Hydraulic Hybrid Excavator: Layout Definition, Experimental Activity, Mathematical Model Validation and Fuel Consumption Evaluation

Professor Dr.-Ing. Paolo Casoli

Industrial Engineering Department, University of Parma. Parco Area delle Scienze 181/A, 43124, Parma, Italy. email: paolo.casoli@unipr.it

Ing. Luca Riccò, Ing. Federico Campanini, Ing. Antonio Lettini*, Ing. Cesare Dolcin**

Industrial Engineering Department, University of Parma. Parco Area delle Scienze 181/A, 43124, Parma, Italy.
* Casappa S.p.A. Via Balestrieri 1 – 43044 Lemignano di Collecchio, Parma – Italy.
** Walvoil S.p.A. Via Adige 13/D – 42124 Reggio Emilia – Italy.

Abstract

Energy saving and fuel consumption reduction techniques are among the principal interests for both academic institutions and industries, in particular, system optimization and hybridization. This paper presents a new hydraulic hybrid system layout for mobile machinery implemented on a middle size excavator. The hybridization procedure took advantage of a dynamic programming (DP) algorithm, which was also utilized for the hybrid components dimensioning and control strategy definition. A dedicated experimental activity on test bench was performed on the main components of the energy recovery system (ERS). The JCMAS working cycle was considered as the reference test for a fuel consumption comparison between the standard and the hybrid excavator. A fuel saving up to 8% on the JCMAS cycle, and up to 11% during the digging cycle, has been allowed by the proposed hybrid system.

KEYWORDS: Hybrid Excavator, Layout Optimization, Control Strategy Definition

1. Introduction

In the field of mobile hydraulic machinery, system hybridization has become one of the most adopted solutions for energy saving, so as to reduce fuel consumption and pollutant emissions.

Considering hydraulic excavators, the most studied and proposed hybrid solutions, by both academic and industrial researchers, involve energy recovery from either the boom or the turret or both of them, with electrical or hydraulic energy storage devices /1/, /2/, /3/, /4/, /5/.

Electric hybrid solutions on one hand enables, for example, the substitution of the turret hydraulic motor with an electric one, leading to hydraulic power reduction, but on the other hand requires more energy conversions than hydraulic hybrid systems, and since the implement hydraulic movements are fast and frequent, hydraulic energy recovery system seems better than electrical ones /6/. Electric hybrid solutions typically find a large usage on high size excavators because the additional costs are affordable.

In this paper a hybrid layout, which exploits a hydraulic ERS involving the boom, is presented and optimized for a middle size (9 t) excavator. The proposed hybrid layout has been defined starting from a previous analysis, where different hydraulic hybrid layouts were compared by means of mathematical models /7/.

Once defined the hybrid layout configuration, a new parameters optimization was performed considering industrial and machinery related constraints, defining both the ERS components size and control strategy.

Both test bench and on the field experimental activities were performed for verifying the ERS functionality and evaluating the hybrid excavator fuel consumption on the selected working cycle /8/.

2. Hybrid Excavator Layout

The results of a previous analysis aimed at comparing different hydraulic hybrid layouts /7/ point out that the energy recovery from the boom is more effective than the energy recovery from the turret for a middle size excavator (9 t). On the basis of these results, the hybrid layout was designed to recover only the potential energy of the front equipment since the predicted energy saving potential from the kinetic energy of the turret was considered insufficient for justifying the additional costs.

The ERS is composed of four components: a Hybrid Control Valve (HCV); a hydraulic accumulator; a pilot pump/motor and an Electronic Control Unit (ECU). The ISO scheme reported in **Figure 1** shows the novel hybrid layout of the excavator under study.

The valve X allows directing the flow from the piston side of the boom cylinder to the hydraulic accumulator (recovery mode) or to the boom flow control valve (standard mode). Since in some operating conditions the accumulator pressure could be not enough to balance the front equipment weight, the proportional valve Y has been introduced in order to throttle the flow thus maintaining the control on the boom descent. The recovered energy is then used to feed a hydraulic motor so as to reduce the engine load and consequently reduce its fuel consumption. In the proposed hybrid system the same hydraulic machine, an external gear pump/motor, is used for both pressurizing the pilot hydraulic circuit and reusing the recovered energy. This choice was made with the purpose of limiting the system cost and the space that it requires on the excavator. The reuse phase is enabled according to the control strategy by means of valve 3. The valve 4 serves to empty the accumulator when the hybrid mode is off while the relief valve 5 preserves the accumulator from overpressures. When the hybrid mode is selected, the ECU controls valves X, Y, 3 and 4 on the basis of the accumulator pressure (p_{ACC}) and the pilot pressure of the boom flow control valve ($p_{V2\text{-}BOOM}$).

