low, mid and high pressure rails. Each HECM is also connected to the two ports of the actuators via a directional control valve (DCV). With 3 options for each of P_{R1} and P_{R2}, and 2 options for the DCV, there are $3 \times 3 \times 2 = 18$ options of CPRs and DCV combinations.

For any given CPRs and DCV combination (of 18 total), the pressure across each HECM pump/motor, ΔP_{HECM}, is related to the load force F by:

$$\begin{aligned}\text{HECM on capside:}&A_1(P_{R1}+\Delta P_{HECM})-A_2P_{R2}=F\\ \text{HECM on rodside:}&A_1P_{R2}-A_2(P_{R1}+\Delta P_{HECM})=F\end{aligned}$$

Similarly, the HECM flow Q_{HECM} is related to the actuator speed $\dot{x}$ by:

$$\begin{aligned}\text{HECM on capside:}&Q_{HECM}=A_1\dot{x}\\ \text{HECM on rodside:}&Q_{HECM}=-A_2\dot{x}\end{aligned}$$

When $A_1 \neq A_2$, typically, there are 9 distinct force levels produced by the different choices of P_{R1} and P_{R2}:

$$F_R(P_{R1},P_{R2}) = A_1P_{R1} - A_2P_{R2}$$

To evaluate the energy consumption, the rails and the DCV position are selected to minimize the total energy loss over the drive cycle, subject to the net change of the electric battery charge being 0. This constraint is to ensure that the battery is not depleted if the cycle is repeated many times, and that the control does not rely excessively on the initial battery charge to perform the duty cycle. Hence, the optimal control problem is:

$$\begin{aligned}&\min_{(P_{R1}(\cdot),P_{R2}(\cdot),DCV(\cdot)}\int_0^T \text{Power loss}(t)\,dt\\ &\text{subject to: }\int_0^T \text{Battery power}(t)\,dt=0\end{aligned} \tag{1}$$

while meeting the force and speed requirements of prescribed duty cycle. Losses considered include hydraulic inefficiencies in the HECM pump/motor and the CPR main pump/motor; inefficiencies of the electric motor/generator and electric drive. The main pump/motor is assumed to operate at fixed speed (1800 RPM), full displacement, and at the pressures of the pressure rails. The axial piston pump/motor efficiency map in [9] is again assumed for the HECM pump/motor at fixed maximum displacement. For simplicity, the same pump/motor used in the baseline load sensing case is also used for both the main pump and the HECM pump/motors in the HHEA. For the main pump operating at 1800 RPM and full displacement, the efficiency to fill the 17.5 MPa and 35.5 MPa rails are respectively 88% and 89%. For the HECM pump/motor, the efficiency map at full displacement but variable speed is shown in Fig. 6.

This constrained optimization problem can be solved efficiently using the Lagrange multiplier technique [10].

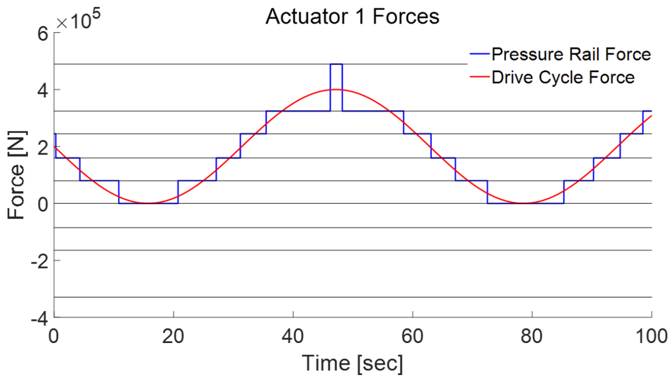

FIGURE 7. Illustrative force levels provided by selected pressure rails and demanded force.

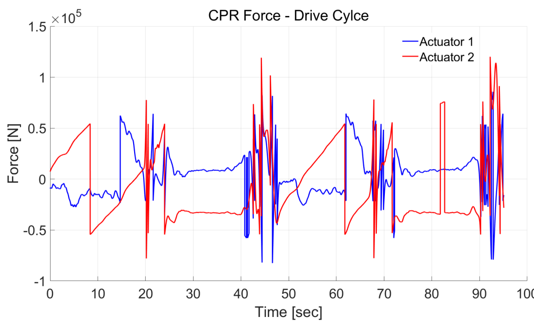

FIGURE 8. Actuator forces provided by the HECM.

