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Energy saving solutions for a hydraulic excavator

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Abstract

Nowadays the improvement of energy efficiency and the reduction of pollutant emissions are the major challenges that the mobile machinery manufacturers have to face with. With rising fuel prices and increasingly stringent regulations, the development of energy saving solutions and efficient hydraulic system have become a priority for researchers and OEM's. One of the most effective approach is the machine hybridization but other solutions can be adopted. This paper proposes with the aid of mathematical tools energy saving solutions for an excavator equipped with a load sensing hydraulic system. A comprehensive energy analysis was conducted through the excavator model to highlight the energy dissipations along the system. Different solutions to reduce losses and improve fuel saving including energy recovery from boom and arm and the introduction of a second pump in the flow generation unit were identified and investigated in detail. Finally, combining the proposed solutions, a new hydraulic hybrid excavator concept was obtained with a 15% of fuel saving.

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Keywords: Hydraulic Excavator; Load Sensing System; Energy Analysis; Fuel Saving.

1. Introduction

Over the last decades, energy saving and fuel consumption reduction are the most topical issues in the world of construction equipment as a logical consequence of more stringent regulations about pollutant emissions and the increasing fuel costs. In this context, the manufacturers of earth-moving machinery and OEMs have to meet market demands developing and offering new solutions with higher energy efficiencies.

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More efficient solutions concern the optimization of the power transmission [1] and of the matching between hydraulic system and internal combustion engine [2], analysis about energy dissipations through the hydraulic system [3], optimization of the engine auxiliary components [4] and of the valves performance [5], better control strategies and recuperation of potential and kinetic energies. In literature, new energy saving architectures have been proposed to reduce throttle losses and improve the system overall efficiency. Finzel et al. [6] developed an electro-hydraulic LS dual pump system dividing the users with similar loads and reducing the energy losses in the sections with lower loads during parallel operations; this solution shows an energy consumption reduced up to 30%. Kim et al. [7] presents an independent swing system installed on a 48 t excavator; by adopting a dedicated pump for the swing motor the pump power was reduced up to 12% compared to the standard one. An interesting solution is to separate meter-in and meter-out in hydraulic valves; this ensures better dynamic performance, increased functionality and the possibility to operate in more efficient ways. Hansen et al. [8] tested an independent metering valve system finding similar performances with traditional LS and a reduction of energy consumption of about 30%. Another architecture is the Displacement Control (DC) system in which each actuator is powered through a dedicated variable displacement pump or through a hydraulic transformer. This system permits to eliminate the lamination losses due to the contemporary actuation of more than one user, typical in valve-controlled systems. The good functioning of DC solution is proved by both numerical results and experimental tests carried out on prototype with fuel savings up to 40% [9]. One of the most effective approach to obtain energy saving and fuel consumption reduction in hydraulic excavators is the system hybridization and the application of energy recovery system. In particular, hydraulic hybrid technology reached a level of advanced development so that for several years the major excavator companies have been developing hybrid excavators prototype or have already made them available on the market [10-12]. Furthermore, new hybrid solutions have been proposed by the academia. Zhao et al. [13] developed an energy recovery system (ERS) exploiting three chamber cylinders and accumulators to recover the potential energy of mechanical arms and load of an excavator. The dissipated energy of the engine can be reduced by around 50%. Kim et al. [14] designed a new regeneration scheme to recover boom potential energy by directly connecting the head chambers of the boom cylinders to a variable displacement hydraulic motor installed on the engine shaft. Simulation results show fuel saving of 10% for the levelling cycle. Li et al. [15] proposed a novel layout for a 21 t excavator which exploits hydraulic accumulators to recover boom potential energy, kinetic swing motor energy and the overflow of the main relief valve, obtaining a 16% fuel saving and higher efficiency compared with the conventional machine. Vukovic et al. [16] developed a new constant pressure system for mobile machines, designed to ensure the engine working in high efficiency regions.

The aim of this paper is that of proposing energy saving solutions for Load Sensing (LS) hydraulic systems to improve the machinery efficiency and permits a reduction in fuel consumption. Starting from the energy analysis of the excavator, through its validated mathematical model, the distribution of the energy losses within the system have been investigated. Different solutions were identified to reduce losses and recover energy; each solution was analyzed in detail with a dedicated energy analysis to highlight pros and cons. At last, a new hydraulic hybrid excavator concept has been presented combining all energy saving solutions. Simulation results showed a 15% of fuel saving and a significant reduction in energy losses.