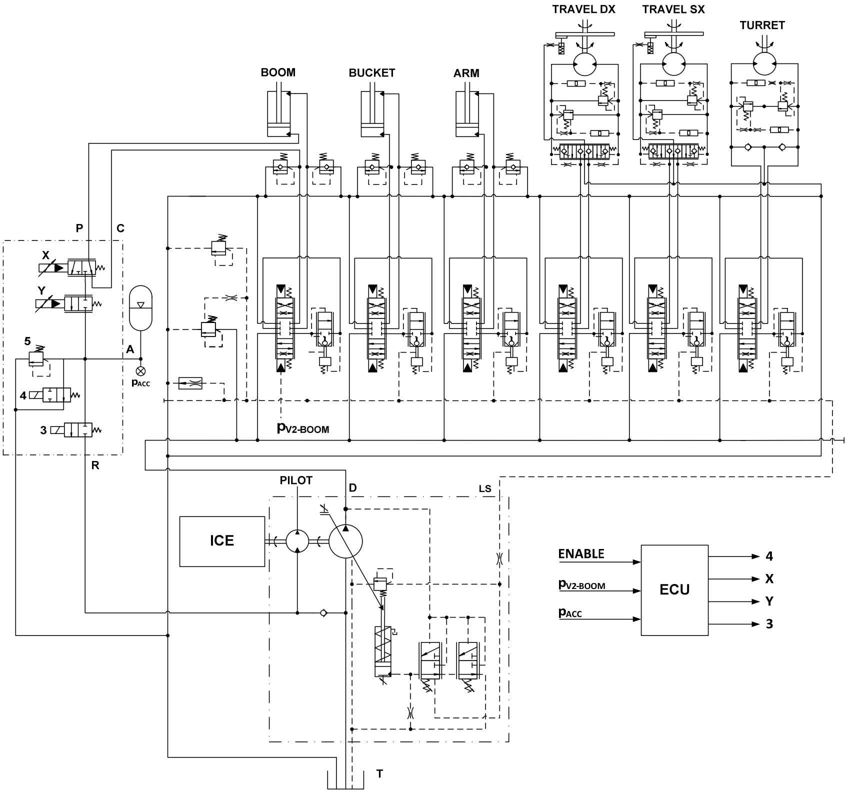
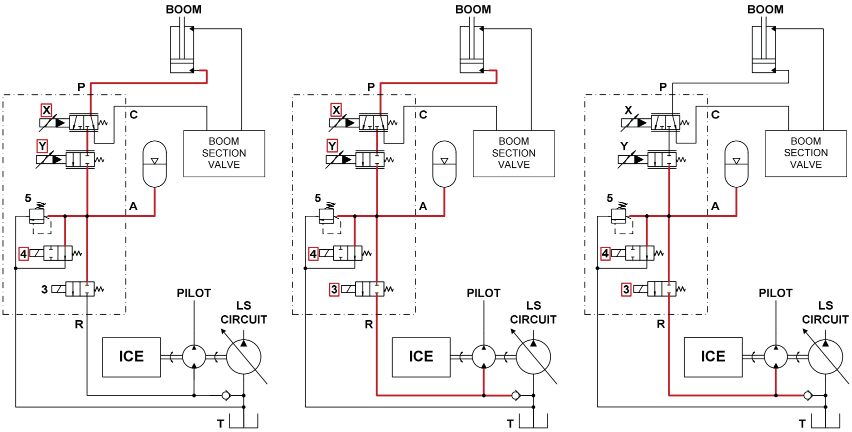


Figure 1: ISO Scheme of the Proposed Hydraulic Hybrid Layout

Figure 2 shows the ERS during the different operating modes: recovery mode (A), recovery and reuse mode (B) and reuse mode (C). The activated valves and hydraulic lines are highlighted in red.



