ENERGY EFFICIENT DRIVE SYSTEM WITH DIGITAL HYDRAULIC CYLINDER FOR CONSTRUCTION AND AGRICULTURAL MACHINERY

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SISTEM DE ACTIONARE EFICIENT ENERGETIC CU CILINDRU HIDRAULIC DIGITAL PENTRU MASINI DE CONSTRUCTII SI AGRICOLE

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DOI: https://doi.org/10.35633/inmateh-68-01

***Keywords:** digital hydraulic cylinder, efficiency, drive system, simulation*

ABSTRACT

Given the need to reduce greenhouse gas emissions, new energy-efficient solutions can be adopted for construction and agricultural machinery. Such a solution is a digital hydraulic cylinder that uses several active areas and a constant pressure supply with which a gradual variation of the driving force can be obtained. Traditional hydraulic systems have high energy losses due to the need to direct and throttle the flow through different valves. The article presents simulations in the AMESim environment and laboratory experiments of a digital hydraulic cylinder with three active areas. Through numerical simulations, the authors aim to highlight the energy efficiency of a digital hydraulic cylinder compared to a hydraulic cylinder in a conventional drive.

REZUMAT

Avand in vedere necesitatea reducerii emisiilor cu efect de sera, se pot adopta noi solutii eficiente energetic pentru utilajele de constructii si agricole. O astfel de solutie este un cilindru hidraulic digital care utilizeaza mai multe suprafete putandu-se obtine o variere în trepte a fortei de acționare cu presiune de alimentare constanta. Sistemele hidraulice traditionale au pierderi energetice mari din cauza necesitatii de a directiona si strangula debitul prin diferite valve. In articol se prezinta simulari in mediul AMESim si experimentari de laborator ale unui cilindru hidraulic digital cu trei arii active. Prin simularile numerice autorii isi propun sa scoata in evidenta eficienta energetica a unui cilindru hidraulic digital fata de un cilindru hidraulic dintr-o actionare clasica.

INTRODUCTION

Reducing fuel consumption and implicitly carbon emissions in the atmosphere requires the adoption of energy efficient solutions for mobile machinery. In order to reduce unnecessary energy consumption in hydraulic actuations, throttling losses that occur when using proportional valves must be avoided.

For mobile machines, solutions have been adopted to reduce energy consumption, such as load sensing systems (LS) through which hydraulic actuators can be controlled depending on the load variation or secondary control systems (SCS) where the output unit (secondary) is connected to a constant pressure pipeline. The system operates in a high pressure network coupled with a hydraulic accumulator. The purpose of the hydraulic accumulator is to store the energy supplied to the network by the secondary unit when it is reversed (e.g. decelerating a load). When operating under load, the accumulated energy is used to compensate for consumption peaks. While the primary actuations work with an interface through volumetric flow, the systems with secondary control are connected through the specific operating pressure. Systems with secondary control are only suitable for actuations with rotating loads, and for linear actuators other solutions must be used in order not to introduce excessive throttling. One solution is the switching control of hydraulic cylinders with multiple chambers, which can be used to achieve force control by discretely varying the area of the hydraulic cylinder. This solution regarding the parallel connection of the chambers of a digital hydraulic cylinder (DHC), is part of the revised digital hydraulic technologies by Zhang, Q. and Kong, X. *(Zhang et al., 2020). Heemskerk, E. and Bonefeld, R.* studied a semi-binary hydraulic four-chamber cylinder with the aim of improving the force resolution to obtain a more precise control of the cylinder *(Heemskerk et al., 2015)*. For this, one of the cylinder chambers is not connected to the pressure source through a switching valve but with a proportional valve. A study on the use of a multi-chamber cylinder, discretely controlled on/off valves and three pressure lines as well as a series of useful examples to reach a new level of efficiency in construction machines were outlined by *Heybroek and Norlin, 2015*.

Heybroek and Sahlman developed a highly efficient hydraulic hybrid system for an excavator that uses a multi-chamber cylinder and secondary control, a detailed energy analysis was carried out that explains the energy flow in the hybrid system (*Heybroek et al., 2018*).

Another solution to minimize or completely eliminate the need for proportional valves, thus avoiding throttling losses associated with metering, is through the use of hydraulic transformers, fed from a common pressure line that operates both the working mechanisms and rotary drives from the propulsion system of a front loader (*Heybroek et al., 2012*).

