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Modelling and energy comparison of system layouts for a hydraulic excavator

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Abstract

For decades the improvement of energy efficiency in mobile hydraulics has forced the research world to develop energy saving solutions and to redesign existing hydraulic circuits. This paper presents an overview about the state of the art of excavator valve systems based on open centre flow control (OFC) and a load sensing principle (LS). The purpose of this study is to compare different hydraulic systems on a middle size (9ton) excavator and to analyse the differences in term of energy saving and fuel consumption. Starting from a validate mathematical model of the considered hydraulic excavator whose functioning is in LS logic, many alternatives are proposed as flow on demand system, positive and negative flow control. Systems comparison has been done on typical excavator working cycles as trench digging and levelling referring to the JCMAS standard. An optimization tool, based on genetic algorithm, has been exploited for the definition of the optimal spool areas to reduce the pressure losses and by-pass flow rate maintaining identical controllability and performance.

Keywords: Hydraulic Excavator; Open center System; Load Sensing System; Flow Area Optimization; Energy Comparison; Fuel Saving.

1. Introduction

Growing energy costs connected with the decrease of fuel resources and stricter regulations about environmental pollution have forced researchers and manufacturers of earth-moving machinery to develop and propose energy saving

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solutions aimed at improving the efficiency of the hydraulic system without penalizing performance and without increasing costs.

There are different approaches that can be followed to reach these goals. The most common one is the system hybridization; nowadays, the hybrid technology has highlighted advantages on fuel economy through the recovery of the potential energy from the boom actuator or of the kinetic energy from the swing drive [1,2] permitting to optimize the working points of the internal combustion engine. Casoli et al. [3,4] compared different hybrid layouts for a hydraulic excavator through a methodology based on DP algorithm and developed an energy recovery system which recovers through a hydraulic accumulator the boom potential energy during the lowering phase. Sahlman et al. [5] designed and tested a new hybrid system which exploits variable displacement linear actuators, secondary controlled pumps/motors and hydraulic accumulators for energy recuperation from overrunning loads. Li et al. [6] presented a 21t hydraulic hybrid excavator which uses hydraulic accumulators to recover the potential energy of the boom, the kinetic energy of the swing motor and the overflow hydraulic energy of the main relief valves. The comparison with the conventional system highlighted a 16% fuel saving with similar sensing of the driver. Furthermore, other concepts for efficiency improvements concern the optimization of the power transmission and the definition of an optimal coupling between hydraulic system and the engine supported by the development of numerical models able to predict the real system behavior [7-11]. Another option is the design of new valve-controlled system; digital hydraulics technology exploits more robust on-off valves with improved reliability as well as the uncoupling of the metering edges which ensures good dynamic performance and potential of energy-efficient control [12-15]. Displacement control actuation represents a valid alternative to the valve-controlled counterpart with fuel consumption up to 40% and the possibility for engine downsizing. This system avoids the use of control valves eliminating lamination losses due to contemporary actuations of multiple users and allows the recuperation and regeneration of potential energy [16-17]. Other solutions involve the implementation of optimal control strategies and the optimization of individual components to improve flow dynamics and to reduce pressure losses on the metering edges. In particular the optimization of spool areas permits to reduce valve losses which represent the most important contribution to energy losses in a hydraulic excavator.

The aim of this paper is that of analyzing different hydraulic system configurations, open and closed center, for a middle size excavator to define the best solution in term of energy efficiency and fuel consumption. Starting from the validated mathematical model of the machinery equipped with LS hydraulic system, three system layouts have been investigated and modelled with dedicated control algorithms.

For each solution, genetic algorithm has been applied to optimize the valve spool flow areas to reduce energy losses related to meter-in, meter-out and bypass orifices and to quantify the influence of flow areas on fuel consumption. Simulation results have highlighted the potentials of the proposed solutions in term of fuel saving as well as the optimization results showed the relevant impact of the spool design on fuel economy.