(A) (B) (C)

Figure 2: Operating Modes of the ERS

3. Hybrid Layout Optimization

The effectiveness, i.e. the fuel consumption reduction, of a hybrid layout strongly depends on both the control strategy and the components dimensions. For this reason, a parameters optimization on the proposed hybrid layout was carried out using the methodology presented in /7/, which is based on a DP algorithm. This allows comparing different parameters combinations considering their optimal control strategy, i.e. the control strategy which leads to the minimum fuel consumption.

The optimization was focused on the accumulator volume (V_{ACC}), the initial accumulator pressure (p_0), i.e. the gas pressure when the accumulator is completely discharged, and the equivalent diameter of the valve Y flow area at fully open position (d_{EQ}). The pump/motor displacement was not considered in the optimization since its value was defined according to installation constraints. The optimal solution was searched exploring all the combinations rising from the following variation ranges: $V_{ACC} \in [2.5, 4, 5, 6, 10]$, in line with the available accumulator sizes; p_0 from 10 bar to 50 bar with an increasing step of 5 bar; d_{EQ} from 1 mm to 8 mm with an increasing step of 0.5 mm. The relief valve 5 breaking pressure (p_{MAX}) was set to 4 times p_0 as specified by the accumulator manufacturer.

The optimization was carried out on the JCMAS digging cycle. The control variables managed by the DP algorithm were the valve X position (u_X), which enables the recovery phase, and the valve 3 position (u_3), which enables the reuse phase. Both these valves are controlled with an ON/OFF strategy. The valve Y was instead controlled proportionally to the boom flow control valve. Furthermore, the algorithm was defined in order to not consider infeasible solutions, i.e. avoid cavitation in the rod side of the boom cylinder during the recovery phase.

The graphs reported in **Figure 3** show the obtainable fuel saving percentage for the considered parameters combinations with the optimal control strategy calculated by the DP algorithm.

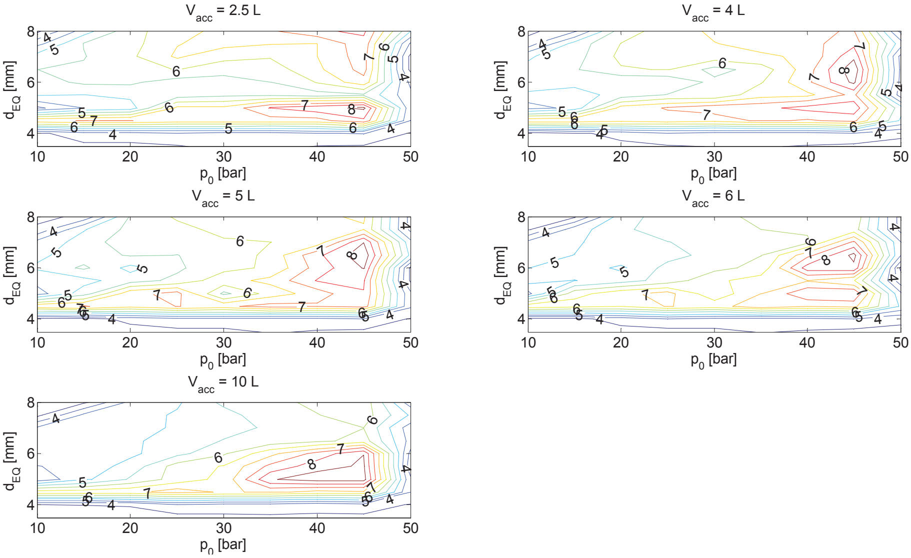


Figure 3: DP Algorithm Results in Terms of Fuel Saving [%]

The maximum fuel saving was obtained with a 10 L accumulator, but, since the difference is very small, a 6 L accumulator was preferred for its major compactness. Consequently, values corresponding to the maximum area shown in Figure 3 were adopted for p_0 and d_{EQ}.

The optimal control strategy defined by the DP algorithm is not causal, i.e. not directly implementable on an ECU. Therefore a suboptimal rule-based control strategy was defined starting from this optimal control strategy. The accumulator pressure (p_{ACC}) and the boom flow control valve pilot pressure ($p_{V2-BOOM}$) were selected as the input variables of the control strategy since they showed a strong relationship with the control variables u_X and u_3.