2. Mathematical model

A mathematical model of the machine was developed to accurately evaluate the energy distribution along the system. The investigated mobile machinery is a middle size (9 t) excavator whose hydraulic system is of a LS type. The excavator is equipped with a 46 kW Diesel engine and the hydraulic system is composed of a flow generation unit (FGU) comprising a variable displacement axial piston pump and an external gear pump, a LS flow sharing valve block with nine actuators (only the principal, i.e. boom; arm; bucket; swing and travels were modelled). The model is composed of hydraulic sub-models including a variable displacement axial piston pump, a load sensing flow sharing directional valve, a 2D kinematics model of the front excavation tool, turret and tracks and the engine model.

The pump mathematical model, presented and verified in [17-18], was conceived as a gray box model composed by the combination of white box model of the pump regulators, pressure and flow compensators, and the black box model of the pump flow characteristics for the accurate prediction of the swash plate motion. The mathematical model of the flow control valve block is a white box model, already developed and validated in [19-20] with a comparison between numerical and experimental results. The model is based on the following differential equations:

$$\frac{dp}{dt}=\frac{B}{V}\cdot\left(\frac{\dot{m}}{\rho}-\frac{dV}{dt}\right) \quad (1) \qquad \dot{m}=sign(\Delta p)\cdot C_d\cdot A\cdot\sqrt{2\cdot|\Delta p|\cdot\rho} \quad (2)$$

Pressures inside the control volumes are obtained from the pressure rise rate equation applied to each chamber element (eq. 1); the mass exchange occurring through the orifices is calculated using Bernoulli's generalized equation in quasi-steady conditions (eq. 2). The 2D kinematics model is based on Lagrange equations and is composed of five rigid bodies bounded with revolute pairs and linear actuators. The coupling between hydraulic and kinematics models permits to recreate realistic forces on the hydraulic actuators. The modelling approach for turret and tracks was that of consider them as rotary loads; coulomb friction force, viscous friction coefficient and the moment of inertia was defined on the basis of experimental results. The ICE model calculates the fuel consumption and reproduces the behavior of the engine regulators during dynamic operations [21]. Furthermore, to guarantee working cycles repeatability and reproduce accurately the actuators movements performed on field test, a feedback control was adopted exploiting a PI regulator to reduce the error between the real position and the desired one. Once developed the excavator model, it was validated through a dedicated experimental activity; the model has proved to be able of recreate realistic loads on the actuators and to define the hydraulic variables of the system [22].

3. Energy analysis

A comprehensive and detailed energy analysis of the excavator hydraulic system was conducted through the mathematical model to evaluate the energy dissipations and propose solutions for improving the system efficiency. The energy analysis refers to the simulation of the trench digging cycle, defined by the JCMAS standard. The standard considers that the excavator simulates the movements without elaborating material, i.e. no interaction with the soil is considered. Furthermore, initial and final position of the implements are the same in this cycle; the useful work of the cycle is null and all the energy consumed to increase mechanical and potential energy of each implement is then fed back. Fig. 1 shows a Sankey diagram of the energy flow for the trench digging cycle.

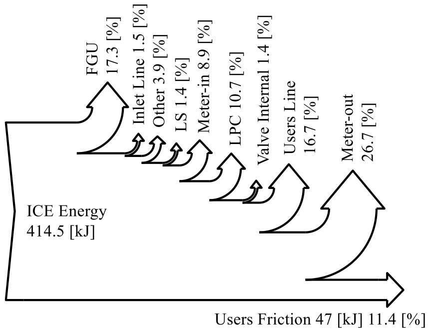

Fig. 1. Sankey diagram of the trench digging cycle.

