Energy Recovery System for Excavators
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Abstract
Increasing fuel costs have become a significant portion of the operating expenses for owners and fleet managers of off-highway vehicles. Additionally, emissions compliance standards, Tier IV/Stage 4, have further increased machine cost as OEM’s are required to add after-treatment and cooling. These challenges are motivating OEM’s and owners to pursuing new technologies aimed to reduce the impact of fuel and emissions.

In a typical off-highway machine, a hydraulic excavator for example, less than 10% of the fuel energy consumed is used to perform productive work. A significant portion of an excavator’s operational losses occur in throttling and control losses in the control valves for each service. Eaton’s proposed Energy Recovery System is capable of meeting the baseline productivity without compromising the functionality and performance of the baseline machine. The system can recover and re-apply energy from both the boom and the swing hydraulic operations.

Background
The baseline excavator’ hydraulic architecture is shown in Figure. 1. The supply pumps send fluid power to a stock control valve manifold with a plurality of spool valves which are controlled by pilot pressure joysticks operated by the machine operator. The metered flow from the spools in the control manifold is connected to the various cylinders and motor in the circuit to provide the functionality of the machine.

ERS Architecture and Control
The energy recovery system proposed retains much of the baseline circuit, with exception of the swing motor which is removed, and the additional components to allow for energy recovery and application functionality. The system includes a tandem pump/motor assembly, a clutch/brake, hydraulic mode valves, fluid conveyance, and accumulators (Figure 2).
In the new design, a tandem pump/motor arrangement, called a transformer, is in selectable communication with the main pump, boom cylinders, and the swing function of the excavator. The transformer can achieve system power (energy) management by manipulate the energy among the main pump’s output, the boom’s overrunning kinetic energy, and the swing’s kinetic energy. This energy can be utilized instantaneously among these functions or stored for future use in a hydraulic accumulator. In addition, the transformer, together with the main boom control valve, can provide flow sharing with the stored accumulator energy and supply torque to operate the swing.

Figure 3 shows the architecture of the transformer integrated into the excavator. For boom operation, the boom cylinder can be supplied from the stock Directional Control Valves (DCV), to the transformer via the accumulator, or a mixture of both. In the case of the stock DCV, flow can be directly supplied from the main pump’s output via the DCV. The second scenario, the boom can be supplied by the transformer alone, where the system controller determines the boom supply pressure from cylinder pressure sensors and flow based on a map of pressure, flow, and sensed pilot pressure. The transformer is commanded to match the pressure and flow requirements and supplies the boom directly. The third scenario is a mixture of boom flow from the DCV and the transformer. The transformer supplies or sinks flow from the boom and the DCV provides the make-up flow depending on the energy status of the energy recovery system.
When utilizing the transformer, the energy can be stored in the accumulator or used to provide torque to the swing.

For the swing service, the upper structure is driven directly from a power take off on the hydraulic transformer. The swing circuit can be operated via the main pumps, overrunning boom flow, or stored energy in the accumulator. When the swing is operated in the first case, the main pumps are commanded from the system controller with a pilot control valve to supply the lower unit of the transformer. The lower unit operates as a motor and sends torque to the upper structure of the machine to swing. In this case torque can also be sent to the upper unit to store energy in the accumulator. In the second case, the boom is in an overrunning state, and the output flow from the boom can supply the lower transformer unit and supply torque to the swing or store energy as stated previously. In the last case, the accumulator has sufficient energy and the upper unit of the transformer can act as a motor supplying torque through the lower unit to the upper structure. In this case, it is also feasible to supply the boom when swinging because the lower unit of the transformer can act as a pump.

![Figure 4: Hydraulic Hybrid Work Circuit (ERS) Control Strategy](image)

To achieve the control goal of maintaining vehicle productivity and improving of fuel efficiency, an advanced control strategy was developed. The model-based control development process consists of several key steps including system characterization testing, plant modeling, control development, model integration, and performance optimization. The topology of the control system is divided into two layers, as shown in Fig. 4. The top layer is a supervisory controller, which determines the vehicle operational mode given the vehicle states and the operator’s command. The second layer is speed/pressure/flow tracking control at the component level. Smooth transition among modes switching is a key controller development challenge.

To illustrate the controller design, two selected key operational modes will be presented here:

- **Swing driven by the accumulator:** The swing is directly driven with energy stored in the accumulator. No power from the main pump is consumed to accelerate the swing inertia. The control objective is to achieve the transformer shaft speed tracking by modulating the upper pump/motor’s displacement. Figure 5 illustrates the hydraulic flow path from the accumulator through the transformer to tank.
Figure 5 - Swing Acceleration with the Accumulator

- **Boom up assist by both the swing braking and accumulator discharging:** In the case when both the accumulator energy is available and the swing is decelerated, the transformer can coordinate both the sources of energy to assist the boom up action. The control objective is to achieve transformer shaft speed tracking while tracking the boom assist flow demand Qx. The lower pump/motor is utilized to regulate the transformer flow Qx, and it is operated as a pump. The upper pump/motor is utilized to regulate the transformer shaft speed. If the accumulator is discharged, and is providing energy to assist boom up, the upper pump/motor is operated as a motor. In this configuration, there is also the possibility that the swing braking energy is more than the required boom up assist energy, and the residual energy can be stored in the accumulator. In this case, the control goal for the transformer stays the same, but the upper pump/motor will be utilized as a pump to store energy into the accumulator.

Figure 6 - Boom Up Assist by Both the Swing Deceleration and Accumulator Discharge

Results and Discussion
The ERS architecture and controller developed by Eaton were implemented on a 25 ton excavator and performance tested across the typical duties: 90°/180° truck loading, trenching, and backfilling. Based on test data and user feedback, the system functions and performs as predicted by system design and simulation. The system provides a productivity improvement of 12% and a fuel efficiency improvement of 20% over the specified duties.
Given the flexibility of architecture and control strategy, ERS system is scalable to a number of platforms and tunable for increased productivity or fuel efficiency.