Poboljšavanje energetske efikasnosti hidrauličnih sistema kod teških mašina

Improving Energy Efficiency of the Hydraulic Power Systems in Heavy Machinery

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Apstrakt – Glavni cilj istraživanja obavljenog u ovom radu je ispitivanje mogućih poboljšanja energetske efikasnosti hidrauličkih elektroenergetskih sistema sa manjom emisijom gasa iz teških mašina. Ovde se daje kratko objašnjenje postojećih hidrauličnih sistema koji posebnu pažnju posvećuju hidrauličnom servo sistemu sa odvojenim dovodnim i odvodnim meračima i (SMISMO). Iako je cilj ovog istraživanja poboljšanje efikasnosti hidrauličke energije uglavnom korišćenjem sistema SMISMO, primenjena su i dodatna istraživanja o upotrebi tih sistema za istovremeno upravljanje brzinom i pritiskom cilindara. Rezultati dobijeni eksperimentalnim studijama koristiće se za dalje poboljšanje hidrauličkog sistema. Dalja nadogradnja ovog sistema je usmerena na dizajniranje automatizovanog SCADA sistema za bolje prikupljanje podataka i kontrolu ventila u servo sistemima.

Ključne reči -- hidraulični sistemi, energetska efikasnost, upravljanje, smismo

Abstract- The main goal of the research done in this paper is to examine possible improvements in energy efficiency of the hydraulic power systems and with this lower gas emission from working machinery. It is here given a brief explanation of the existing hydraulic systems putting special attention on a hydraulic system with separate meter-in and separate meter-out (SMISMO). While the aim of this research is to improve the hydraulic energy efficiency mainly using the SMISMO system, additional research on using those systems for simultaneous speed and pressure control of the cylinders is also observed. The results obtained through experimental studies will be used to further improve the hydraulic system. Further upgrade of this system is to design automated SCADA system for improved data acquisition and control the valves in servo systems.

Index Terms- Hydraulics, mobile machines, energy efficiency, SMISMO systems, control strategies.

I. INTRODUCTION

Today the energy efficiency of hydraulic machines has become one of the most important issues in designing the system, mainly due to environmental protection and increased fuel costs. Various hydraulic systems have been developed over the years to meet the increasing demands for greater efficiency and better functionality of the components. One of the solutions to this problem which improve the energy consumptions in heavy machinery is to change the conventional valve system with individual metering systems (in some literature also called separate meter-in separate meter-out or SMISMO). This gives possibility for energy regeneration and recuperation and effective deceleration control which leads to energy efficiency improvement of the machine [2-9]. This kind of system gives possibility for other improvements, like for example damping the oscillations of the machine structure using active oscillation damping technologies [1]. Oder possible improvement is to make cylinder movement more stiff during the motion, controlling the pressure in the meter-out side of the active cylinder as well as the speed of the cylinder.
Therefore, it is here presented modeling and simulation of the movement of a servo valve controlled hydraulic cylinder, possible control strategies for SMISMO system, laboratory equipment, measurements and conclusions.

II. SEPARATE meter-in and separate meter-out

This system provides freedom to control the actuator speed and pressure independently, which can be used to save the energy by minimizing pressure losses. Since there are different ways of connecting, Figure 2.1. shows three different ways of connecting.

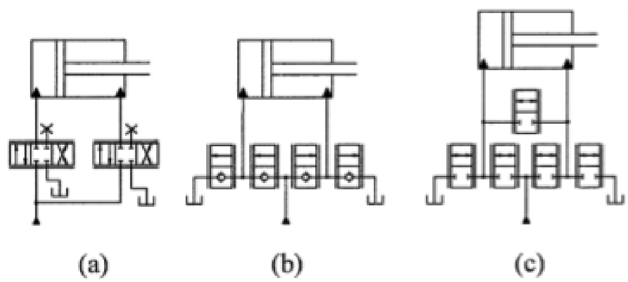


Figure 2.1. Different SMISMO systems found in the literature [2-9]