The diagram reveals all the energy losses contributors through the system, from the ICE mechanical energy, which is the total amount of energy entering the system, to the energy lost as friction in the actuators. About 17% of the ICE mechanical energy is lost in the flow generation unit. The largest energy consumer in the hydraulic system is the directional flow control valve (DFCV); 77.3% of the inlet energy is delivered to the DFCV to supply actuators demands. Energy dissipations in LS control valves concern mainly meter-in and meter-out orifices and the local pressure compensators (LPC), respectively quantified as 8.9%, 26.7% and 10.7%. Minor losses occurring in the DFCV are related to internal and LS losses. Other energy dissipations occur in the hydraulic lines between FGU and DFCV (1.5%), between the DFCV and the hydraulic actuators (16.7%) and in pressure relief valves (3.9%). 11.4% of the total inlet energy is related to actuators losses. To evaluate the machine efficiency in LS systems it is fundamental to know the load pressure relative to each actuator. The user requiring the highest pressure is the most efficient while the others at lower pressure require a pressure reduction in the LPC to meet the LS control logic. The power demand of each user is directly proportional to the actuator force or torque and the relative velocity. Fig. 2 reports actuators power demand during the trench digging cycle, according to the energy flow just presented. As can be noticed from the power demand, some users are contemporary actuated (the boom and the arm, the boom and the turret), while others are never actuated together (the boom and the bucket, the arm and the turret). An effective method to avoid energy dissipations in the LPC of the actuators requiring lower pressures is that of adopting two LS pumps instead of one, dividing the users according to the power demand. Another solution to reduce typical LS losses concerning laminations across the compensated meter-in orifices is the reduction of the pump margin setup. However, the most widespread solution is the system hybridization with the introduction of energy recovery systems. The energy available for recovery in hydraulic excavators is the gravitational potential energy or the kinetic energy. Fig. 3 reports the boom power demand during the trench digging cycle. The rising phase is composed of two sequential movements and the hydraulic power is exploited to increase the boom potential energy. In the lowering phase, the boom could move by itself exploiting its potential energy, but to provide a reliable control of the lowering velocity to the operator and to avoid cavitation in the actuator rod side, the outflow from the cylinder is throttled in the meter-out orifice and therefore the potential energy is laminated. As a consequence, the meter-out energy losses are considerably high. The most adopted solution to recover the energy is that of adopting an energy recovery system to control the boom lowering and recover its potential energy. Boom power demand highlights a potential energy recovery of about 33 kJ during the lowering phase. Furthermore, Fig. 3 shows the power at the inlet ports of the actuator, calculated as the product of pressure and flow rate.

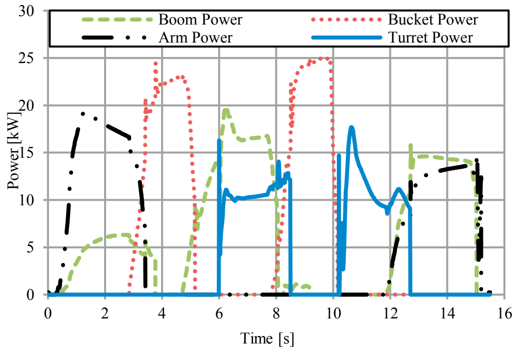

Fig. 2. Actuators power demand.

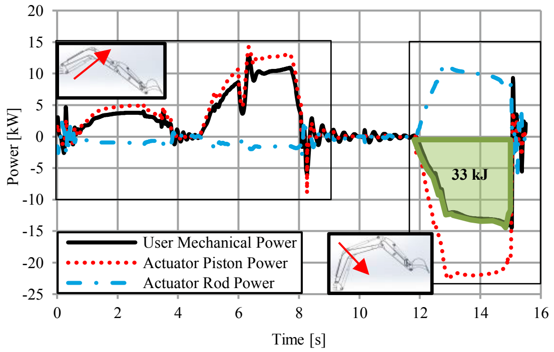

Fig. 3. Boom power demand.

Analogue considerations could be stated analyzing the arm actuator power demand. Four time less energy (8.5 kJ) can be recovered from the arm actuator due to the lower mass of the structure and to the lower height exploited during the lowering phase. Furthermore, simulation results show that the brake energy recoverable from the swing drive (3 kJ) for this excavator size is considerably low and the costs for any ERS implementation would not be justified.

4. Energy saving solutions

Based on the results obtained from the energy analysis conducted on the hydraulic excavator mathematical model, different energy saving solutions in LS systems have been identified. The results in terms of energy flow diagrams and fuel saving of each solution will be presented. To define the excavator performance in term of fuel consumption the JCMAS H020:2007 norm was adopted as reference [23]. The norm defines the characteristic operating conditions as trench digging and levelling and evaluates an equivalent fuel consumption referred to a typical working hour which combines the different working modes (JCMAS cycle). The percentage difference Δm_f was evaluated between the standard machine and all the proposed solutions.