2. Mathematical model

The machine under study is a 9t hydraulic excavator equipped with a 46 kW Diesel engine. The flow generation unit (FGU) is composed of a variable displacement axial piston pump and an external gear pump; the valve block is of LS Flow Sharing type and serves to control the nine actuators and to manage the flow rate delivered. The mathematical model of the excavator has been developed using the LMS AMESim® software and is composed of hydraulic sub-models including the main pump, the LS flow sharing directional valve, a 2D kinematics model of the front excavation tool, turret and tracks, the engine model and the operator model. Different modeling approach can be applied depending on the target of the model [18-23]. In this research activity, the pump mathematical model is based on a gray box approach while the valve block model on a lumped parameter approach; both were already validated with a comparison between numerical and experimental results [24-26]. The dynamic model of the users, based on Lagrange equations, reproduces the realistic forces and torques on the hydraulic actuators developed during the simulated cycles referring to the JCMAS standard [27]. The engine model calculates the fuel consumption from a steady-state map as a function of torque and rotational speed and simulates the engine regulators behavior during dynamic operations [28]. Furthermore, to reproduce accurately the operator behaviour and guarantee working cycles repeatability a feedback control was adopted exploiting a PI regulator to reduce the error between the real position and the desired one. As reported in Fig. 1, an error band was introduced to reset the integral part and avoid valve spool oscillations allowing a feasible control of the joysticks by the operator. Finally, to avoid a lag when a user changes the movement direction, if the product between the proportional and integral parts is over zero the integral part is summed to the proportional one, otherwise it is not. Upper and lower limits were fixed to the controller output. Once created the excavator model, it was calibrated and validated with dedicated tests on field; the model has revealed its capability of estimating fuel consumption and defining correctly the hydraulic variables of the system [29].

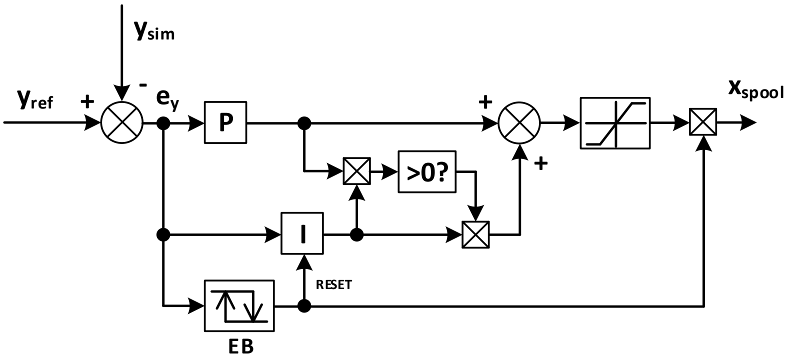

Fig. 1 Block diagram of PI controller

3. System layouts

Starting from the validated mathematical model of a middle size excavator, the paper presents different configurations of valve-controlled hydraulic systems. The investigated solutions are the following:

- Load Sensing Flow Sharing (LS)
- Electronic Flow Matching (EFM)
- Negative Flow Control (NFC)
- Electronic Positive Flow Control (EPC)

The Load Sensing system represents the reference in this study and nowadays acts as the state of the art for most mobile applications. This system is a well-developed hydraulic control system which combines robustness with low energy consumption; the principle is to control the pump displacement referring to the highest load signal and maintaining a small but constant pressure drop, usually 20-30 bar, on the metering edges.

3.1. Electronic Flow Matching

Electronic Flow Matching is known in literature with other expressions as Flow on Demand, Electrohydraulic Load Sensing, Flow Controlled system; it consists of an evolution of the Load Sensing Flow Sharing system in which the hydromechanical regulator of the pump is replaced with an electro-proportional one. Fig. 2 reports the EFM system with two users. An electronic control unit (ECU) receives the command signals on which the operator acts and regulates the pump displacement to provide exactly the flow required by the users. The ECU, reported in Fig. 3, controls both the pump displacement and the spool positions referring to the signals coming from the operator commands and to the engine speed information. The control algorithm of the ECU can be optimized to maximize the system energy efficiency. The considered optimal control strategy consists in keeping the user control valve which requires the greatest flow rate completely open. The opening of the other valves must be defined accordingly to obtain the division of the flow delivered by the pump between the various users in the desired proportions. In this system, there is no longer a pump margin nor a pressure drop fixed in the control algorithm; the distributors are controlled so as to minimize, in any operating conditions, the difference between the pressure at the pump delivery and the pressure required by the users, reducing the meter-in losses.