Figure (a) shows a hydraulic circuit with two 4/3 proportional valves. In figure (b) is used four 2/2 valves to achieve better results. There are several different control strategies, including the differential connecting. In the figure (c), another valve is added for control the meter – in and meter – out form cylinder. This valve is used to minimize pump flow at to big loads. The basic problems of the SMISMO systems are the need for several high quality proportional/servo valves and complexity of controlling of the systems. Usually it is used control based on closed – loop and controllers with flow/speed. Successful pressure control requires a wide valves with good system dynamics.
The idea of the SMISMO system is to provide independent control of the speed and pressure of some cylinder and can be used to reduce vibration when the cylinder needs to be extracted with low speeds [1]. In some types of machinery requiring specific parts of them to move with low speeds when operating, for example tunnel excavators the cutter move with low speed but when cut the rocks, inertial forces from rocks create vibration. This requires the SMISMO system, where we control separate meter – in and meter – out chamber on cylinders, when the cylinder is pulls out, in chamber for meter – out we will control the pressure if we increase the pressure in this chamber we will reduce the vibration and the cutter will work more calmly, which will result in reduced vibration of the entire machine and comfort of the operator will be higher [1].

A. Hydraulic system and components

In figure 2.2. is shown a system of SMISMO which will be elaborated in this scientific work. When cylinder is extracting (lifting the load), valve A and B will be used as in normal conventional system. The advantage of using SMISMO system comes in place when we need to retract the cylinder (lower the load) because we can use the gravitation force of load and not energy from the pump. The idea is that when the cylinder is retracted, the pump will work only to overcome the losses in the system rather than producing pressure to retract the cylinder. When the cylinder is retracted, the pump will operate at minimum speed while the cylinder is retracted under load, and the speed will be controlled by valve A, while valve B and minimum pump operation will fill the chamber on cylinder to prevent undesired cavitation. In this system, the energy efficiency will be due to the cylinder being retracted as the pump will not operate under load and we will have electricity or other energy savings depending on how the pump is powered either by electric motor or internal combustion engine.

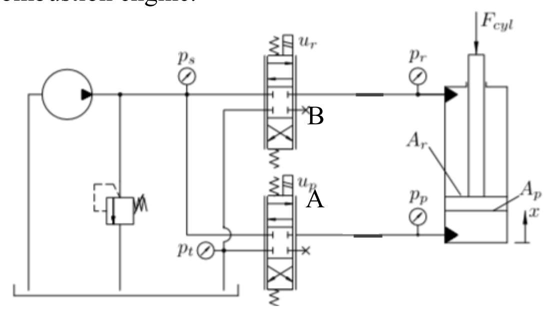


Figure 2.2. Schematic representation of the system

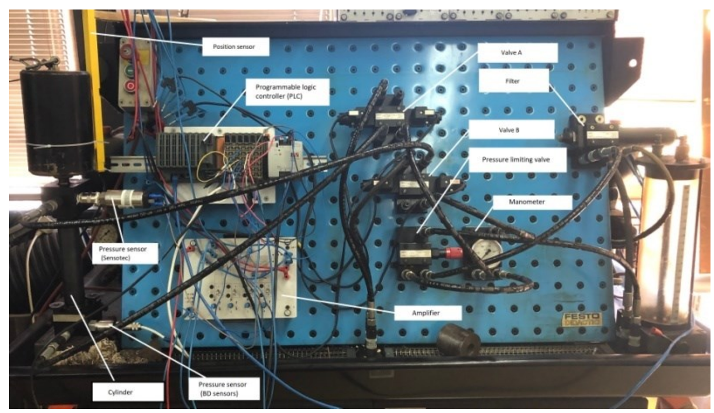


Figure 2.3. Picture of the hydraulic system and component labeling

Figure 2.3. shows the physical appearance of the system build for this study. It should be said that the cylinder will be loaded with weight of m=25 [kg], which will play a load role in making the measurement because the cylinder will be loaded. The system is composed of the following components:

- Two valves 4/3
- Filter
- Manometers
- Amplifier
- Cylinder
- Position sensor
- Pressure sensor
- Programmable logic controller (PLC)

Cylinder	Ø32/Ø22/200 mm
Proportional valve	Nominal flow 1.5 l/min at ΔP_N = 5 bar
Working pressure	40 bar

B. Modeling of the system

The pressure build up in respectively the piston and rod side of the cylinder may be described by the continuity equation as:

$$\frac{dp_p}{dt} = \frac{\beta_{e,p}}{V_p}(Q_p - A_p\dot{x}) \quad (1)$$

$$\frac{dp_r}{dt} = \frac{\beta_{e,r}}{V_r}(A_r\dot{x} - Q_r) \quad (2)$$

Where $V_p = V_{p,0} + A_p x$ is the volume of the piston side chamber and $V_r = V_{r,0} + A_r x$ is the volume of the rod side chamber, with $V_{p,0}$ and $V_{r,0}$ being the default volumes in the cylinder and connected hoses, for the cylinder in the bottom position. $\beta_{e,p}$ is the effective oil bulk modulus and is for the piston side chamber modeled as (similar for rod side chamber):

$$\beta_{e,p} = \frac{1}{\frac{1}{\beta_{oil}} + \frac{V_{\%,air}}{V_p \beta_{air}}} \quad (3)$$