4.1. Dual LS pump

In complex systems like excavators, which require the contemporary actuation of several users, the functioning of the hydraulic system in LS logic leads to high energy dissipations in the LPCs. An effective solution to reduce losses in the LPCs is that of dividing the actuators in two separate groups exploiting two LS pumps instead of one. Users distribution was defined according to the power demand charts (Fig. 2) coupling the actuators that do not operate during the same time interval: Boom, Bucket, Travel dx and Arm, Turret, Travel sx. The solution with two LS pumps reduces the energy dissipations due to the functioning in LS logic of the hydraulic circuit; the negative counterpart concerns the increased space and costs for the installation. Fig. 4 reports the Sankey plot of the dual LS pump configuration.

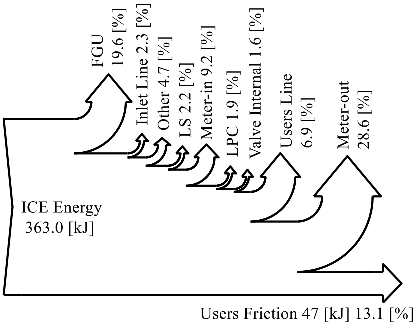

Fig. 4. Sankey diagram-Dual LS pump.

Table 1. Fuel saving numerical results – Dual LS pump.

Cycles	Standard	Dual LS pump	Δm_f[%]
Digging	34.12 (g/cycle)	31.87 (g/cycle)	-6.59
Grading	10.53 (g/cycle)	9.89 (g/cycle)	-6.07
JCMAS	8.77 (L/h)	8.35 (L/h)	-4.78

Dual LS system on one hand reduces the energy dissipation in the LPCs more than the 80% and on the other hand the energy dissipations related to the FGU increase of about 10% because the two pumps run at lower overall efficiencies in comparison with the single pump in the reference configuration. Table 1 reports the fuel saving percentage of the dual LS pump configuration.

4.2. Pump margin reduction

LS systems are characterized by the energy losses due to lamination across the compensated metering orifices to ensure a flow rate proportional with the valve opening and independent from load pressure. An effective solution to reduce energy losses is that of reducing the pump margin (PM) setup. This operation is not trivial because it could result in a modification of the machine performance. If the PM is reduced too much compared to the original setting, the users movements will be slower. In the performed analysis, a 23% reduction (from the original 22 bar to 17 bar) of the PM setting was introduced to not penalize the machine behaviour and to obtain improvements in energy saving to justify this solution.

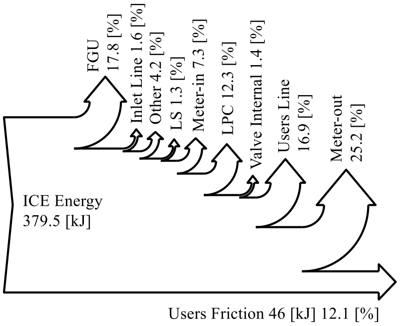

Fig. 5. Sankey Diagram-PM reduction.

Table 2. Fuel saving numerical results – PM reduction.

Cycles	Standard	ERSs	Δm_f [%]
Digging	34.12 (g/cycle)	32.58 (g/cycle)	-4.51
Grading	10.53 (g/cycle)	10.07 (g/cycle)	-4.37
JCMAS	8.77 (L/h)	8.4 (L/h)	-4.21

The energy saving advantages are related to the meter-in and meter-out energy dissipations reduction. This solution can be easily implemented paying the price of a slight reduction in movement actuators speed perceived by the operator. Fig. 5 reports the Sankey diagram. The PM reduction permits to decrease the meter-in losses by 18%. Table 2 reports the fuel saving percentage of the configuration with reduced PM.