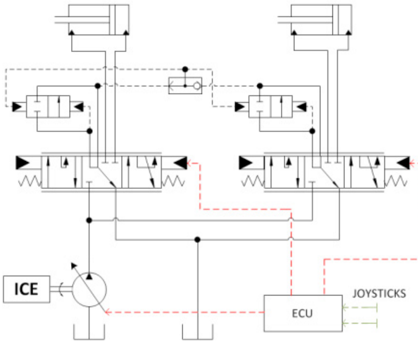

Fig. 2 EFM system

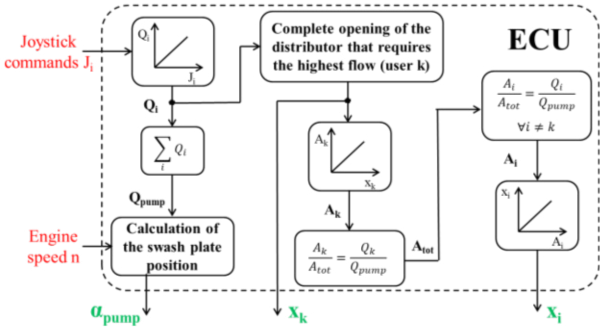

Fig. 3 EFM control strategy

3.2. Negative Flow Control

The Negative Flow Control (NFC) system exploits open center control valves. Pump displacement is controlled with a negative logic by the pressure upstream of the fixed orifice placed at the end of the bypass line. The bypass orifices of all the valves are placed in series forming the line which connects the pump outlet to the tank. In stand-by condition the flow rate delivered by the pump passes through the bypass line, the pressure signal upstream the fixed orifice increases and the pump displacement decreases until it reaches the minimum. The characteristic of the negative control implemented in the pump regulator which connects the displacement with the control pressure as well as the fixed orifice dimension have significant relevance on the performance and efficiency of the system. These factors were defined according to the manufacturer to have a prompt response from the commands of the operator and to maintain pump delivery pressure at 30 bar, eventually to feed the pilot line. Flow areas definition is another important concept with a strong impact on fuel consumption and needs a detailed analysis also to obtain a compromise between the system controllability and efficiency improvements. Figure 4 reports the NFC system with two users. A relief valve is placed at the end of the bypass to avoid overpressures when the commands are suddenly brought to a neutral position and the pump regulator. Figure 5 shows the pump flow rate variation with the control pressure and the outflow characteristics of the fixed orifice corresponding to the bypass flow rate.

