Acta of Turin Polytechnic University in Tashkent

Volume 9 | Issue 4 Article 9

12-1-2019

# A Review of Energy Efficient Fluid Power Systems: Fluid Power Impact on Energy, Emissions and Economics

Sanjar Mirzaliev
*Tashkent State Economic University*, sanjar2611@gmail.com

Kongratbay Sharipov
*Turin Polytechnic University in Tashkent*

ACTA TTPU

III. ENGINEERING SCIENCE

# A REVIEW OF ENERGY EFFICIENT FLUID POWER SYSTEMS: FLUID POWER IMPACT ON ENERGY, EMISSIONS AND ECONOMICS

Sanjar Mirzaliev, Kongratbay Sharipov

*Turin Polytechnic University in Tashkent,*

**Abstract**

Fluid power (hydraulic and pneumatic actuation) as an integral part of manufacturing and transportation has big impact in real sector of economy. In 2008, according to the U.S. Census Bureau, average efficiency of Fluid Power Systems amounted 22%, while the sales of systems using fluid power exceeded $226B. As large as the industry is, it has had little fundamental research that could lead to improved efficiency since the 1970 energy crisis. While there have been some attempts to improve fluid powered components separately, there has been lack of attention to the societal impact of the whole industry. This article analyzes energy specific measurements (consumption, emissions, efficiency) of current systems from energy perspective and stresses societal impact of improvements proposed from the fluid power research community.

*Keywords: fluid power, energy saving*

## 1. Introduction and problem statement

Fluid power (hydraulic and pneumatic actuation) is the generation, control, and application of pumped or compressed fluids when this power is used to provide force and motion to mechanisms. This form of mechanical power is an integral part of manufacturing and transportation. In 2008, according to the U.S. Census Bureau, sales of fluid power components exceeded $17.7B, sales of systems using fluid power exceeded $226B [1]. As large as the industry is, it has had little fundamental research that could lead to improved efficiency since the late 1960s (prior to the 1970 energy crisis). While there have been some attempts to replace fluid powered components with electric systems, its performance and rugged operating condition limit the impact of simple part replacement. Oak Ridge National Laboratory and the National Fluid Power Association (NFPA) collaborated with 31 industrial partners to collect and consolidate energy specific measurements (consumption, emissions, efficiency) of deployed fluid power systems. Their objective of study was to establish a rudimentary order of magnitude estimate of the energy consumed by fluid powered systems. Their analysis conducted that fluid powered systems consumed between 2.0 and 2.9 Quadrillion (1015) Btus (Quads) of energy per year; producing between 310 and 380 million metric tons (MMT) of Carbon Dioxide (CO2) with an average efficiency of 22%. The British Fluid Power Association also reported that the downstream efficiency of fluid power systems is between 23% to 30%[2].

This article reviews opportunities to impact energy savings in both the manufacturing and transportation sectors by the development and deployment of energy efficient fluid power architectures to be implemented in hydraulic circuits.

## 2. Methods to tackle the challenge

In general, mobile machines have multiple actuators and the operator’s task is to regulate the speed of each actuator and drive. A typical example is the mobile excavator having Internal Combustion Engine (ICE), power of which generates the fluid power to propel swing, boom, arm and bucket cylinders [3].

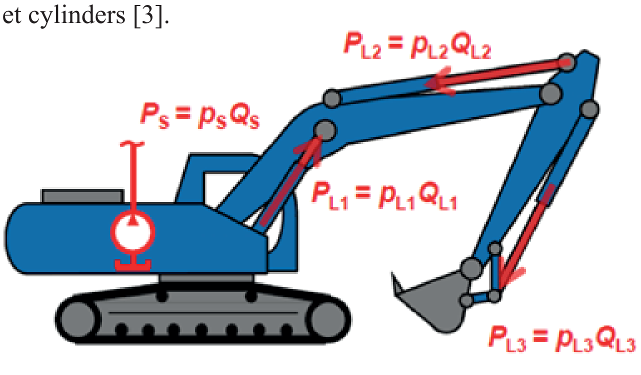


**Figure 1. Mobile excavator with indication of powers [3]**



Published by 2030 Uzbekistan Research Online, 2019

Energy consumption for a hydraulic system is defined as:

$$E = \int_{t_0}^{t_1} p_s Q_s dt = \int_{t_0}^{t_1} (p_{LS} + s) \cdot (Q_L + Q_C) dt \quad (1)$$

where E represents the hydraulic energy used for a certain task from t0 to t1; ps, pLS, and s are the hydraulic supply pressure, load pressure and pressure loss respectively; Qs, QL, and Qc are the flow rates of the pump, load and other flow rate such as leakage respectively. Reducing the energy consumption is equivalent to reducing the power, the integrand ps·Qs. It is obvious that there are the following two ways to save energy: (1) reduce the supply pressure, which can be realized by the decrease of pressure loss in valves; (2) reduce the pump flow rate, which can be realized by the flow regeneration with a differential hydraulic circuit.

In overall, to increase the energy efficiency of the mobile machine is to decrease throttling losses, avoid inefficient operating points and recover potential energy.

## 4. Proposed solutions of Energy saving architectures

Nowadays, Load Sensing technique is current as an industry standard, where pump flow is matched follow the flow demands of all actuators. Pump pressure is set to “sense” the highest load pressure present in the circuit via pilot lines. For the sake of simplicity, a typical example of Load Sensing technique is explained in figure below [4].

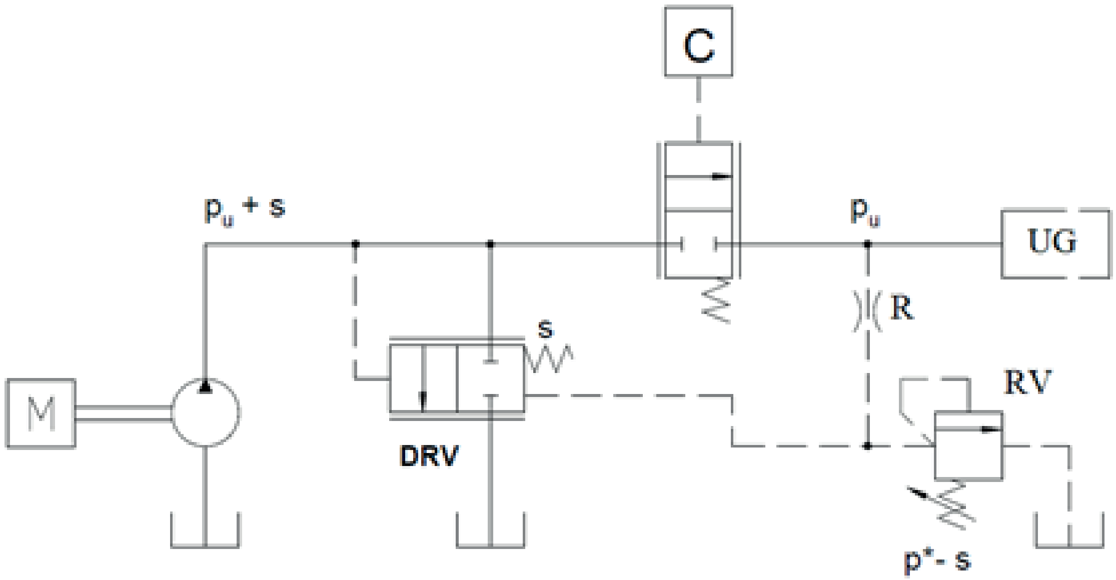


**Figure 2. Load sensing plant with constant displacement pump [4]**

In this case the pressure at the pump outlet follows the pressure at the user group. Therefore, the pump works at pressure pu+s. Power is calculated as