The logic scheme of the control strategy implemented on the ECU is reported in **Figure 4**. During the recovery phase (valve X enabled), a further rule is introduced in order to minimize the throttle losses in valve Y when the accumulator pressure is sufficient ($p_{ACC} > p_K$) for balancing the front equipment weight. Moreover, suitable hystereses were introduced in order to avoid frequent valves commutations.

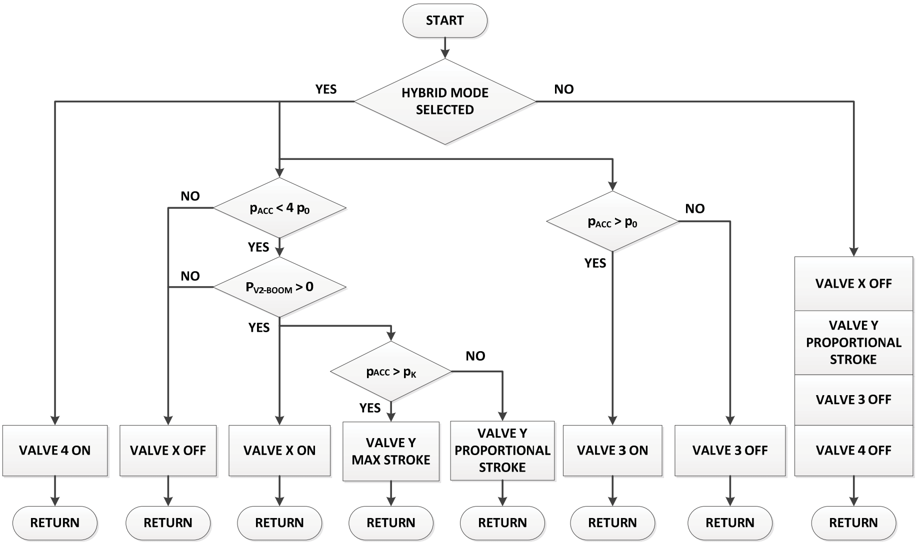


Figure 4: Logic Scheme of the Adopted Rule-Based Control Strategy

4. Energy Recovery System Mathematical Model

The mathematical model of the proposed ERS was developed in the AMESim® environment and interfaced with the excavator one /9/ in order to obtain the mathematical model of the hybrid version. The hydraulic model was realized following a filling/emptying and lumped parameters approach, hence alternating capacitive elements which evaluate pressures (volumes, accumulator) and elements which calculate flow rates (orifices, motor). The diagram in **Figure 5** shows the input, the output and the causality of the mathematical model.

The pressure time derivative inside volumes is evaluated through the continuity equation (1) while in the accumulator it is calculated considering an adiabatic gas transformation (2).

$$\frac{dp_i}{dt} = \frac{B(p_i)}{V_i} \cdot \frac{\dot{m}_i}{\rho(p_i)} \tag{1}$$

$$\frac{dp_{ACC}}{dt} = \gamma \cdot \frac{p_{ACC}}{V_{gas}} \cdot \frac{\dot{m}_{ACC}}{\rho(p_{ACC})} \tag{2}$$

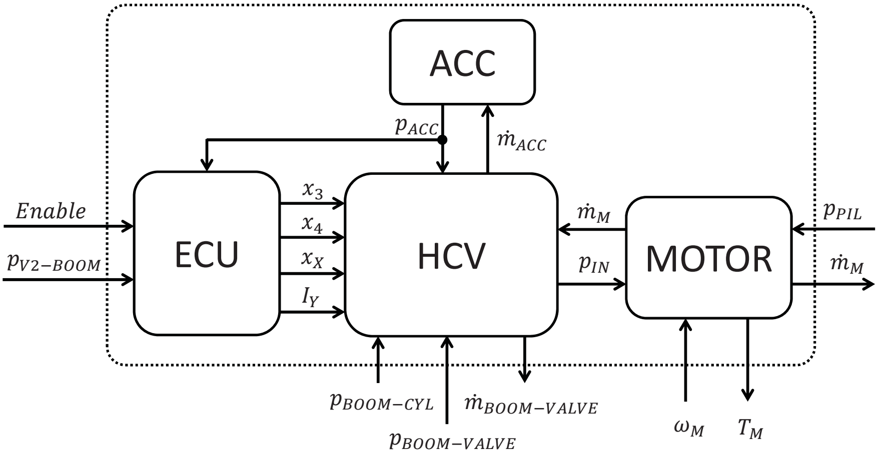


Figure 5: Causality of the ERS Mathematical Model

The flow rates through the valves are calculated by means of the orifice equation under quasi steady hypothesis (3) while the flow rate through the motor is evaluated using equation (4).