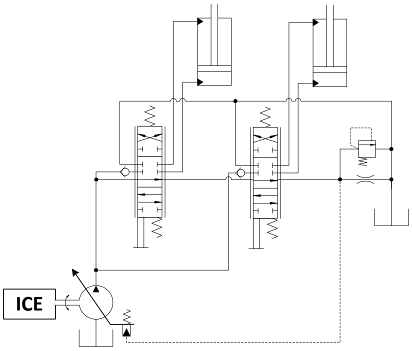

Fig. 4 NFC system

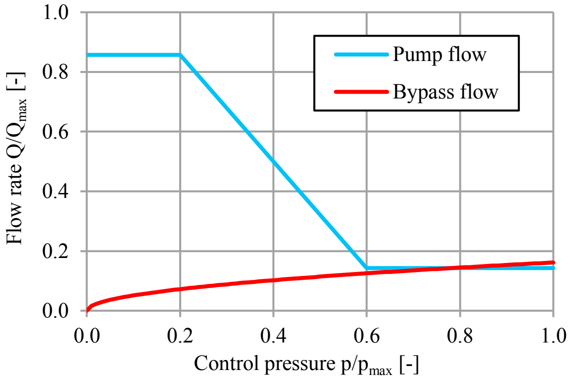

Fig. 5 NFC characteristics

3.3. Electronic Positive Flow Control

Positive Flow Control hydraulic systems similar to NFC systems use open center distributors powered by a variable displacement pump. What differentiates these two systems is the control of the pump displacement. In the traditional architecture of PFC systems, the displacement of the pump is controlled on the basis of the highest pressure among all the driving pressures of the valve spools. The controller is designed to increase the pump displacement as the pressure signal increases. In standby condition, the drive pressures of the distributors are zero and the regulator takes the pump to the minimum displacement. When a user is actuated, the pilot pressure of the corresponding distributor grows and the regulator increases the displacement of the pump. The relationship between pilot pressure and pump displacement depends on the design of the regulator and is very important for the behavior of the system, both under the controllability level and from an energy efficiency point of view. With the development of electronic control units and electro-proportional hydraulic components, the classical architecture is giving way to systems in which the displacement of the pump is electronically controlled on the basis of the electrical signals coming from the joysticks controlled by the operator. Figure 6 reports the EPC system with two users. The considered pump control strategy, reported in Fig. 7, converts the operator signal into a flow rate signal for each user. This signal is first dimensioned with respect to the maximum flow delivered by the pump and then is weighted in relation to the joystick position. Summing the signal of each actuator, the algorithm calculates the swash plate angle to provide the flow rate required by the system.

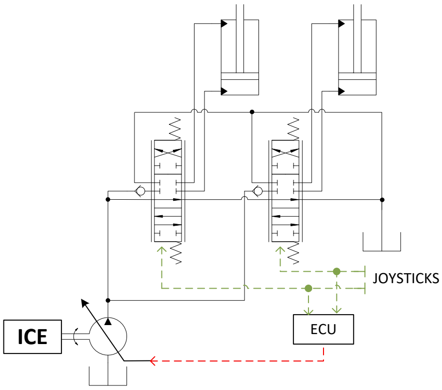

Fig. 6 EPC system

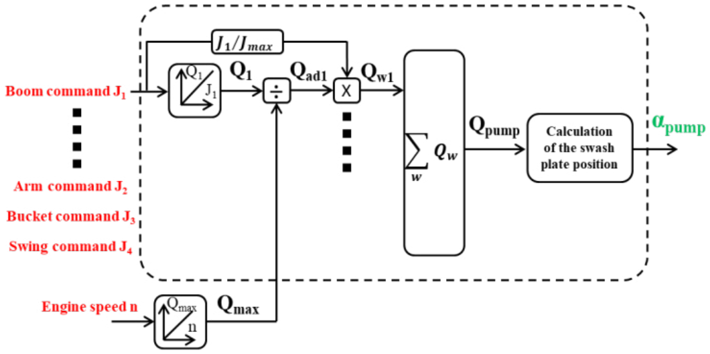

Fig. 7 EPC control logic

4. Flow area optimization

The part of the hydraulic circuit more subject to energy losses in valve-controlled system is the valve block; the pressure losses can be divided in meter-in, meter-out and bypass (only for open center valves). The design of the opening area is a critical factor which could reduce these losses; its influence on fuel consumption should be quantified to compare properly the investigated layouts in their best potential. The goal of this study is that of quantifying the energy improvements obtainable from the optimization of the spool opening areas. The objective is that of reducing pump pressure to decrease power delivered to the system because pump flow rate cannot be reduced to guarantee the required actuators velocity.

The proposed methodology is based on genetic algorithm (GA) theory and is aimed to minimize the fuel consumption of each solution while maintaining the excavator performance requirements. GA is a heuristic global searching method based on mechanics of natural selection derived from Darwin's theory which have found applications in different engineering fields [30,31]. The structure of GA is composed by an iterative procedure. The first step is the creation of an initial population; the best individuals are selected and exploited to obtain children while the others are removed from the population. Genetic operators as crossover and mutation are randomly applied to extend the search space. The iterations of these steps terminate once individuals converge to a global minimum point.