$$P_{exp} = Q_0 \cdot (p_u + s) \quad (2)$$

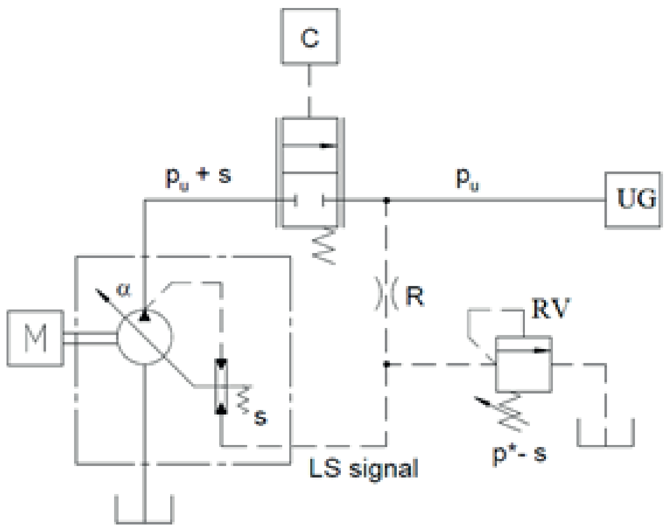


**Figure 3. Configuration with differential pressure variable displacement pump [4].**

$$P_w = Q_s \cdot s + (Q_0 - Q_u) \cdot (p_u + s) \quad (3)$$

There is also a better yet expensive solution as in figure below. By using the pump with differential pressure limiter, the flow rate wasted in DRV is not generated.

A lot of material has been published throughout the years, explaining the basic working principles of LS-systems and the benefits and drawbacks they introduce as compared to traditional constant pressure systems, see e.g. [5-9], including minor modifications that may be made, see e.g. [10-13]. When it comes to the understanding of the dynamic behavior of a LS-system, the saturation problems were addressed in [14], where the reasons for and the effects of both pressure and flow saturation was described. The reasons for instability in a LS-system are referenced in [15-19].

For example, Independent Metering (IM) reduces throttling losses and pump flow can be reduced because energy regeneration is possible. High responsive valves and control is needed to deliver this solution to the market. Many researchers highlighted the independent control strategies of flow and pressure [20-31].