4.3. Energy recovery systems

The energy analysis conducted on the hydraulic system of the excavator pointed out that the larger amount of energy dissipations is related to the meter-out orifices and that potential energy could be recovered during actuators lowering phase instead of wasting it as heat. The introduction of ERSs allows the recovery and reuse of the energy otherwise laminated in the meter-out orifices of the DFCV. The proposed ERS layout, reported in Fig. 7, was designed to recover the potential energy of the boom and arm actuator and is composed of four components: a Hybrid Control Valve (HCV), a hydraulic accumulator, a hydraulic motor and an Electronic Control Unit (ECU). The HCV is a valve block composed of three on/off directional flow control valves (1, 3, 4), a pressure relief valve (5) and a proportional flow control valve (2). The valve 1 allows directing the flow outcoming from the cylinder to the hydraulic accumulator (recovery mode) or to the DFCV section (standard mode). Since in some operating conditions the accumulator pressure could be not enough to balance the front equipment weight, the proportional valve 2 throttles the flow rate thus maintaining the control on the descent avoiding both the implement fugue and cavitation, while the pressure relief valve 5 preserves the accumulator from overpressures. The valve 4 serves to empty the accumulator when the ERS is turn off or the machinery is not working. The recovered energy is then used to feed a hydraulic motor so as to reduce the engine load and the fuel consumption. The reuse phase is enabled by means of valve 3, which connects the hydraulic accumulator with the hydraulic motor. The ECU controls the valves 1, 2, 3 and 4 according to the control strategies defined on the basis of the accumulator pressure (p_{ACC}) and the pilot pressure of the flow control valve (p_{V2}), which are its inputs. The control strategy to manage the energy flow of the proposed ERSs is based on the results of the Dynamic Programming (DP) algorithm. This powerful optimization methodology, presented by the authors in [24], defines the optimal control law for the opening of the ERS valves and the optimal sizing of the components of interest to minimize the fuel consumption. The optimal control strategy is not casual and represents only a benchmark for the online implementation on the machine. Starting from the DP optimal results a suboptimal rule-based control strategy was defined and already presented in [25].

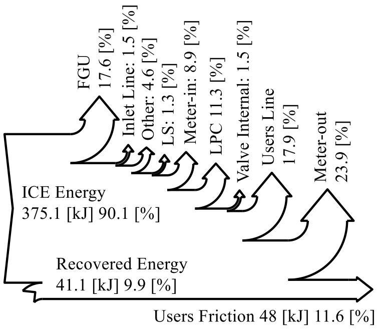

Fig. 6. Sankey Diagram-ERSs.

Table 3. Fuel saving numerical results – ERSs.

Cycles	Standard	ERSs	Δm_f [%]
Digging	34.12 (g/cycle)	32 (g/cycle)	-6.21
Grading	10.53 (g/cycle)	10.1 (g/cycle)	-4.08
JCMAS	8.77 (L/h)	8.39 (L/h)	-4.33

Fig. 6 reports the Sankey plot of the excavator equipped with the boom and arm ERSs. The introduction of the proposed ERSs in the hydraulic system allows both the energy recovery and reuse from the boom and arm actuators during the lowering phase and the meter-out energy dissipations reduction for the same users (10.5%), due to the lower outlet pressure imposed by the HCV in the first part of the actuator movement. The advantages in the meter-out, in term of energy saving, are however countered by the increasing of the LPCs energy losses of about 6%. Table 3 reports the fuel saving percentage of the configuration with the ERSs compared to the standard one.

4.4. Novel hybrid layout

Once analysed the proposed energy saving solutions for the LS system and identified their advantages and drawbacks, a novel hydraulic hybrid excavator concept was defined combining the investigated solutions. As previously reported, the dual pump system reduces considerably the LPC losses as well as pump margin reduction leads to a reduction in meter-in energy dissipations. Furthermore, ERSs allow a reduction in meter-out losses and the recovered energy is exploited to reduce the energy supplied by the ICE. These solutions result in a slight increase in costs and space installation on the machine balanced by a significant reduction in fuel consumption which justifies the economic feasibility of the novel hybrid layout. Fig. 7 reports the hydraulic scheme of the new architecture and fig. 8 reports the related energy flow diagrams to evaluate the interaction between the different solutions and quantify the improvements obtained with this innovative hybrid layout.