With the volume content of air for the piston chamber being determined as:

$$V_{\%,air} = (p_0 V_{\%,air,0}{}^{k} / P_p)^{1/k} \quad (4)$$

Here p_0 is the atmospheric pressure, $\kappa = 1.4$ (assuming an adiabatic process), β_{oil} = 16,000 bar (oil bulk modulus) and β_{air} = 1.4p. The above model primarily accounts for variations in bulk modulus at low pressures, where the air contribution is significant. At high pressure, hose stiffness etc. also comes into play, which is not accounted for in the in the model. Based on experience the effective oil bulk modulus is therefore limited to 10,000 bars to compensate for limited hose stiffness. The force from the cylinder piston may be described as:

$$F_{cyl} = P_p A_p - P_r A_r - F_{fric} \quad (5)$$

The friction force can be represented as:

$$F_{fric} = B_V \dot{x} + F_c \tanh(\frac{\dot{x}}{\gamma}) \quad (6)$$

Where γ controls the slope of the friction curve around zero velocity to compensate for numerical switching problems. The friction in the mechanical system is included in the cylinder friction. The model for the mechanical system may be written on standard closed form:

$$M(x)\ddot{x} + B(x,\dot{x})\,\dot{x} + G(x) = F_{cyl} \quad (7)$$

Where M(x) is the equivalent inertia mass on the cylinder, G(x) is the gravitational force and B(x,$\dot{x}$) contain the Coriolis and centripetal-terms, which for the considered system is negligible for normal operating velocities. Finally the proportional valves are modeled by the orifice equation and a critically damped second order system ($\zeta = 1$) as:

$$Q_p = \begin{cases} K_v u_p \sqrt{P_s - P_p}\,, & u_p \geq 0 \\ K_v u_p \sqrt{P_s - P_t} & u_p < 0 \end{cases} \quad (8)$$

$$Q_r = \begin{cases} -K_v u_r \sqrt{P_s - P_r}\,, & u_r \geq 0 \\ -K_v u_r \sqrt{P_r - P_t} & u_r < 0 \end{cases} \quad (9)$$

$$u_i = \frac{\omega^2{}_n}{s^2 + 2\zeta\,\omega_n s + \omega^2{}_n} u_{ref.i} \quad (10)$$

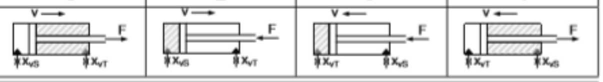
Where Kv is the valve coefficient, and $u_{ref.i}$ is the reference voltage to the i'th valve. Notice here the sign convention used, where a negative voltage to the rod side valve will lead to a positive flow. With the valves used the valve dynamics may generally be neglected compared to the dynamics of the systems. The valves dynamics are, however, still included in the nonlinear model to ensure that the model behaves similar to the test system if the control signals contain high frequency content. In the linear model the valves dynamics are neglected and accounted for in the controller design instead as discussed below.

C. Single actuator control

The working hydraulics mobile machines should be operated by a joystick, why the overall purpose of the control is to move the actuators at the speed corresponding to the joystick position. This is to be done when running the combustion engine at low speed. Control strategy and configuration is given in [11][12][13]. As proposed, an energy efficient control of each actuator and ELS control of the pump is proposed [13]. The proposed control strategy implies that an individual actuator controller is used for each cylinder, hence when an additional actuator is to be added, the actuator control of the present actuators are not affected. The pump system is controlled by usage of Electronic Load Sensing (ELS). Hence the cylinder chamber pressures and the velocity reference for the actuators are fed to the pump controller. The pump pressure reference is then based on the highest working pressure connected to a pump spool.

The control of each actuator is preformed as open loop velocity control with an integrated pressure controller [13]. The control strategy is based on that the spool connected to the load carrying chamber of a cylinder is used to control the velocity by controlling the flow in or out, while the spool connected to the non-load carying chamber controls the pressure in the corresponding chamber. An overview of the control strategy for a single actuator is given in Table 1 [13].