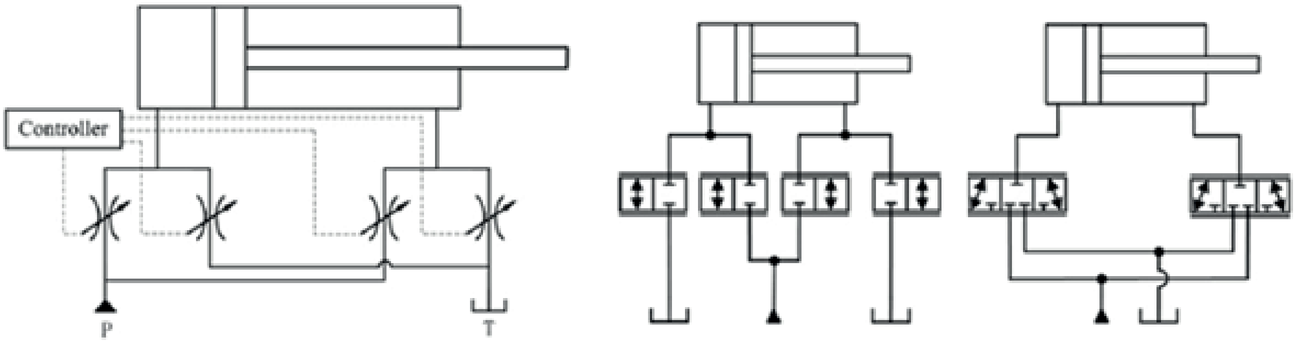


**Figure 4. Possible layouts of independent metering.**

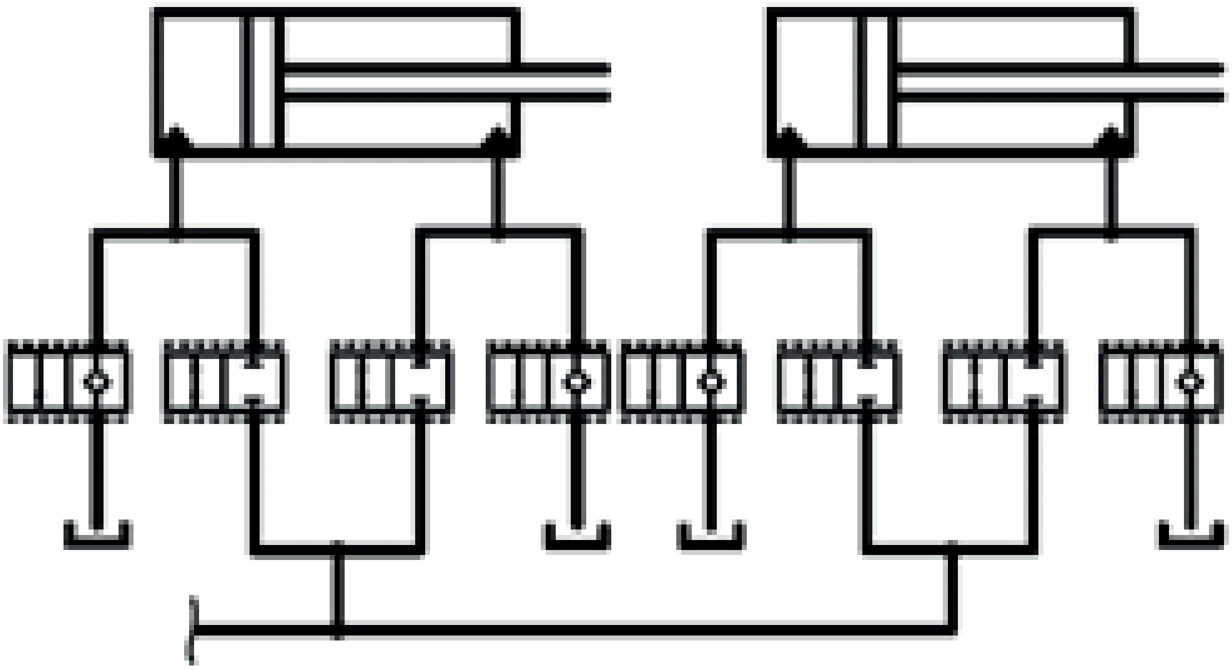

**Figure 5. Digital flow control ISO scheme.**

Digital flow control is made with analog supply concept with digital control concept. Simple on/off valves with affordable high response. In other literature, it is also known as flow matching. A challenge of this layout is to smoothen pressure peaks and obtain smooth motion control. Linjama [32] is a good references of digital flow control.

Other energy efficient alternatives to LS-systems are pump controlled drives [33], where one dedicated pump is used for controlling each actuator. Actuator speed is controlled by displacement control of the pump. Until now this solution has not been used commercially, due to the high cost of variable displacement pumps and the lower dynamic performance as compared to valve-controlled drives. With the advances of digital displacement pumps, as the Artemis

[34], this may however change in the future. This layout has no inherent throttling losses. Pump displacement is designed for peak flows. Energy regeneration is possible as well. Displacement Control coupled with independent metering allow pump flow reduction. Open loop pump displacement control with independent metering, as in figure below, is the combination of flow supply concept and control concept at the same time. It has great potential to reduce pump flow, since Wheatstone bridge valves are used for flow regeneration.

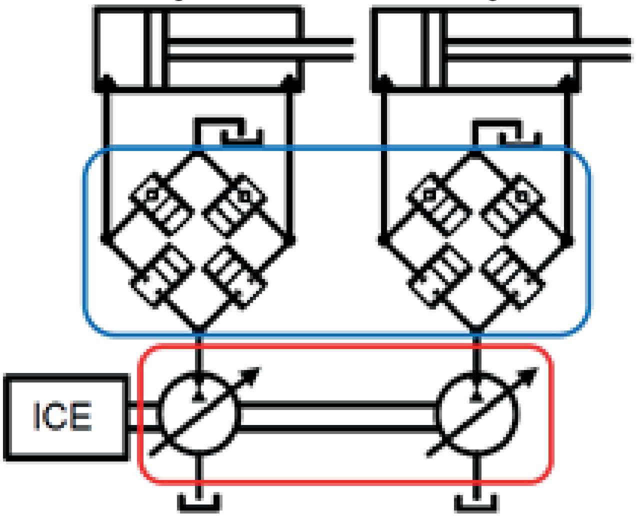


**Figure 6. Displacement control with independent metering.**

Constant pressure systems allow avoiding throttling losses caused by the control principle. For example, ICE runs the pump, which in turn supplies High-Pressure and Low-Pressure supply lines. Hydraulic Transformers are installed between supply lines and actuators, which allow smooth transient conditions. Analogue and digital valves can be used to accomplish flow regeneration and recuperation.