In nearly all cases, the optimal control chooses the pressure rail combination that produces a force level that is just above or below the desire force level. An illustration is shown in Fig. 7 for the forces achieved by the selected pressure rails alone, compared to the required actuator force, for an illustrative drive cycle[2]. The difference is accounted for by the HECM. Besides minimizing the energy loss, the choice also has the effect of reducing the HECM torque or force requirement. For the OEM drive cycle, the maximum HECM forces are less than 151kN and 199kN which corresponds roughly to half of the maximum difference between the force produced by the pressure rails 8. For the uniformly distributed pressure rails levels, these force requirements for the two HECMs are 28% and 34% of the force requirement for direct EHA (Table 1).

For this test duty cycle, both actuator 1 and actuator 2 forces are positive. Consequently the 3 negative force levels (of 9 total) provided by the pressure rails are not utilized. Thus, it is possible to optimize the rail pressure levels to further reduce the force requirements for the HECM. For example, by setting the middle rail pressure to be 0.72 (instead of 0.5) of the maximum pressure, the force requirements for the two HECMs will further be

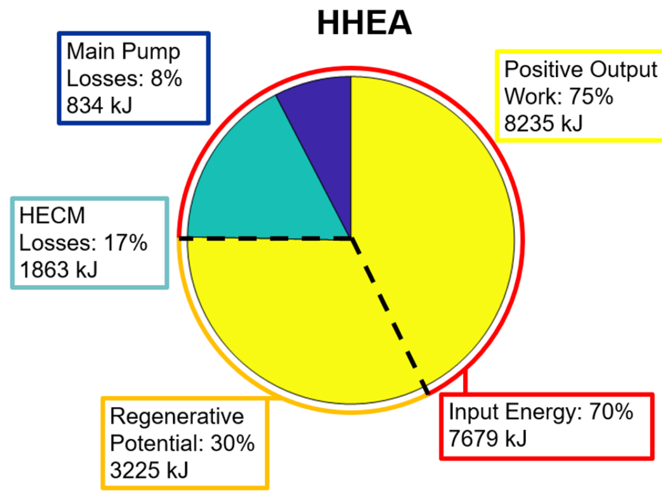

FIGURE 9. Energy use in the HHEA system.

reduced to 68.5 kN and 105 kN. The force requirements can be reduced even more if 4 or more pressure rails are used.

The energy consumption for the HHEA is shown in Fig. 9. The total input energy is 7.7 MJ, which is 61% lower compared to the load sensing system. The input work is smaller than the total positive work of 8.2 MJ to produce an apparent efficiency of:

$$\eta_{HHEA} = \frac{\text{Positive Work}}{\text{Input Work}} = 107\%.$$

This is possible because energy from the overrunning load (potential of 3.2 MJ) is recaptured. If the potentially regenerative work (negative work) is included as energy, the system efficiency is:

$$\eta_{sys,HHEA} = \frac{\text{Positive Work}}{\text{Input Work} + \text{Negative Works}} = 75.6\%$$

which is a measure of how efficient the components are in transmitting power. This is reasonable considering that the main pump efficiencies to fill the rails are at 88-89% and the efficiency of the electric motor-drive is 90%.

Energy losses in the CPR main pump and the HECM account for 8% and 17%, respectively, of the overall energy input (including input work and potential regenerative work). One reason these losses are small compared to the LS pump loss in the baseline is that both the HECM pump/motor and the main CPR pump/motor operate at fixed full displacements.

The motivation for the HHEA is to allow the majority power to be provided via hydraulics and the electrical power is used for modulation. To evaluate this claim, the ratio of electric power to

[2] since the duty cycle used in the analysis is confidential

output power defined below is computed:

$$\text{Ratio}_E := \frac{\int |\text{Electric Power(t)}|\, dt}{\int |\text{Output Power(t)}|\, dt} = 28\% \tag{2}$$

This confirms that indeed, slight more than one quarter of the power is provided electrically with the rest provided hydraulically.

5 CONCLUSION

A novel system architecture for mobile machine with multiple degrees-of-freedom that blends hydraulic power with electric power has been presented. By allowing hydraulics to provide the majority of power while electrical power is used for modulation, it is possible to simultaneously improve efficiency and control performance while keeping the size of electrical components modest. A feasibility case study suggests that the proposed architecture has the potential to more than double the efficiency compared to the baseline load sensing system, while requiring relatively small electrical motor/drives.

The study of the HHEA is only at the initial phase. Current work focuses on establishing energy saving potential for several machines and applications from various off-highway mobile machine sectors. Strategies are being developed to maintain control performance, and seamless and tight integration of the hydraulic pump/motor and the electric machine within the HECM is being investigated. The results presented in this paper will be fortified using a more detailed dynamic model. A real time controller to select operating valve positions will be developed alongside a controller for the HECM units. A detailed analysis of the components such as valves, accumulators,etc and their sizing will also be conducted. These results will inform design decisions for a test stand where the models can be validated through experiments.

ACKNOWLEDGEMENTS

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