The objective function is the minimization of fuel consumption with the constraint of maintaining the required velocity for the simulated working cycle. The maximum flow area and the overlap are the same supplied by the manufacturer and are not involved in the optimization process. The meter-in and meter-out flow areas shape has been reduced to a quadratic polynomial passing through two fixed constraint points, highlighted in red in Fig. 8, the variable a is the parameter of the polynomial function. The bypass flow area has been optimized by translating the curve and not modifying its shape. For NFC and EPC system the optimization has been conducted on the meter-in, meter-out and bypass spool areas while for the LS and EFM system only for the meter-out one due to the presence of compensators which work to keep a constant pressure margin on the meter-in orifices and due to the absence of bypass orifice in closed centre circuit. Figure 9 shows the optimized spool areas compared to the standard design related to the boom section of the EPC.

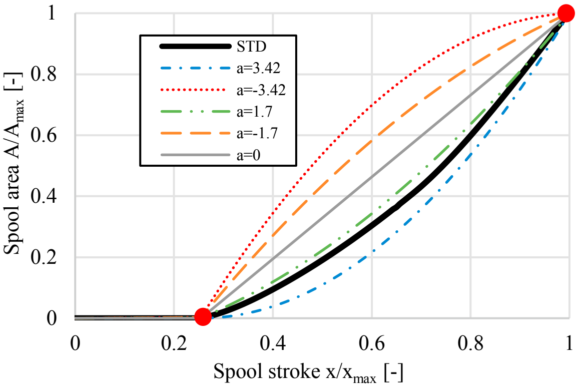

Fig. 8 Optimization procedure

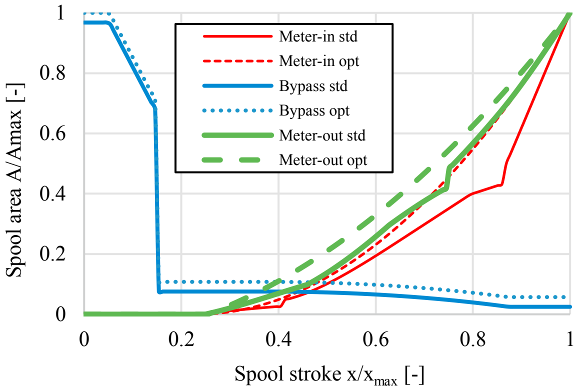

Fig. 9 EPC flow area of the boom section

The effectiveness of the new spool areas has been verified for each configuration in term of controllability of the users by the operator and as respect of actuator movements and time cycle. The comparison has been made on the trench digging and levelling cycle, according to the JCMAS standard. Optimization results have been applied to the investigated system and have revealed the validity of the adopted methodology.

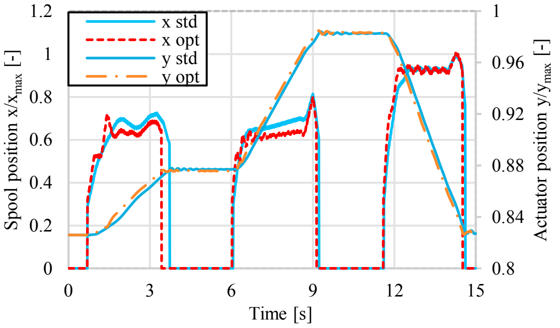

Fig. 10 Position of the spool and actuator of boom in NFC system

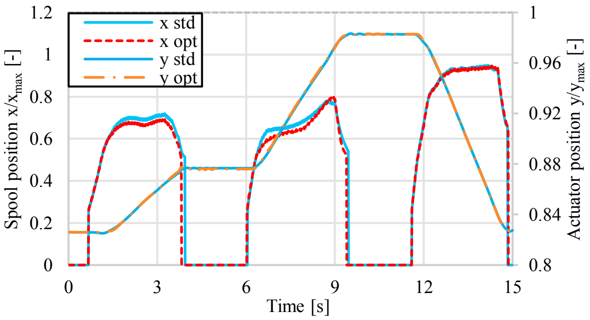

Fig. 11 Position of the spool and actuator of boom in EPC system

Figures 10-11 highlights the good match between the optimized and standard system configurations in term of boom actuator movements for the trench digging cycle for EPC and NFC. Analogue considerations can be extended for the other actuators involved in the optimization process and for LS and EFM layouts. In some cases, the oscillations or instabilities highlighted on the operator control and therefore on the movements of the actuators at the end of the optimization process have been corrected with a tuning of the proportional and integral parameters of the operator's model. Once verified the capability of the developed solutions in optimized and standard conditions of reproducing correctly the required movements and time cycle with a realistic operator control, a comparison in term of fuel economy has been made to compare the layouts and to evaluate the improvements derived from the optimization.