$$\dot{m}_i = sign(\Delta p_i) \cdot C_{d,i} \cdot A_i(x_i) \cdot \sqrt{2 \cdot |\Delta p_i| \cdot \bar{\rho}} \tag{3}$$

$$\dot{m}_M = \rho \cdot \frac{\omega_M}{2\pi} \cdot V_d \cdot \frac{1}{\eta_v} \tag{4}$$

The torque exerted by the hydraulic motor is calculated using equation (5).

$$T_M = \frac{(p_{IN} - p_{PIL}) \cdot V_d}{2\pi} \cdot \frac{1}{\eta_{hm}} \tag{5}$$

The valves positions (x_i) are calculated by the model according to the rule-based strategy reported in the previous paragraph. For the non-proportionally controlled valves, i.e. valves X, 3 and 4, the spool dynamic response is approximated with a first order lag, whereas for the valve Y the spool dynamics is modeled as a second order system by means of the Newton’s second law (6).

$$m_Y \cdot \frac{d^2 x_Y}{dt^2} + c_Y \cdot \frac{dx_Y}{dt} + k_Y \cdot x_Y = p_Y \cdot \Omega_Y \tag{6}$$

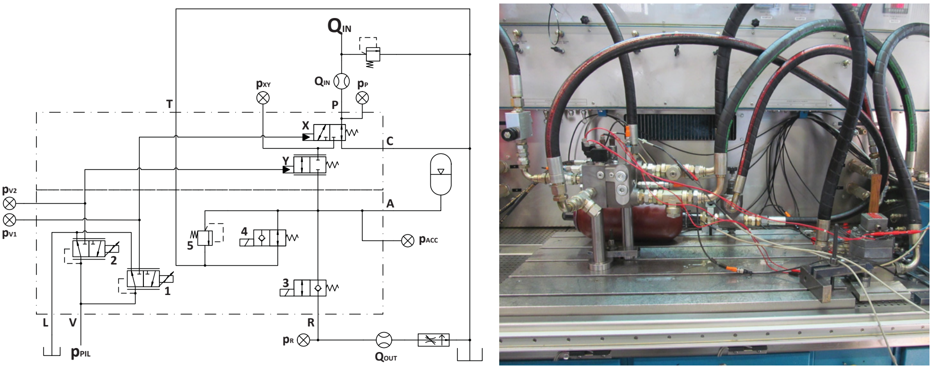
The pilot pressure p_Y is calculated starting from the control current I_Y through the static characteristic of the pilot valve, whose dynamics is modeled by means of a first order lag.

5. Experimental Activity and Results

The experimental activity carried out on the hybrid version of the excavator was principally focused on the ERS and on the machinery fuel consumption evaluation. A previous experimental activity regarding the standard version of the same excavator has been already presented in /9/. Thus a quantitative comparison between the standard and the hybrid version of the excavator has been reported in this paper.

5.1. Energy Recovery System

The experimental activity on the ERS had the objectives of both verifying its correct functioning before the installation on the excavator and acquiring data in order to calibrate and validate its mathematical model. **Figure 6** reports the test bench ISO scheme **(A)** and a photograph of the installation **(B)**.



(A) **(B)**

Figure 6: ERS Test Bench Experimental Layout

The ERS was instrumented with both pressure and flow rate transducers. Static and dynamic operating conditions were investigated. The static ones for the valve characterization, defining the valve sections $\Delta p - Q$ characteristics, while the dynamic ones for the valve functioning and performance verification during the energy recovery/reuse operating modes.

The transducers features for the ERS test bench configuration are reported in **Table 1**.