A team from Tampere University of Technology and Aalto University, Espoo in Finland designed, simulated and tested a digital hydraulic multi-pressure actuator with high energy saving potential. It contains a piston pressure accumulator and 4 pressure converters, and the system allows 6 different supply pressure levels that can be connected to the cylinder chambers through on/off valves (*Huova et al., 2017*).

Mäkelä J. determined the traditional, total and regeneration energy efficiencies of the digital hydraulic multi-pressure actuator (DHMPA) used in load-lifting applications in his thesis (*Mäkelä J., 2020*). The efficiency values were determined experimentally. The results showed that DHMPA is feasible to be used in load-lifting applications. *Pedersen* proposed an energy-efficient hydraulic cylinder concept with three pressure lines, which allows reducing throttling losses compared to conventional solutions while maintaining accuracy and control. The final design of the concept was implemented in simulation models to investigate the performance of the developed control system (*Pedersen et al., 2018*).

Changlin, M. and Feng, L. modelled and simulated the mechanism of a variant of DHC, a digital hydraulic cylinder with screw feedback and stepper motor control in order to optimize DHC performance (*Changlin, M. et al., 2020*).

For each machine actuation application, following a complex analysis, modern solutions can be adopted to minimize energy losses. The energy losses of inefficient hydraulic installations lead to the excessive heating of the hydraulic fluid, a fact that can lead to the premature failure of the machines, in addition to the emission of greenhouse gases.

MATERIALS AND METHODS

Digital hydraulic system

A series of laboratory experiments were carried out with a DHC with three active chambers that highlighted the 7 stages of force and speed that can be achieved by connecting the cylinder chambers in parallel. The diagram of the stand can be found in figure 1, and in figure 2 it can be seen the block with 4 valves for connecting the DHC chambers according to the command stages. The surfaces of the active chambers of the cylinder are: 5 cm^2, 13.5 cm^2, 14.7 cm^2, the rod backward chamber having 20.6 cm^2. A pump with a maximum flow rate of 20 l/min and a fastening device for the DHC and the hydraulic load cylinder were used, connecting the rods by means of a force transducer.