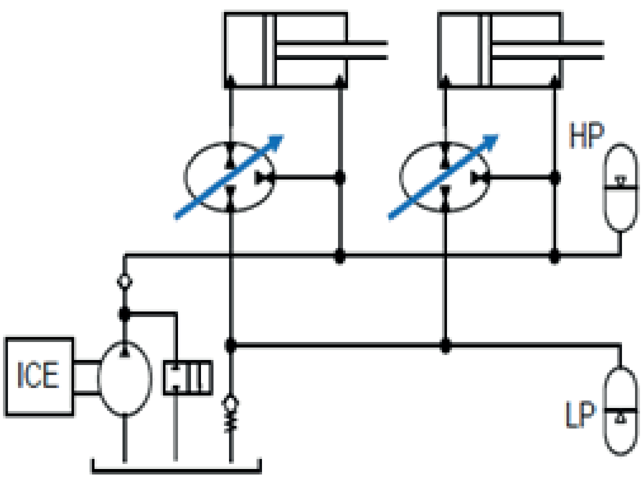


**Figure 7. Constant pressure system with hydraulic transformers**

**5. Economic benefits**

Using the formula shown in Equation 4, the impact of this improvement (increasing efficiency from φ_1 to φ_2 for an industry) would save industry and consumers energy amountingΔE as in Equation 5. The group in [1] projected that a more aggressive 15 year research and development (R&D) effort, focusing on sensing, design, controls and advanced materials could increase this efficiency by 15% to an average efficiency of 37%. The impact of this long-term improvement, using Equation 4 with an efficiency improvement from 22% to 37% for an industry consuming more than 2.0 Quads, would save U.S. industry and consumers approximately 0.8 Quads/year.

$$W = \varphi_1 E_1 = \varphi_2 E_2 \tag{4}$$

$$\Delta E = E_1 - E_2 = E_1 (1 - \frac{\varphi_1}{\varphi_2}) \tag{5}$$

A series of case studies, as described below, provide insight into the feasibility and magnitude of potential energy savings through both best practices and new design and control strategies.

Case 1: Load Sensing (LS) Systems – For constant pressure systems, the energy required to raise a light load (pressure times displaced actuator volume) is the same as the energy required to raise a light load. Liang and Virvalo show an efficiency increase in a hydraulic crane from 10.6% to 27.4% using LS pumps [35].

Case 2: Energy Recuperation - Conventional valve controlled systems use energy to both raise, and lower, a load. Palmberg is exploring mode switching and energy recuperation by replacing conventional spool valves with programmable valves that enable more flexibility in the direction of energy. His study suggests an additional 5% to 10% increase in efficiency [36]. This is reinforced by Liang and Virvalo who demonstrated an increase of efficiency from 27.4% with LS to 35.6% with programmable valves. An internal study by Incova showed a 10% increase in fuel efficiency for an excavator during digging and an even greater benefit during grading.

Case 3: Hydraulic Transformers. There are tremendous losses through the control valves. Throttling losses introduce both energy losses as well as generation of heat. There is growing interest in the area of valveless controls eliminating throttling losses. To achieve this goal, there must be a variable displacement actuator or hydraulic transformer [37-38].

Case 4: Compressed Air – According to a recent Parker-Hannifin study, there are tremendous demand side opportunities for energy savings. Only $0.12 to $0.17 of every dollar spent on electricity to generate compressed air for pneumatic systems is doing useful work.11 Luo showed that recovery of exhaust power from pneumatic systems could increase efficiency by 14% to 23% [39].