Table 1. Different control strategies [13]

	Operation Mode			
	1	2	3	4
				
Spool	Control strategy			
x_{vS}	p_p	Q_p	p_r	Q_r
x_{vT}	Q_r	p_r	Q_p	p_p
	Meter-Out	Meter-In	Meter-Out	Meter-In

D. Position Control

In SMISMO systems, there are different control modes possible such as: position control, speed control, pressure control and ect. For this system the control will be per position, which means that when we assign a position to the cylinder, cylinder will move to the desired position, while the speed depends on the control variable Kp. If we increase Kp then we get high speed of movement of the cylinder and there is a bigger jump to the position assigned to it, while if we decrease Kp the cylinder moves with lower speed. It is here determinate that the value of Kp=300 gives best results for our system. On Figure 2.5. is showed block diagram of the control system.

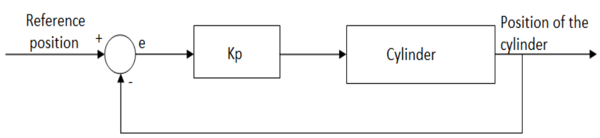
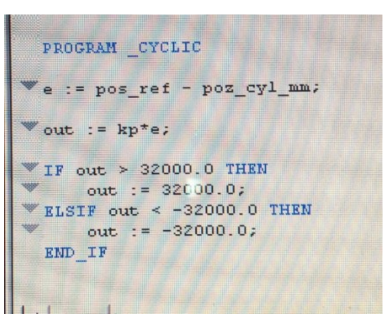


Figure 2.5 Block diagram of the control systenm

On Figure 2.6. is showed the code that is attached to the PLC while linearization and control with proportional valves is programmed with ladder diagram.



```
PROGRAM _CYCLIC
e := pos_ref - poz_cyl_mm;
out := kp*e;
IF out > 32000.0 THEN
    out := 32000.0;
ELSIF out < -32000.0 THEN
    out := -32000.0;
END_IF
```

Figure 2.6. Programmable logic controller code

Initially, measurements were made when extracting the cylinder from position position x = 50 [mm] to x = 150 [mm], the values obtained from the measurement are presented in Table 1.1.

Table 1.1. Extracted measured values

Reference position x_{ref}[mm]	150	150	150	150	150	150	150	150	150	150	150	150	150
Position of cylinder x[mm]	50	51	59	66	75	101	113	126	131	133	135	137	138
Pa [bar]	31	18	18	4	4	5	7	4	4	5	6	9	16
Pb [bar]	16	25	25	5	5	6	6	3	3	4	5	13	26
t [sec]	0	0.1	0.2	0.3	0.4	0.5	1	2	3	4	5	6	7