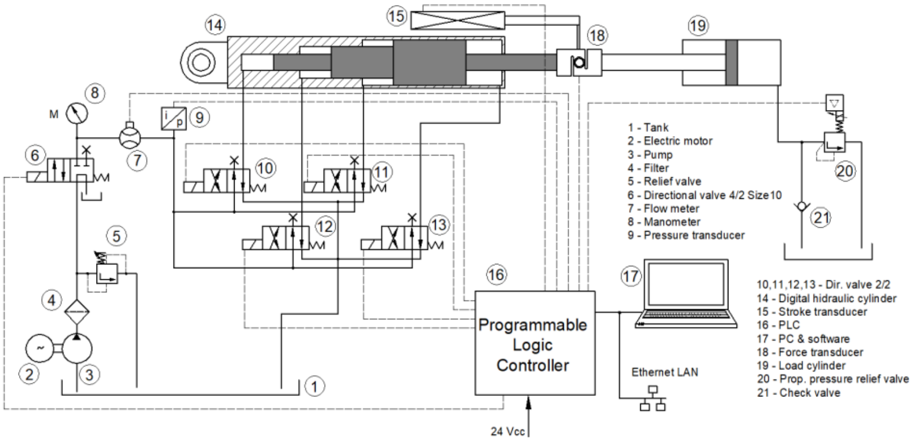


Fig. 1 - Scheme of the test stand for DHC with three chambers

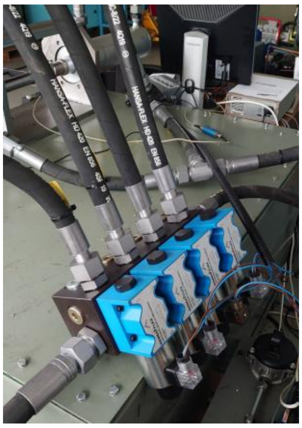


Fig. 2 - Block with 4 valves for connecting DHC chambers

A programmable logic controller was used to control the solenoid valves and to acquire data. The tests were carried out with a virtual instrument application made in the LabView environment. The application communicates with the programmable logic controller through the Modbus TCP/IP protocol, each solenoid of the directional valves, the proportional valve and the transducers having each assigned an address in the programmable logic controller. The test method consisted in the successive command of the electrovalves in order to realize the combinations of the cylinder chambers to obtain a successive increase in the active surface of the DHC. The switching of the stages was done in short times so that the 250 mm stroke of the hydraulic cylinder did not end until all the control stages were achieved. On the diagrams recorded for the force and stroke of the hydraulic cylinder rod, one can see the 7 stages that the three-chamber DHC can achieve. Summing up the combinations of areas of the chambers of the hydraulic cylinder with several lines of pressure, the number of force stages that a DHC can achieve, can be increased. *Dell-Amico, A. and Carsson, M.* investigated an actuation system with a multi-chamber hydraulic cylinder for an excavator arm. The aim of the work was to investigate a cylinder with four chambers with three pressure lines with the generation of 81 force levels, applied to an excavator arm. The different control strategies showed that there is a compromise between accuracy, smoothness of the arm movement and the switching frequencies *(Dell'Amico et al., 2013)*. Figure 3 shows the graphs recorded for the force from the DHC rod for a maximum load set to the load cylinder of 1000 daN. In order to create a gap between steps, the control was deactivated for a short time between steps.

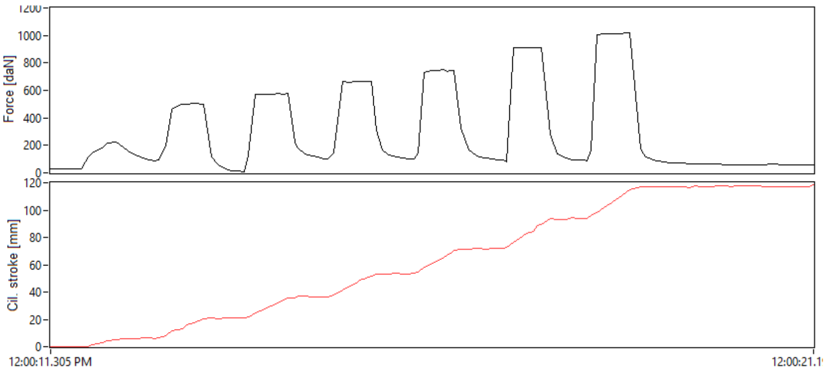


Fig. 3 - Graphs with the variation of the force and stroke of the DHC

In order to determine the energy consumption of the DHC, an actuation system with a digital cylinder with 3 active chambers for advance and a chamber for retraction of the rod was designed and modelled in Amesim (Figure 4). The diameters of the pistons for forward stroke are ∅50 / ∅90 / ∅125, and for backward stroke ∅125. The simulation scheme contains 5 blocks: 1 - ECU, 2 - motor-pump group, 3 - block with valves, 4 - modelled DHC and 5 - load unit. The ECU block: electronic unit control, ensures the command cycle (Figure 5) for obtaining the power levels at the DHC rod. During the simulation, it performs the sequence of the 7 command steps according to Table 1.

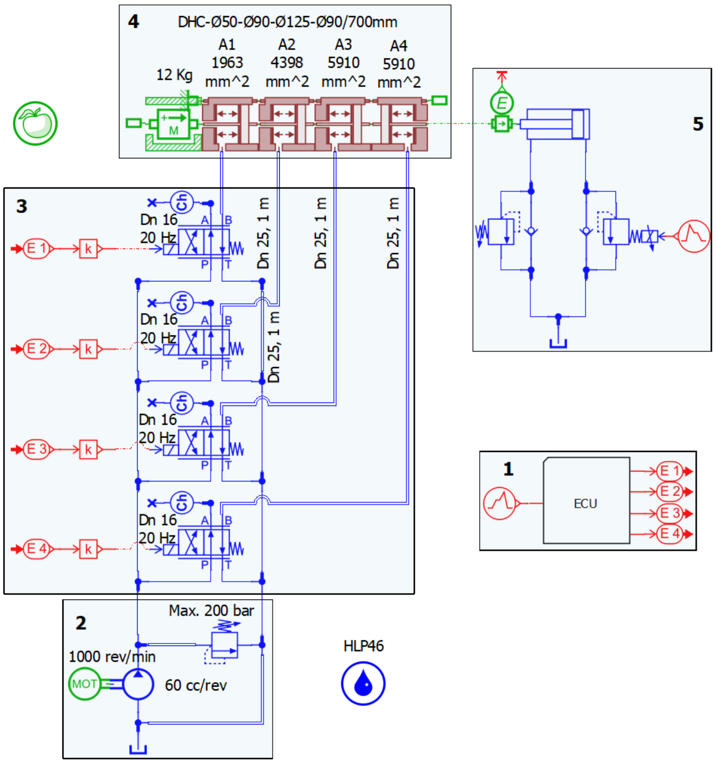
Table 1

Energized valves solenoids for different DHC stages

Valve solenoid	DHC Stages							
	Backward	Forward 1	Forward 2	Forward 3	Forward 4	Forward 5	Forward 6	Forward 7
E1		■		■		■		■
E2			■	■			■	■
E3					■	■	■	■
E4	■							