Variable Name	Transducer	Main Features
p_{V1}, p_{V2}, p_R	TRAFAG® Pressure Transducer	0 – 60 bar ±0.3% FS
p_P, p_{ACC}, p_{XY}	TRAFAG® Pressure Transducer	0 – 400 bar ±0.1% FS
Q_{IN}	VSE® Flow Meter	120 l/min ±0.2% FS
Q_{OUT}	VSE® Flow Meter	60 l/min ±0.2% FS

Table 1: Transducers Type and Features

Realistic operating conditions of the ERS were recreated during the test rig experimental activity. A constant inlet flow rate (Q_{IN}) was imposed to port P for recreating the outlet flow rate from the boom cylinder piston side during the boom lowering phase. The outlet flow rate from port R was limited through the usage of a two-way flow regulation valve, to replicate the pump/motor, and the accumulator was connected to port A. Finally, controlling the X, Y, 3 and 4 valves, as defined in the control strategy, the ERS functioning was recreated and verified.

Figure 7 reports the comparison between the experimental (Exp) and the numerical (Sim) HCV inlet pressure (p_P) and accumulator pressure (p_{ACC}) obtained through the presented mathematical model on the recovery/reuse operating mode. The comparison results point out that the developed model is able to replicate both the ERS functioning and its influence on the hydraulic system.

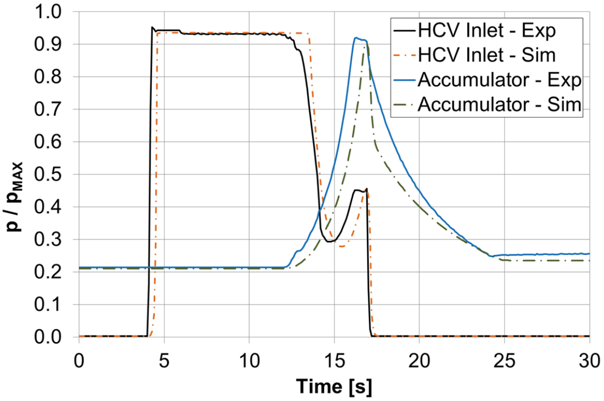


Figure 7: Comparison between Experimental (Exp) and Numerical (Sim) Results on the Recovery/Reuse Phase

5.2. Hybrid Excavator

As previously carried out on the standard excavator, the hybrid excavator fuel consumption was evaluated according to the JCMAS standard /8/, which defines four different working modes: trench digging, grading, travelling and standby. **Figure 8** reports a photograph of the hybrid excavator prototype.

The comparison between the standard and the hybrid excavator fuel consumptions in the most significant working cycles of the JCMAS standard is reported in **Table 2**. The reported results were defined according to the testing and the elaboration procedures described in /8/.

Figure 8: Hydraulic Hybrid Excavator Prototype on the Testing Field

Working Cycle	Standard Excavator Fuel Consumption	Hybrid Excavator Fuel Consumption	Fuel Saving
Trench Digging	166.3 [g]	158.9 [g]	-4.5%
Leveling	103.4 [g]	101.1 [g]	-2.2%
JCMAS	8.6 [l/h]	8.3 [l/h]	-3.5%

Table 2: Comparison between Standard and Hybrid Excavator Fuel Consumptions

The fuel saving percentage of the hybrid excavator has been further improved, **Table 3**, tuning the outlet flow areas of the directional control valves of the users (boom, arm, bucket) on the proposed ERS in order to reduce the energy dissipations in the local pressure compensators during multiple users actuations. In the considered operating cycles, during the recovery phases the boom and the arm are actuated simultaneously. In these phases the introduction of the proposed ERS allows the boom rod pressure to be reduced compared to the standard version, making the arm rod pressure the system LS pressure. Therefore by means of the optimization of the arm outlet flow area the LS pressure could be reduced, so as the fuel consumption. Similarly, the tuning of the boom and the bucket outlet flow areas leads to a LS pressure reduction during other phases of the considered cycles.

Working Cycle	Standard Excavator Fuel Consumption	Hybrid Excavator Fuel Consumption	Fuel Saving
Trench Digging	166.3 [g]	147.4 [g]	-11.4%
Leveling	103.4 [g]	98.6 [g]	-4.6%
JCMAS	8.6 [l/h]	7.9 [l/h]	-8.1%

Table 3: Comparison between Standard and Hybrid Excavator Fuel Consumptions after the Flow Control Valve Tuning

6. Conclusions

A novel hydraulic energy recovery system (ERS) for the boom potential energy recuperation is presented in this paper. The proposed system has been optimally designed on a middle size excavator (9 t) under study, and its control strategy has been defined with the aid of a DP algorithm.