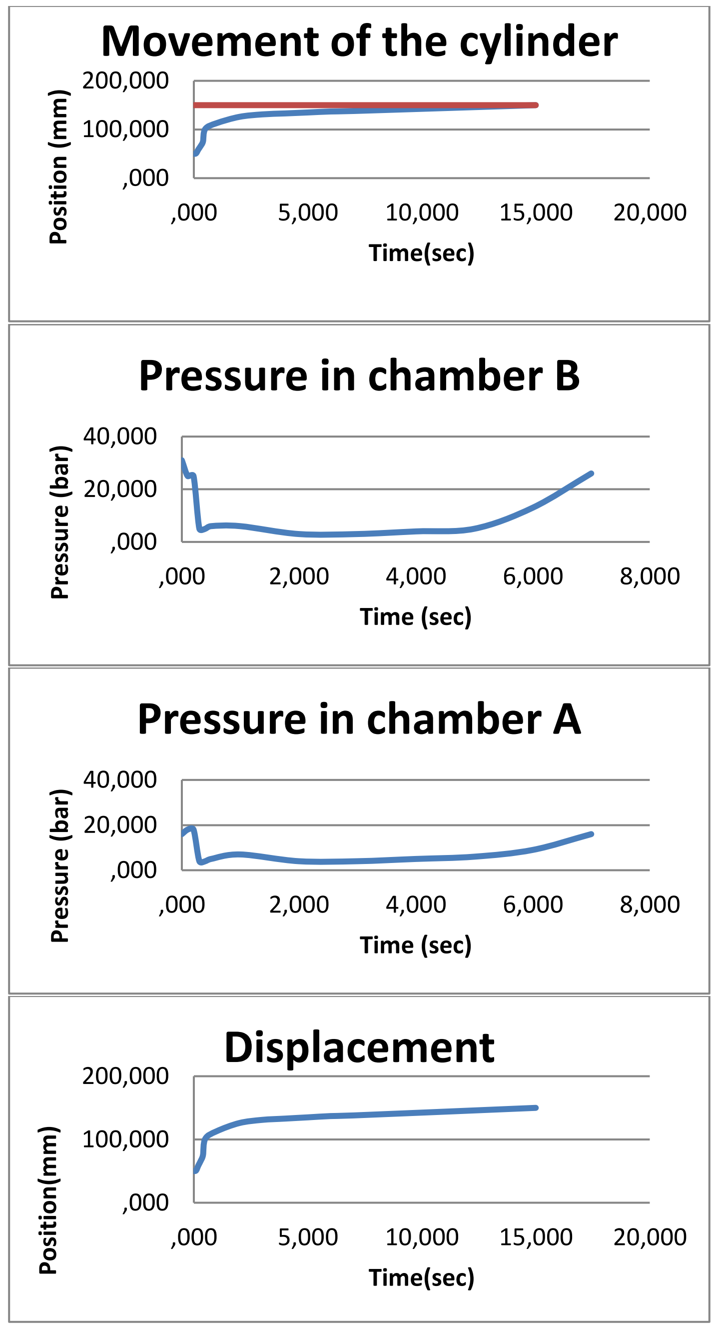


Figure 2.7 Cylinder extraction measurements

From simulation and experimental results it's seen that when controlling the position initially we have oscillations of the pressure, i.e. the pressure in the chamber A start to increase, and the pressure in the chamber B decreases to some extent as the cylinder accelerates when it reach a constant speed the pressures decrease respectively and we have pressure only to overcome the load while as the cylinder approaches the desired point the pressures increase in both chambers to have precise positioning. The movement of the cylinder as can be seen at the beginning has some delay that occurs until it's moved the spool in valve and as seen from the curve, cylinder begins to rapidly pull out at some point. When the cylinder starts to approach the specified position, the speed decreases i.e. the cylinder is positioned at the specified position with slow-moving.

Initially, measurements were made when retraction the cylinder from position position x = 150 [mm] to x = 50 [mm], the values obtained from the measurement are presented in Table 1.2.
The graphs show that we have some similarities to extraction. At induction at the beginning the pressure in chamber A decreases to a certain value and then start to increase slightly, which is constant until the cylinder is positioned, while in chamber B we have opposite initially the pressure increases for short period of time and we have slight decrease until achieving constant pressure value. The movement of the cylinder over time is right when we give the signal to the programmable logic controller we have slight delay until the valve react and then the cylinder begins to extraction more rapidly until it reaches the desired position when the cylinder approaches, when the cylinder approaches the position it slows down and slowly positions itself at the desired position, as shown in the movement graph of the cylinder as it gradually approaches the default position.

Table 1.2. Retraction measured values

Reference position x_{ref}[mm]	50	50	50	50	50	50	50	50	50	50	50	50	50
Position of cylinder x[mm]	150	148	135	123	116	92	73	67	63	59	57	56	55
Pa [bar]	15	15	14	13	13	14	15	16	16	16	16	16	16
Pb [bar]	28	30	24	23	23	24	28	30	30	30	31	31	31
t [sec]	0	0,1	0,2	0,3	0,4	0,5	1	2	3	4	5	6	7