An important issue is related to the structuring of the hydraulic scheme and the appropriate sizing of valves and pipes because in certain situations, e.g. when the cylinder rod is withdrawn and the flow from all the other 3 chambers must be evacuated, high pressure drops may occur. Similarly, when feeding the piston with the smallest area, the speed of the fluid that is evacuated from the other chambers is high and large power losses can occur. The appropriate dimensioning of the exhaust routes to the tank must be taken into account, possibly each valve should have a pipeline directly to the tank or if it is connected to a main pipeline, it should have an increased size.

In the case of conventional actuation systems, there is the situation in figure 6 where the unused power is transformed into heat and eliminated in the environment.



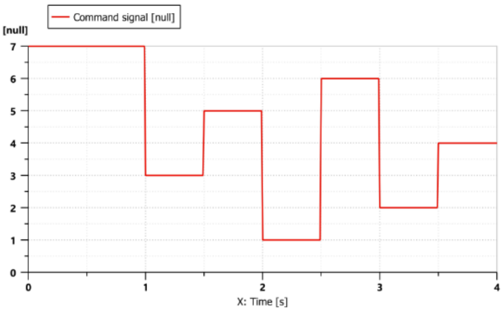


Fig. 5 - Signal for controlling the DHC during simulation

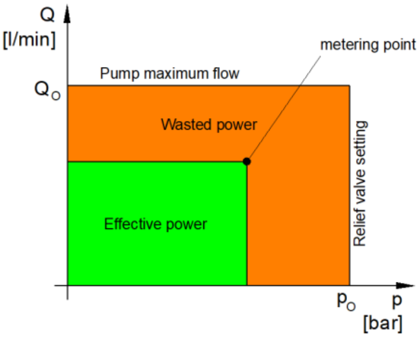


Fig. 4 - The simulation scheme for a drive unit with DHC
1 – electronic control unit ECU; 2 – motor – pump group; 3 – block with valves; 4 – modelled DHC; 5 - load unit

Fig. 6 - Effective power and wasted power

The hydraulic power P of the actuation system can be calculated from the operating pressure p_O and the operating flow rate Q_O provided at the outlet of the pump according to formula (1).

$$P = p_O \cdot Q_O \tag{1}$$

Hydraulic power can also be obtained from the mechanical parameters of the hydraulic motor (DHC), i.e. force F, displacement x or speed $\dot{x}$ according to the formula (2)

$$P = \frac{F \cdot x}{\Delta t} = F \cdot \dot{x} \tag{2}$$

The estimation of the energy consumption E of the actuation system is carried out from flow Q and pressure p, according to the formula (3)

$$E = \int_0^t Q(t) \cdot p(t) dt \tag{3}$$

To determine the total efficiency of the system η_{tot}, the ratio between the output power P_{out} and input power P_{in}, can be calculated as follows:

$$\eta_{tot} = \frac{P_{out}}{P_{in}} \tag{4}$$

At the same time, the total efficiency can be calculated as the product of the volumetric efficiency η_{vol} and the mechanical-hydraulic efficiency η_{mh} according to (5).

$$\eta_{tot} = \eta_{vol} \cdot \eta_{mh} \tag{5}$$

Conventional hydraulic system

In order to evaluate the energy losses from a conventional actuation system with a servo valve, a system like the one in figure 7 was also modelled and simulated. The system is composed of an electric pump that supplies 57 l/min, the system pressure being limited to 250 bar, a servo valve, a hydraulic cylinder with a bilateral rod with bore diameter 100 mm, rod diameter 50 mm and a stroke of 1100 mm. The cylinder rod is coupled with a friction mass. A speed sensor was also placed in the diagram to measure the speed of the cylinder rod. At the running parameters of the simulation, at additional computations, those for power and energy were checked.

The simulation consisted in obtaining several speed steps at the hydraulic cylinder rod by using a signal source configured in 5 stages according to figure 8.