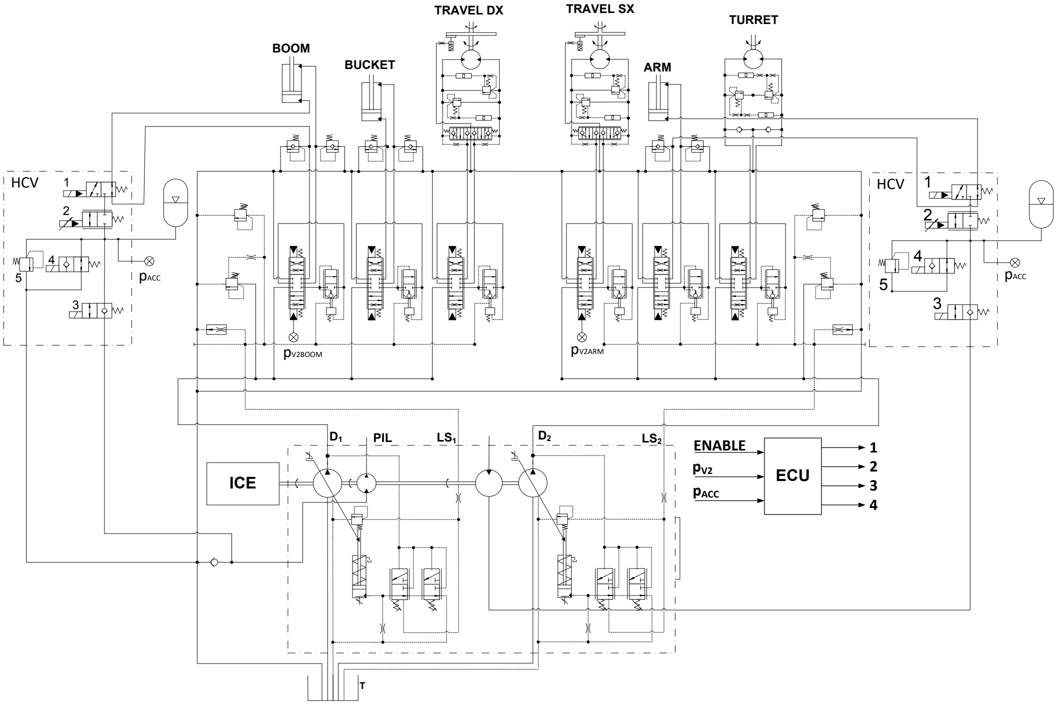

Fig. 7. Hydraulic scheme of the hybrid excavator concept.

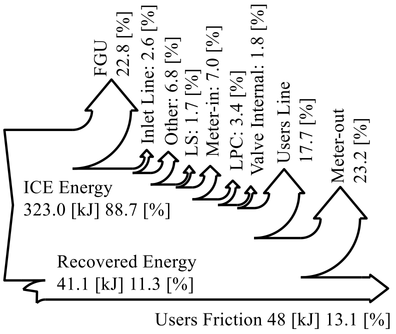

Fig. 8. Sankey Diagram-Novel layout.

Table 4. Fuel saving numerical results – Novel layout.

Cycles	Standard	Novel layout	Δm_f [%]
Digging	34.12 (g/cycle)	29.1 (g/cycle)	-14.7
Grading	10.53 (g/cycle)	9.3 (g/cycle)	-11.6
JCMAS	8.77 (L/h)	7.8 (L/h)	-11

The energy dissipations in meter-in and meter-out orifices were reduced of 21% and 13% respectively. The most important energy saving was highlighted in LPC with a reduction of 70% compared to the standard machinery. Table 4 reports the fuel saving percentage of the novel hydraulic hybrid excavator.

5. Conclusions

Energy saving solutions for LS systems applied to a hydraulic excavator have been presented and analysed in detail. A comprehensive energy analysis through the excavator mathematical model permitted to evaluate the energy losses and the potential for energy recovery with the main objective of improving the machinery efficiency. As expected, the most important energy losses occur in the DFCV, related to the meter-in and meter-out orifices and to the LPCs for a total energy loss around 45%. In particular, LPCs and meter-in losses represent an energy consumption closely connected to the system functioning in LS logic. Effective solutions to reduce these losses are that of introducing a second LS pump, dividing the actuators on the basis of the power demand, and that of reducing the pump margin setup without penalizing the performance of the excavator but improving the energy saving with the reduction of meter-in losses. Furthermore, considerable amount of energy is dissipated as heat through the meter-out orifices (26%). This energy could be recovered through ERSs exploiting the potential energy of each actuator. Simulation results showed that for this excavator size the best energy savings can be achieved with the boom and arm actuator. For each proposed solution, a detailed energy analysis was conducted to highlight advantages and disadvantages. Finally, the combination of the investigated solutions has led to the development of a novel hydraulic hybrid excavator concept. Numerical results showed a fuel saving of about 15% on the digging cycle; the energy dissipations in the meter-in, the LPC and the meter-out orifices have been reduced respectively of the 21%, 70% and 13% highlighting an important energy efficiency improvement. Future works will consider the implementation of this novel architecture on a real excavator.

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