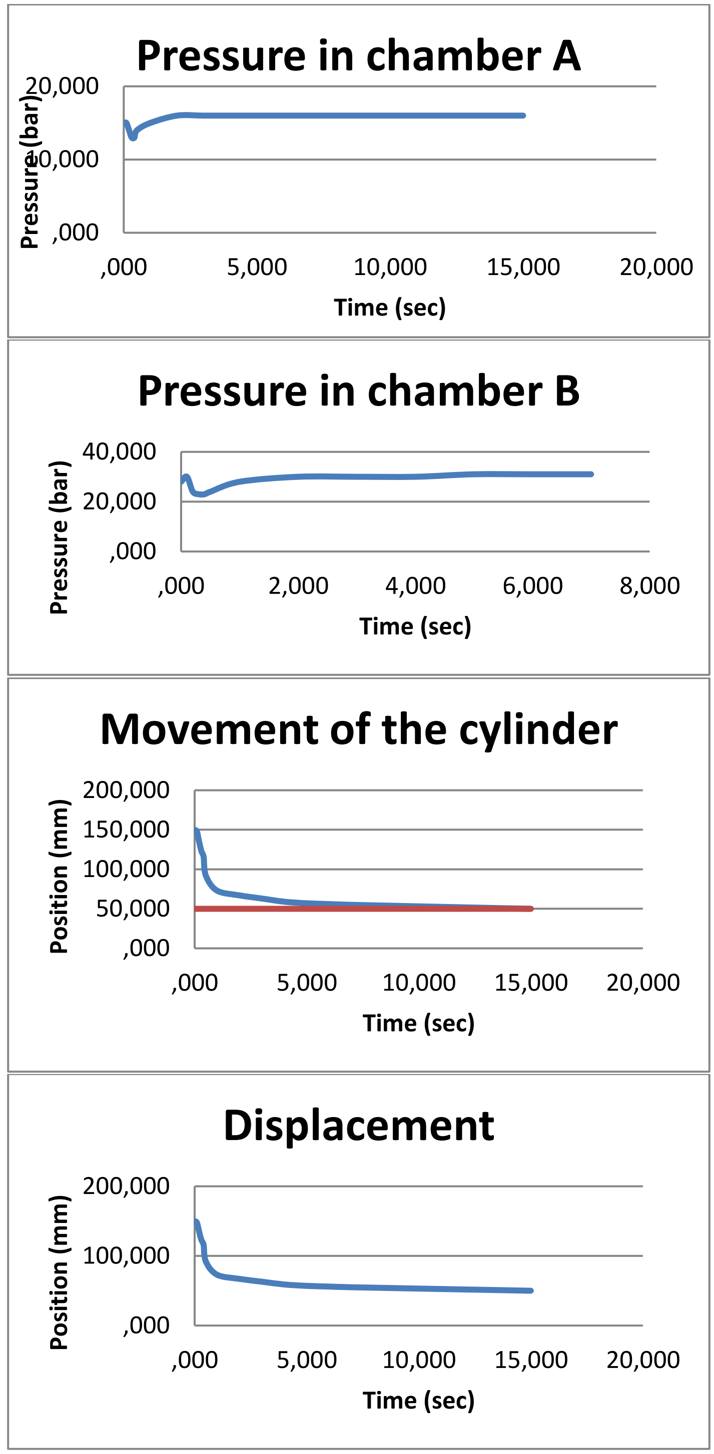


Figure 2.8. Cylinder retraction measurements

E. Calculation the velocity

In addition to the preceding chapter, it's also necessary to calculate the speed at which cylinder moves, i.e. the speed at which the cylinder will be positioned at the desired position. Since there are no flow sensors installed on our system to read the speed immediately, we must calculate the speed of the cylinder over time depending on the path it has passed. The velocity will be calculated manuel by the equation (11) and the average velocity by the equation (12), this will be done for both directions of motion i.e. for extraction and retraction.

$$V_{iz/vov}=\frac{s}{t_{izv}} \quad \text{[m/sec]} \qquad (11)$$

Where **s** is the path we have passed and **t** is the time for a given trajectory

$$V_{iz,vov\ sr}=\frac{\sum V_{iz}}{n} \quad \text{[m/sec]} \qquad (12)$$

Extraction

t [sec]	0	0.1	0.2	0.3	0.4	0.5	1	2	3	4	5	6	7
V_{iz} [m/sec]	0	0.01	0.045	0.053	0.062	0.1	0.063	0.038	0.027	0.02	0.017	0.014	0.013

Table 1.3. Extraction speed

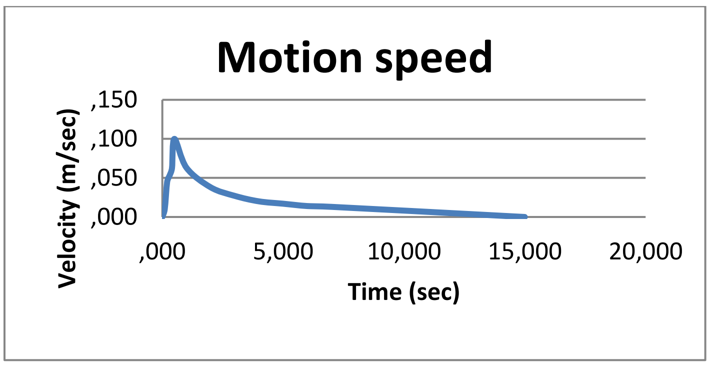


Figure 2.9. Speed growth graph when cylinder extraction

As you can see in the Figure 2.9 at the beginning when the valve opens we have a big jump in velocity i.e. we have a big acceleration while the cylinder is still far from the desired position. When the cylinder crosses 50% of the given trajectory it starts to slow down and the speed decreases, as it approaches the position its set and the speed gradually decreases and eventually reaches zero. The average rolling speed of the cylinder at extraction is V_{izsr}= 0,035 [m/s].