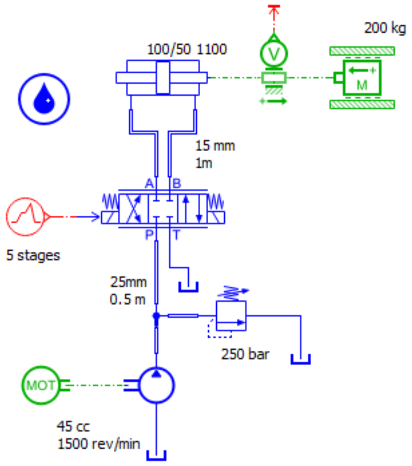


Fig. 7 - Scheme of conventional hydraulic system

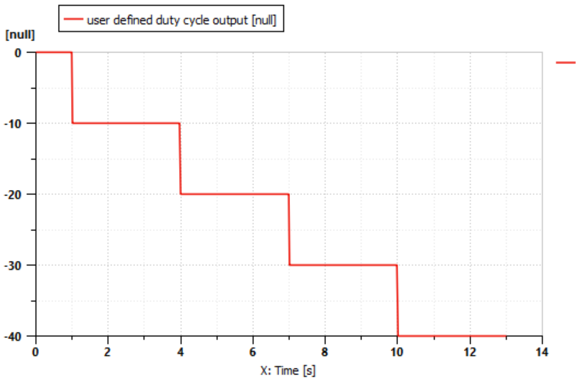


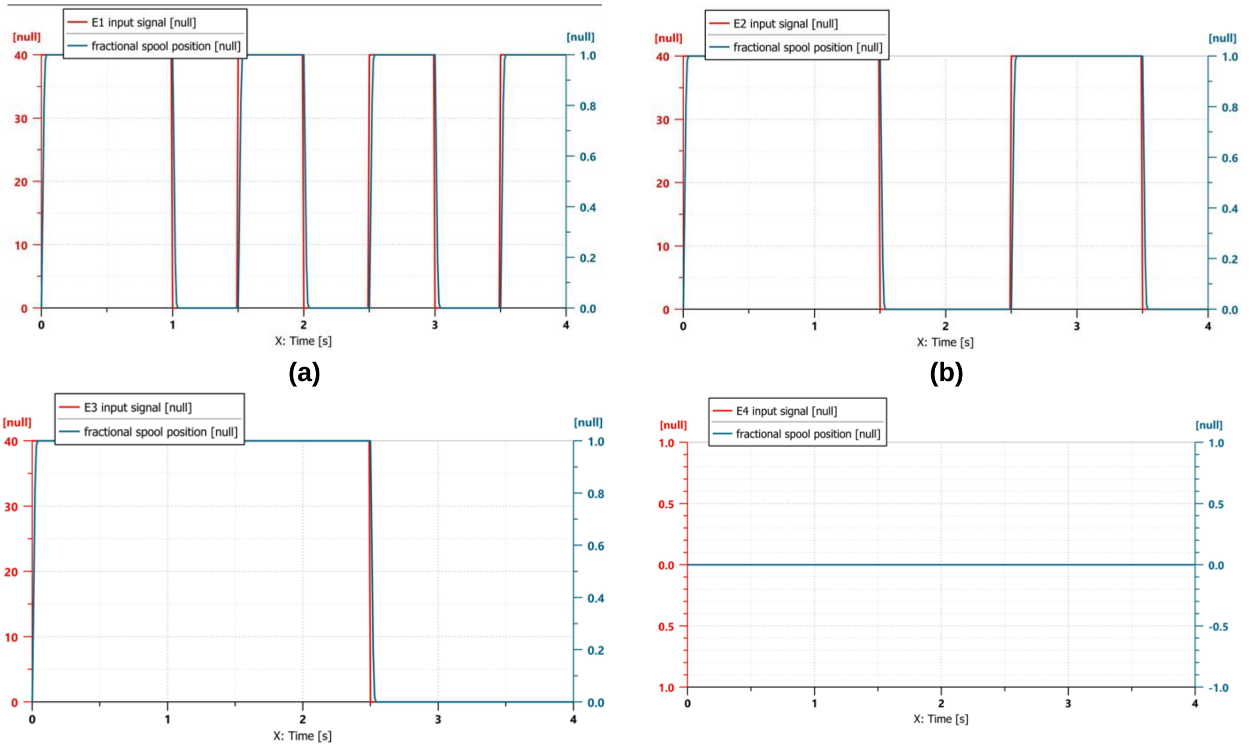
Fig. 8 - Signal for control the servo valve during simulation

RESULTS

The results of the simulations for the digital hydraulic cylinder system and the conventional actuation system are presented below.