5. Fuel Consumption Results

Fuel consumption evaluation was carried out with the aid of mathematical models to quantify the differences between the analysed configurations referring to trench digging and levelling cycle. The results of the standard layouts are reported in Table 1. The second comparison refers to the optimized solutions of each layout in order to evaluate the impact of flow area optimization on fuel consumption and is reported in Table 2. The fuel saving Δm_f is expressed as percentage difference between the LS reference configuration and each analysed solution.

Table 1. Fuel consumption of the standard layouts.

Investigated solutions	Fuel consumption [g/cycle]		Fuel saving Δm_f[%]	
	Trench digging	Levelling	Trench digging	Levelling
LS	29.06	9.46	ref	ref
EFM	23.61	4.99	-17.7	-47.2
NFC	31.64	8.32	+8.9	-12.1
EPC	24.35	6.97	-16.2	-26.3

Table 2. Fuel consumption of the optimized layouts.

Optimized solutions	Fuel consumption [g/cycle]		Fuel saving Δm_f[%]	
	Trench digging	Levelling	Trench digging	Levelling
LS opt	26.59	7.2	ref	ref
EFM opt	20.4	4.06	-23.3	-43.6
NFC opt	25.1	6.59	-5.6	-8.5
EPC opt	19.37	5.21	-27.15	-27.6

Results highlights the strong impact on fuel consumption of the spool area optimization with fuel economy improved of about 20% for NFC and EPC while the meter-out optimization for the closed-center system has highlighted a decrease of fuel consumption of 10 % on the trench digging cycle. Concluding, the most promising results in term of fuel saving come from the EFM and EPC system; the optimization methodology has revealed further possibility of efficiency improvements for all the considered solutions.

6. Conclusions

In this paper three system layouts (EFM, NFC, EPC) for a middle size excavator have been presented and compared to the conventional LS system with the aid of mathematical tools. The comparison has been made on the trench digging and levelling cycle defined by the JCMAS norm in term of fuel consumption ensuring compliance with the desired movements and cycle times. An optimization methodology applied to meter-in, meter-out and bypass flow areas has been developed to quantify the impact of spool area design on the energy efficiency and to improve the energy saving with the reduction of valve losses without penalizing the performance of the excavator. The proposed methodology is based on the application of genetic algorithm with the objective of minimizing fuel consumption taking into account the compliance of the desired movements and cycle times. Simulation results have proved the validity of the applied methodology which has led to important energy savings for each investigated solution. Fuel comparison has highlighted the energy saving potentials of the proposed solutions; the best fuel saving is obtained with the EFM and EPC system whose fuel saving are higher than 20% on the trench digging cycle. NFC system has however showed a considerable improvement in fuel consumption with the optimization of the valve spool flow area.

References

[1] Hießl, A.; Scheidl, R.; Energy consumption and efficiency measurements of different excavators—Does hybridization pay? In Proceedings of the ASME/BATH Symposium on Fluid Power and Motion Control, Chicago, IL, USA, 12–14 October 2015.

[2] Thompson, B.; Yoon, H.; Kim, J.; Lee, J. Swing Energy Recuperation Scheme for Hydraulic Excavators; SAE Technical Paper 2014.

[3] Casoli, P.; Gambarotta, A.; Pompini, N.; Riccò, L. Hybridization methodology based on DP algorithm for hydraulic mobile machinery-Application to a middle size excavator. *Automation in Construction* Volume 61, January 2016, Pages 42–57. doi:10.1016/j.autcon.2015.09.012.