**6. Conclusions**

In this paper the current state of fluid power architectures is discussed and load sensing systems is described as the current industry standard. Fluid Power energy consumption, emission and energy efficiency is described in the case of USA with data of 2012 year. Several alternative system types have been reviewed, such as independent metering, digital flow control, displacement control and constant pressure systems. Their pros and cons are discussed with reference to controllability, energy efficiency and technical feasibility. There is still research in those new areas that needs to be studied before the systems will reach their optimal condition. The current state in industry is using both analog and digital power supply concepts. The trend instead is to control hydraulic circuits with more digital valves. Energy recovery is implied by using recuperation and regeneration techniques.

Hence, it is reasonable to conclude that fluid power community faces big challenge in terms of increasing energy efficiency, which will have considerable societal impact.

**Acknowledgments**

This work is done during author's mobility exchange period in Fluid Power Research Laboratory (FPRL) of the Politecnico di Torino in the framework of Erasmus program for non-EU countries. The author acknowledges that no grant is received from FRPL to write this paper.

**Notations**

| | |
|---|---|
| UG | user group |
| RV | relief valve |
| R | restrictor |
| DRV | directional relief valve |
| M | motor |
| P_exp | expended power |
| P_w | wasted power |
| Q0 | flow rate generated by the pump |
| Qu | flow rate received by the user |
| pu | pressure drop across proportional direction control valve |
| s | cracking pressure of proportional directional control valve |
| Pu | useful power |
| Pexp | expended power |
| C | control signal |
| α | swash plate index |
| u | flow control parameter |
| ML | load torque |
| FL | load force |
| $\dot{\varphi}$ | load speed |
| $\ddot{\varphi}$ | load acceleration |
| n | rotary speed |
| ICE | internal combustion engine |

**References**

1. Love, L., Lanke, E., & Alles, P. (2012). Estimating the Impact (Energy, Emissions and Economics) of the US Fluid Power Industry. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN.

2. Belforte, G. (2000). New developments and new trends in pneumatics. In Proceedings of Sixth Triennial International Symposium on Fluid Control, Measurement and Visualization, Canada. http://fluid. power. net/techbriefs/hangzhau/1_5. pdf.

3. Hubertus Murrenhoff - An Overview of Energy Saving Architectures for Mobile Applications, IFAS March 25, 2014

4. Nervegna, N., Rundo, M.: Fluid power 2, Politeko, 2012, ISBN 978-88-97862-00-0.

5. B.R. Anderson. A survey of load sensing systems, BFPR Journal, no. 13, 1980.

6. H.W. Nikolaus. Loadsensing - lastunabhängige dosierung von verbraucherströmen.

Ölhydraulik und Pneumatik, 38(4), 1994.

7. R.N. Rathi. A load sensing hydraulic system as applies to hydraulic lift cranes. 31st

National Conference on Fluid Power, 1975.

8. G.K. Warren. Efficient and flexible hydraulic systems for mobile equipment. Proc. of

the 7. Aachener Fluidtechnisches Kolloqium, 1986.

9. W. Backé. Hydraulic drives with high efficiency. Fluid Power Systems and

Technology (ASME), (2), p. 45-73, 1995.

10. K. Ichiryu. Recent trend and future forecast of hydraulic system and control of hydraulic excavator. Proc. of the 9. Aachener Fluidtechnisches Kolloquium, 1990.

11. J.P. Kipp. Load-sensing - zentralhydraulik für traktoren. Ölhydraulik und Pneumatik, No. 1, Jan. 1993.

12. W. Backé. Present and future of fluid power. Journal of Systems & Control Engineering, Part I, 207(4), 1993.

13. A. Wolf and U. Maier. Load-sensing systeme in der erntechnik. Ölhydraulik und Pneumatik, 45(10), 2001.

14. L.G. Zarotti and N. Nervegna. Saturation problems in load-sensing architectures. Proc. 43rd National Conference on Fluid Power, volume 43, 1988.

15. P. Krus. On Load Sensing Fluid Power Systems, with Special Reference to Dynamic Properties and Control Aspects. PhD thesis no. 183, Linköping University, Sweden,

1989.

16. P. Krus. Modelling and analysis of the dynamic properties of mobile hydraulic systems. Proc. 2nd Bath International FPWCS, 1989.

17. P. Krus and T. Persson. Dynamic properties of load sensing systems. Proc. of International Conference on Fluid Power, Tampere Finland, 1987.