Digital hydraulic system

Figure 9 shows the diagrams for the control signals to the solenoids of the block with electrovalves. The shape of the signals corresponds to a typical sequence of the binary states for a 3-bit system.



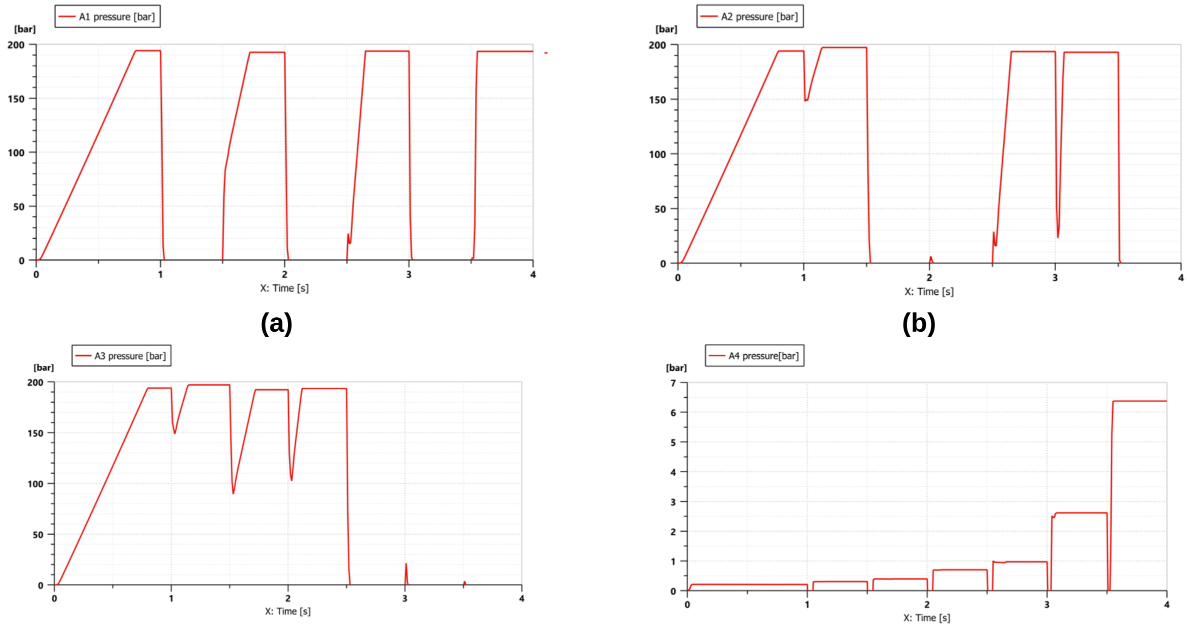
(a) (b)

(c) (d)

Fig. 9 - Input signals for valves solenoids and fractional spool position

a – E1 solenoid signal / spool position; b – E2 solenoid signal / spool position;
c – E3 solenoid signal / spool position; d – E4 solenoid signal / spool position

Figure 10 shows the pressure variation diagrams in the DHC chambers. The pressure variation in the three active chambers also corresponds to the binary states of the 3-bit system. The pressure variation in chamber A4 is due to a pressure drop that reaches a maximum of 6.4 bar on the hydraulic fluid discharge route to the tank, in correspondence with the movement speed of the DHC piston or the flow rate of hydraulic fluid discharged from the chamber.