[4] Casoli, P.; Riccò, L.; Campanini, F.; Bedotti A. ;Hydraulic Hybrid Excavator—Mathematical Model Validation and Energy Analysis. *Energies MDPI* 2016, 9, 1002; doi:10.3390/en9121002

[5] Kim Heybroek & Mika Sahlman (2018): A hydraulic hybrid excavator based on multi-chamber cylinders and secondary control – design and experimental validation, International Journal of Fluid Power, DOI: 10.1080/14399776.2018.1447065

[6] Li, S., Wei, J., Fang, J, Guo. K, Liu. W.; Design and Control of Hydraulic Hybrid System for Excavators. ASME/BATH 2015 Symposium on Fluid Power and Motion Control, Chicago, Illinois, USA, October 12–14, 2015, doi:10.1115/FPMC2015-9564

[7] Rossetti A., Macor A., Scamperle M. "Optimization of components and layouts of hydromechanical transmissions"International Journal of Fluid Power Volume 18, Issue 2, 4 May 2017, Pages 123-134. DOI: 10.1080/14399776.2017.1296746. Codice Scopus:2-s2.0-85015076287

[8] Macor A., Rossetti A., Scamperle M. "Prediction of sound pressure level for a dual-stage hydromechanical transmission". International Journal of Fluid Power, Volume 17, Issue 1, 2 January 2016, Pages 25-35. DOI: 10.1080/14399776.2015.1120137. Codice Scopus: 2-s2.0-84958945379.

[9] Casoli P., Gambarotta A., Pompini N., Riccò L.; Coupling excavator hydraulic system and internal combustion engine models for the real-time simulation; *Control Engineering Practice*, 2015, pp. 26–37 http://dx.doi.org/10.1016/j.conengprac.2015.04.003.

[10] Pintore F., Borghi M., Morselli R., Benevelli A., Zardin B., Belluzzi F.; Modelling and Simulation of the Hydraulic Circuit of an Agricultural Tractor. ASME. Fluid Power Systems Technology, 8th FPNI Ph.D Symposium on Fluid Power; V001T04A004. doi:10.1115/FPNI2014-7848.

[11] Casoli P., Vacca A., G.,Berta, Meleti S., Vescovini M. (2007) "A numerical model for the simulation of Diesel/CVT power split transmission" SAE paper n. 2007-24-137, SAE-NA ICE2007, 17-20 Settembre, 2007 Capri-Napoli. ISBN: 978-88-900399-3-0. DOI: 10.4271/2007-24-0137

[12] Linjama, M. (2011, May). Digital fluid power: State of the art. In *12th Scandinavian International Conference on Fluid Power, Tampere,* Finland, May (pp. 18-20).

[13] Karvonen M, Heikkilä M, Tikkanen S, Linjama M, Huhtala K.; Aspects of the Energy Consumption of a Digital Hydraulic Power Management System Supplying a Digital and Proportional Valve Controlled Multi Actuator System. ASME. Fluid Power Systems Technology, ASME/BATH 2014 Symposium on Fluid Power and Motion Control ():V001T01A012. doi:10.1115/FPMC2014-7817.

[14] Zhong Q, Zhang B, Niu M, Hong H, Yang H.; Research on Dynamic Performance of Independent Metering Control System. ASME. Fluid Power Systems Technology, ASME/BATH 2017 Symposium on Fluid Power and Motion Control: V001T01A006. doi:10.1115/FPMC2017-4221.

[15] Lee J, Jin K, Kwon Y, Choi L, Choi J, Lee B.; Development of the Independent Metering Valve Control System and Analysis of its Performance for an Excavator. ASME. Fluid Power Systems Technology, BATH/ASME 2016 Symposium on Fluid Power and Motion Control : V001T01A021. doi:10.1115/FPMC2016-1745.

[16] Hippalgaonkar, R.; Ivantysynova, M.; A Series-Parallel hydraulic hybrid mini-excavator with displacement-controlled actuators. The 13th Scandinavian International Conference on Fluid Power, SICFP2013, June 3-5, 2013, Linköping, Sweden.

[17] M. Inderelst, S. Losse, S. Sgro, H. Murrenhoff.; Energy Efficient System Layout for Work Hydraulics of Excavators. The Twelfth International Conference on Fluid Power. May 18-20, 2011. Tampere. Finland.