Retraction

Table 1.4. Retraction speed

t [sec]	0	0.1	0.2	0.3	0.4	0.5	1	2	3	4	5	6	7
V_{vov} [m/sec]	0	0.02	0.075	0.09	0.085	0.116	0.077	0.041	0.029	0.022	0.018	0.015	0.013

As shown in Figure 2.10 at the beginning we have an acceleration which is bigger than the acceleration when extracting the cylinder due to the load we have with mass m = 25 [kg]. When the cylinder crosses 50% of the trajectory, the speed starts to decrease until the position is reached and the cylinder stops. The average rolling speed of the cylinder at retraction is $V_{vov\ s}$ = 0.046 [m/sec]. The average retraction speed is higher than the average retraction speed which means that retraction will have a faster positioning than retraction.

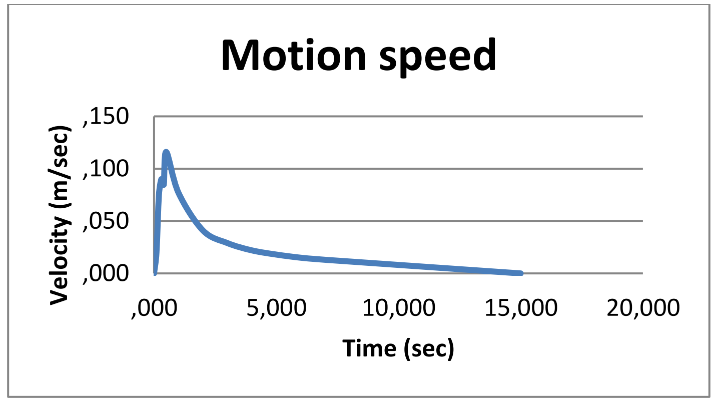


Figure 2.10. Speed growth graph when cylinder retraction

III. Discussion of Results

It is here shown successful movement of the cylinder using two valves (a type of a SMISMO system). More precisely, it is here shown successful implementation of the SMISMO position control of a cylinder loaded with mass. Measurements here presented are showing promising results. With our system, it is possible to control the speed of the cylinder (using meter-in chamber of the cylinder) and pressure of the meter-out chamber of the cylinder, which makes our system to be MIMO (multi input multi output system). Measurements of the pressure in chamber B (Figure 2.8) during standard motion (as it is one servo valve used) show extremely high pressure in B, pressure which is absolutely unnecessary. This makes improvements in energy consumption possible when cylinder is extending if we are able to completely relax opposite cylinder chamber B. This can be done using the second valve (valve B), bringing fluid in chamber A trough valve A. Energy efficiency can be improved much more when cylinder is retracting (lowering the load). In that case using the force from the load (gravitational force), and not the energy of the pump, we can drastically reduce the energy consumption from the pump. Control of the movement in this case is completely done by the valve A (valve at the piston side).

When cylinder is extracting, it's important to control the flow which is coming from the pump and the pressure in the chamber of the side from piston rod, as can be seen from the results when the cylinder is extracted, there is bigger pressure in the chamber on the side of the piston rod than on the other side, this is good in some cases if the hydraulic losses are neglected but this study is about reducing losses. To reduce the pressure in the chamber on the side of the piston rod it's by adding another proportional valve that would regulate the pressure in the chamber or if we had separate (independent) control on both proportional valves so that we would control the openness of the second valve B. Cylinder retraction is much more complex as we have a load that acts on the cylinder and helps the retraction, here it's important to control the pump flow and the pressure in the chamber form the piston rod side, here to reduce the energy who give the pump is to operate separate with both valves, i.e. when retracting the cylinder the valve who operate with chamber from piston rod side to be little open and pump pressure to overcome losses and fill the chamber with fluid. As can be seen when we increase the Kp then we have much faster cylinder movement but there is a bigger jump of position and more unstable movement. Therefore some system with PID control will give much better signal stability and faster cylinder positioning.