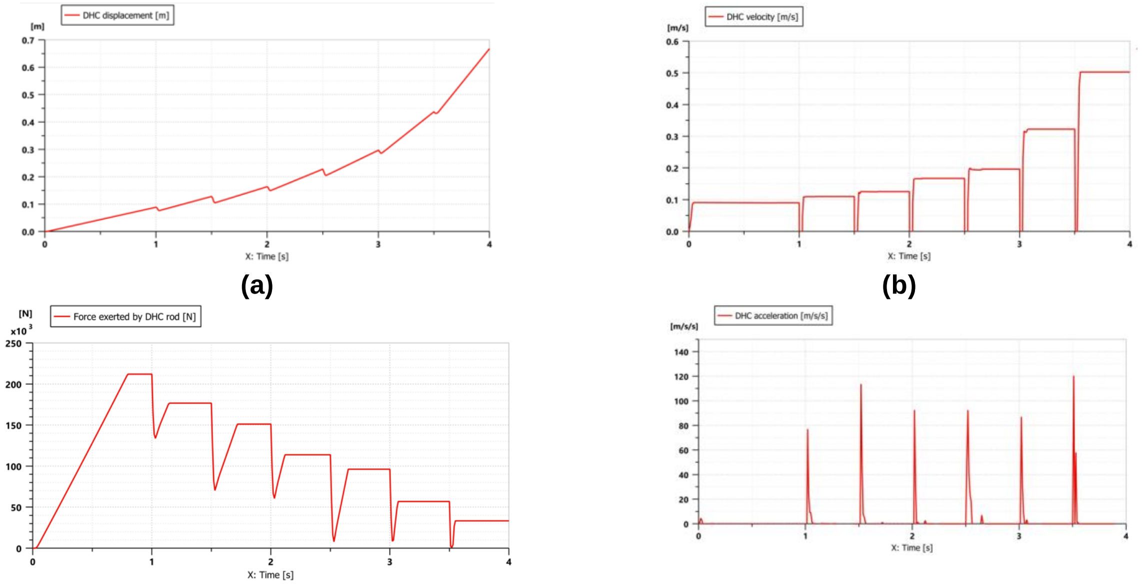
(a) (b)

(c) (d)

Fig. 10 - Pressure for DHC chambers

a – A1 DHC chamber; b – A2 DHC chamber; c – A3 DHC chamber; d – A4 DHC chamber

The graphs with the variation of the DHC parameters during the simulation can be found in figure 11. In figure 11(a) one can see the movement of the DHC rod. The DHC speed depending on the control step is in figure 11(b). The force exerted on the DHC rod depending on the control stage can be found in figure 11(c), the force obtained being dependent on the level set in the load block by the command transmitted to the valve. In figure 11(d), one can see the DHC acceleration when switching the control stages.



(a) (b)

(c) (d)

Fig. 11 - The response diagrams of the DHC during the simulation

a – DHC displacement; b – DHC acceleration; c – DHC velocity;
d – Force exerted by DHC

Figure 12 shows the diagrams with shaft speed and torque of the pump. It can be seen that the torque at the pump shaft is constant throughout the simulation, in correspondence with the maximum pressure in the system of approximately 195 bar. Figure 13 shows the graphs with the useful power provided by DCH and the energy consumed during the simulation. The power graph is useful for calculating the efficiency of the DHC drive system. By averaging the power used on each DHC control stage, a useful power of 18.5 kW is obtained. Drive power is 22 kW taking into account also the total efficiency. Using formula (4) results in an efficiency of DHC drive system of 84%, which varies very little with the command stage of the valves block.

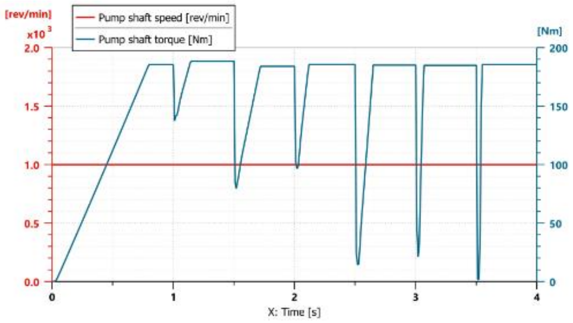


Fig. 12 - Pump shaft speed and torque

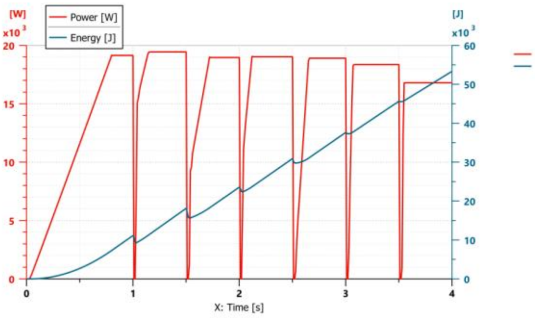


Fig. 13 -The useful power of DCH and the energy consumed

Conventional hydraulic system

In the case of the conventional hydraulic system, the simulation was carried out to obtain speed steps at the rod of a servo cylinder that moves a mass with friction. In order to obtain distinct speed steps during the 1100 mm stroke, the servo valve command was limited to 30%. This fact allowed a precise metering of the flow, which feeds the cylinder, but with the disadvantage of additional throttling losses. After the simulation, the pressure and flow variation at port A of the servo valve was obtained (figure 14). The flow steps obtained for the command stages were 15, 29, 43 and 57 l/min, and the pressure level was at 125 bar. In figure 15, the graphs for the stroke and speed of the piston of the hydraulic cylinder were obtained. Each speed step is found in segments with different slopes on the displacement diagram up to the maximum stroke of the cylinder.