[18] Borghi, M.; Specchia, E.; Zardin, B.; Corradini, E.;The Critical Speed of Slipper Bearings in Axial Piston Swash Plate Type Pumps and Motors. ASME. Dynamic Systems and Control Conference, ASME 2009 Dynamic Systems and Control Conference, Volume 1:267-274. doi:10.1115/DSCC2009-2604.

[19] Borghi, M.; Zardin, B.; Axial Balance of External Gear Pumps and Motors: Modelling and Discussing the Influence of Elastohydrodynamic Lubrication in the Axial Gap. ASME 2015 International Mechanical Engineering Congress and Exposition. Volume 15: Advances in Multidisciplinary Engineering. p. 1-10, ASME, ISBN: 9780791857588, Houston, Texas, 13-19 November 2015, doi: 10.1115/IMECE2015-51632

[20] Altare G., Rundo M.; Advances in simulation of gerotor pumps: An integrated approach, Proc. IMechE Part C: J. Mechanical Engineering Science 231(7): 1221-1236, 2017. DOI: 10.1177/0954406217694663. Scopus: 2-s2.0-85016261465. WOS: 000398206700003

[21] Altare G., Rundo M.; CFD Analysis of gerotor lubricating pumps at high speed: geometric features influencing the filling capability, Proceedings of the ASME/BATH 2015 Symposium on Fluid Power and Motion Control (FPMC), Oct. 12-14, 2015, Chicago, IL, USA. Paper no. FPMC2015-9539. DOI: 10.1115/FPMC2015-9539. Scopus: 2-s2.0-84964403756.

[22] E. Frosina, D. Buono, A. Senatore, K. A. Stelson; A modeling approach to study the fluid dynamic forces acting on the spool of a flow control valve", J. Fluids Eng 139(1), pp. 011103 – 011115, doi:10.1115/1.4034418, Scopus code: 2-s2.0-84992390117.

[23] E. Frosina, D. Buono, A. Senatore, I. J. Costin; A Simulation Methodology Applied on Hydraulic Valves for High Fluxes. International Review on Modelling and Simulations 9(3):217, doi: 10.15866/iremos.v9i3.9612, Scopus Code: 2-s2.0-84983050183

[24] Casoli, P.; Anthony, A.; Rigosi M.; Modeling of an Excavator System – Semi empirical hydraulic pump model SAE 2011 Commercial Vehicle Engineering Congress, Rosemont, Illinois, USA, 13-14 September 2011. doi:10.4271/2011-01-2278.

[25] Casoli, P.; Anthony, A.; Riccò, L.; Modeling simulation and experimental verification of an excavator hydraulic system—Load sensing flow sharing valve model. In Proceedings of the SAE 2012 Commercial Vehicle Engineering Congress, doi:10.4271/2012-01-2042.

[26] Casoli, P.; Pompini, N.; Riccò, L.; Simulation of an Excavator Hydraulic System Using Nonlinear Mathematical Models; *Strojniški vestnik - Journal of Mechanical Engineering* 61(2015)10, 583-593, doi:10.5545/sv-jme.2015.2570.

[27] Earth-Moving Machinery—Fuel Consumption on Hydraulic Excavator—Test Procedure; JCMAS H020:2007; Tokyo, Japan, 2007.

[28] Casoli, P.; Gambarotta, A.; Pompini, N.; Riccò L.;Development and application of co-simulation and control-oriented modeling in the improvement of performance and energy saving of mobile machinery", *Energy Procedia*, http://dx.doi.org/10.1016/j.egypro.2014.01.090

[29] Casoli, P.; Riccò, L.; Campanini, F.; Lettini, A.; Dolcin, C.; Mathematical model of a hydraulic excavator for fuel consumption predictions. In Proceedings of the ASME/BATH 2015 Symposium on Fluid Power and Motion Control, Chicago, USA, 2015. doi:10.1115/FPMC2015-9566

[30] K.F. Man, K.S. Tang, S. Kwong, Genetic algorithms: concepts and applications, IEEE Trans. Ind. Electron. 43 (5) (1996).

[31] J. Richardson, M. Palmer, G. Liepins, M. Hilliard, Some guidelines for genetic algorithms with penalty functions, Proceedings of the Third International Conference on Genetic Algorithms, 1989.