A prototype of the presented ERS has been realized. A dedicated experimental activity on test rig was performed for characterizing and verifying the ERS functionality as well as validating its mathematical model. Furthermore, fuel consumption tests were carried out during on the field experimental activity in order to quantify the impact of the energy recovery system introduction on the excavator efficiency.

The reported results validate the mathematical model of the ERS, which will be inserted in the already presented excavator mathematical model in order to further study and optimize the proposed energy recovery system, and quantify the fuel saving due to the introduction of the novel hybrid architecture.

The experimental activity pointed out that the proposed ERS allows fuel consumption reduction up to 11% on trench digging working cycle defined in the JCMAS standard.

7. References

/1/ M. Ochiai, S. Ryu. Hybrid in Construction Machinery. Proceeding of the 7th JFPS International Symposium on Fluid Power. 2008. Toyama. ISBN: 4-931070-07-X.

/2/ T. Lin, Q. Wang, B. Hu, W. Gong. Research on the Energy Regeneration Systems for Hybrid Hydraulic Excavators. Automation in Construction 19 (2010) 1013-1026. doi:10.1016/j.autcon.2010.08.002

/3/ T. Wang. Q. Wang. Design and Analysis of Compound Potential Energy Regeneration System for Hybrid Hydraulic Excavator. Proceedings of the Institution of Mechanical Engineering, Part I: Journal of Systems and Control Engineering. 2012. DOI: 10.1177/0959651812456642

/4/ T. Lin, Q. Wang, B. Hu, W. Gong. Development of Hybrid Powered Hydraulic Construction Machinery. Automation in Construction 19 (2010) 11-19. doi:10.1016/j.autcon.2009.09.005

/5/ J. Amrhein. PRB – Regeneration of Potential Energy while Boom-Down. Proceedings of the 8th International Fluid Power Conference. IFK2012. Dresden. Germany

/6/ M. Erkkila, F. Bauer, D. Feld. Universal energy storage and recovery system – A novel approach for hydraulic hybrid. The 13th Scandinavian International Conference on Fluid Power, SICFP2013, June 3-5, 2013, Linkoping, Sweden. ISBN 978-91-7519-572-8

/7/ P. Casoli, A. Gambarotta, N. Pompini, L. Riccò. Hybridization Methodology based on DP Algorithm for Hydraulic Mobile Machinery – Application to a Middle Size Excavator. Automation in Construction. doi:10.1016/j.autcon.2015.09.012. In press.

/8/ JCMAS H020:2007. Earth-moving machinery – Fuel consumption on hydraulic excavator – Test Procedure

/9/ P. Casoli, L. Riccò, F. Campanini, A. Lettini, C. Dolcin. Mathematical Model of a Hydraulic Excavator for Fuel Consumption Predictions. Proceeding of the ASME/BATH 2015 Symposium on Fluid Power & Motion Control. FPMC2015-9566. October 12-14, 2015, Chicago, Illinois.

8. Nomenclature

Symbols

A	Flow area	m^2
B	Bulk modulus	Pa
c	Damping coefficient	Ns/m
C_d	Discharge coefficient	-
d_{EQ}	Equivalent diameter	m
I	Current	A
k	Spring stiffness	N/m
$\dot{m}$	Mass flow rate	kg/s
p	Pressure	Pa
T	Motor Torque	Nm
u	Control signal	-
V	Volume	m^3

V_d	Pump/motor displacement	m^3/rev
x	Spool position	m
γ	Adiabatic index	-
η_{hm}	Hydro-mechanical efficiency	-
η_v	Volumetric efficiency	-
ρ	Fluid density	kg/m^3
Ω	Area	m^2
ω	Pump/motor angular velocity	rad/s

Subscripts

0	Initial condition
3	Valve 3 HCV
4	Valve 4 HCV
ACC	Accumulator
CYL	Cylinder
IN	Inlet
i	i-th chamber
k	Switch setting
M	Motor
MAX	Maximum
OUT	Outlet
P	HCV port P
PIL	Pilot
R	HCV port R
$V1$	Pilot chamber 1
$V2$	Pilot chamber 2
X	Valve X HCV
XY	XY chamber HCV
Y	Valve Y HCV