IV. Conclusion

It is here presented successful movement of the cylinder at a desired position using SMISMO system with two proportional valves, during lifting and lowering the load and developed control strategies. This system will be used in order to improve energy efficiency of the hydraulic system as well as to make the movement of the cylinder more stable and stiffer.

From the information presented in this study, it can be concluded that the energy efficiency of hydraulic systems can be raised; the system who developed here with further editing can achieve good results. If the two proportional valves are controlled separate (independently) of each other, i.e. if the valves receive a separate control signal from the PLC we would have much greater freedom in controlling, actually we would be able to separate control speed and pressure. If these two parameters are controlled individually then at any point in the movement of the cylinder we would be able to control the speed as well at what speed the cylinder would move when approaching the given position. Further upgrading of this system is to implement acquisition system like small SCADA system. For this new digitally controlled hydraulic system all controlling on proportional valves and positioning of the cylinder will be done via SCADA system. Whit this we will control the speed and position for extracting and retracting on cylinder, also we can make monitoring of the entire system operation process and storing data from pressure and position sensors and by incorporating flow sensors to read the cylinder speed at each moment of the cylinder movement as well storing data from sensors. With data stored in the computer we can easily get all the curves for the system with high precision.

In the future, it is expected to accelerate the development of different hydraulic systems or improve older systems with newer developed components that will be much easier to control, with newly developed programmable logic controllers that will controlling the components much faster and reduce delays.

References

[1] Emil Zaev, Gerhard Rath, and Hubert Kargl, "Energy Efficient Active Vibration Damping", Proc. of 13th Scandinavian International Conference on Fluid Power, SICFP2013, Linköping, Sweden, 2013

[2] Andersen, T., Munzer, M., and Hansen, M., 2001. "Evaluation of control strategies for separate meter-in separate meter-out boom actuation in mobile applications". InProc. 17th Int. Conference on Hydraulics and Pneumatics.

[3] Anders H. Hansen, Henrik C. Pedersen, Torben O. Andersen and Lasse Wachmann. "Design of Energy Efficient SMISMO-ELS Control Strategies".

[4] B. Eriksson. Mobile Fluid Power Systems Design with a Focus on Energy Efficiency. PhD thesis, Univ. of Linkoping, Linkoping, Sweden, 2010.

[5] K. Heybroek. Saving energy in construction machinery using displacement control hydraulics-concept realization and validation. Master's thesis, Univ. of Linkoping, Linkoping, Sweden, 2009.

[6] Q.H. Yuan and Jae Y. Lew. Modeling and control of two stage twin spool servo-valve for energy-saving. In American Control Conference, Portland, OR, USA, 2005.

[7] B. Yao and S. Liu. Energy-saving control of hydraulic systems with novel programmable valves. In Proc. Of the 4th World Congress on Intelligent Control and Automation, Shanghai, P.R. China, 2002.

[8] T. Hajek et al. Hydraulic system with an actuator having independent meter-in meter-out control, 2005.

[9] M. Linjama and M. Vilenius. Energy-efficient motion control of a digital hydraulic joint actuator. In Proceedings of the 6th JFPS International Symposium on Fluid Power, SUKUBA, 2005.

[10] Yingjie Liu, Bing Xu, Huayong Yang, and Dingrong Zeng. 2009. "Modeling of Separate Meter In and Separate Meter Out Control System"

[11] Henrik C. Pedersen, Tobias Skouboe, Morten S. Jacobsen and Torben O. Andersen. 2013. "INVESTIGATION AND COMPARISON OF SEPARATE METER-IN SEPARATE METER-OUT CONTROL STRATEGIES" .

[12] Andersen, T., Munzer, M., and Hansen, M., 2001. "Evaluation of control strategies for separate meter-in separate meter-out boom actuation in mobile applications". InProc. 17th Int. Conference on Hydraulics and Pneumatics.

[13] Anders H. Hansen, Henrik C. Pedersen, Torben O. Andersen and Lasse Wachmann. "Design of Energy Efficient SMISMO-ELS Control Strategies", Proceedings of 2011 International Conference on Fluid Power and Mechatronics, China, 2011.

Acknowledgment

Research done in this paper is supported from bilateral Macedonian–Austrian project "Development of concepts and control strategies with improved energy efficiency for hydraulic systems in heavy machinery" supported from Ministry of Education and Science in N. Macedonia as well as from WTZ Austria.

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