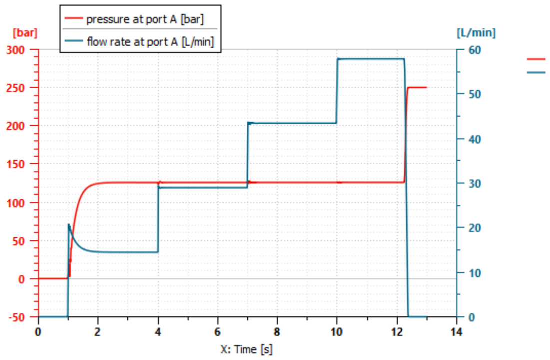


Fig. 14 - Pressure and flow at port A
of servo valve

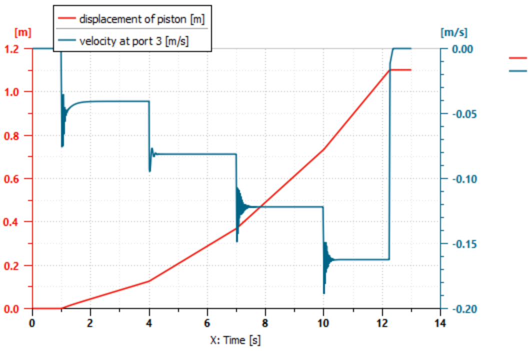


Fig. 15 - Piston stroke and speed
of hydraulic cylinder

Figure 16 shows the power and energy dissipated during the simulation by the servo valve. One can see the correspondence with figure 17 in which the power dissipated by the relief valve is in inverted magnitude to the power dissipated by the servo valve.

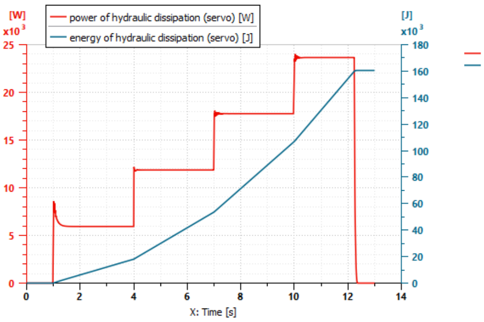


Fig. 16 - Energy and power dissipated by the servo valve at different control stages

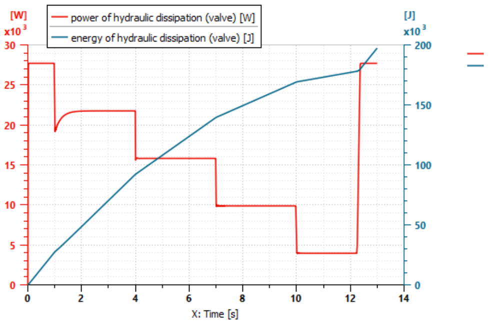


Fig. 17 - Energy and power dissipated by the valve at different control stages

When the metering section from the servo valve is small, the excess flow is discharged through the relief valve, and at maximum command, the power dissipated by the servo valve is maximum, and that dissipated by the relief valve is minimum. Considering the simulation scheme from fig. 7 the maximum efficiency obtained after the simulation was 42.5% for last stage of the simulation.

CONCLUSIONS

Conventional actuation systems involve large power losses of a mechano-hydraulic and volumetric nature. In order to increase the energy efficiency, the linear actuators can be provided with secondary control by using some hydraulic cylinders to which the nominal area can be discreetly adjusted. These actuation systems can be fed at constant pressure by pumps with fixed nominal volume which can be gear pumps that have a low price. The simulation carried out for an actuation system with DHC showed a much better energy efficiency compared to a conventional actuation system. Digital hydraulic cylinders in combination with digital on/off valves and controllers with specialized software can lead to an increase in energy efficiency in actuation systems for construction or agricultural machines. Future work will consider using more pressure lines for DHC and obtaining a greater number of force control steps.

ACKNOWLEDGEMENT

This paper has been funded by the Romanian Ministry of Research and Innovation under NUCLEU Programme, Financial Agreement no. 18N/2019, Ad 14/2021, Project code PN 19-18.01.01, Phase 19 “Research on the realization of mechatronic systems for the control of speeds and forces with digital hydraulic equipment or piezoelectric pneumatic equipment”.

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