18. S.D. Kim, H.S. Cho, and C.O. Lee. Stability analysis of a load-sensing hydraulic system. Proc. of the Institution of Mechanical Engineers, part A, 202(A2), 1988.

19. Y. Sakurai, K. Takahashi, and S. Ikeo. Study on the dynamics of a load sensing ystem. Proc. IMECE'96, ASME, 1996.

20. M. Linjama, M. Huova, M. Vilenius, On stability and dynamic characteristics of hydraulic drives with distributed valves, in: D.N. Johnston (Ed.), Power transmission and motion control 2007, University of Bath, UK 2007, pp. 67–79.

21. M. Elfving, J.O. Palmberg, Distributed control of fluid power actuators—decoupled hamber pressure controlled cylinder, Proceedings of the 9th Bath International Fluid Power Workshop, Bath, UK, 1996.

22. M. Elfving, A concept for a distributed controller of fluid power actuators(Dissertation) College of Mechanical Engineering, Linköping University, Sweden, 1997.

23. B. Eriksson, J. Larsson, J.-O. Palmberg, Study on Individual Pressure Control in Energy Efficient Cylinder Drives, in: M. Ivantysynova (Ed.), 4th FPNI-phD Symposium,

Sarasota, USA 2006, pp. 77–99.

24. B. Eriksson, M. Rosth, J.-O. Palmberg, Energy saving system utilizing LQ-technique design, in: Y.X. Lu, Q.F. Wang, et al., (Eds.),Proceedings of the 7th International

Conference on Fluid power transmission and control, Hangzhou, China 2009, pp. 224–229.

25. Q. Yuan, J. Lew, Modelling and Control of Two Stage Twin Spool Servo-Valve for Energy-Saving, American Control Conference; Portland, USA, 2005.

26. B. Nielsen, Controller Development for a Separate Meter-In Separate Meter-Out Fluid Power Valve for Mobile Applications(Dissertation) Aalborg University, Denmark, 2005.

27. B. Yao, L. Song, Energy-saving control of hydraulic systems with novel programmable valves, The 4th World Congress on Intelligent Control and Automation, 4, IEEE Press, Shanghai 2002, pp. 3219–3223.

28. L. Song, B. Yao, Coordinate control of energy saving programmable valves, IEEE Transactions on Control Systems Technology 16 (1) (2008) 34–45.

29. P. Opdenbosch, N. Sadegh, W.J. Book, Modeling and control of an electro-hydraulic poppet valve, Fluid Power Systems & Technology Division-ASME 11 (2004) 103–110.

30. P. Opdenbosch, N. Sadegh, W.J. Book, Intelligent controls for electro-hydraulic poppet valves, Control Engineering Practice 21 (2013) 789–796.

31. A. Hansen, T. Andersen, H. Pedersen, L. Wachmann, Investigation of energy saving separatemeter-in separate meter-out control strategies, 12th Scandinavian International Conference on Fluid Power, SICFP '11, Tampere, Finland, 2011.

32. Linjama, Matti. "Is it time for digital hydraulics?." The proceedings of the 5th Scandinavian Int. Conf. on Fluid Power, SICFP'03, May 7-9, Tampere, Finland. 2003.

33. X. Liang. On Improving Energy Utilization in Hydraulic Booms. PhD thesis, Acta Polytechnica Scandinavia: Mechanical Engineering Series, 2002.

34. Salter, Stephen H., and William HS Rampen. "Pump control method and poppet valve therefor." U.S. Patent No. 5,190,446. 2 Mar. 1993.

35. Liang, X., & Virvalo, T. (2001). What's wrong with en-

ergy utilization in hydraulic cranes. In The 5th international conference on fluid power transmission and control.

36. Heybroek, K., Larsson, J., & Palmberg, J. O. (2007). Mode switching and energy recuperation in open-circuit pump control.

37. Ho, T. H., & Ahn, K. K. (2009, August). Saving energy control of cylinder drive using hydraulic transformer combined with an assisted hydraulic circuit. In ICCAS-SICE, 2009 (pp. 2115-2120). IEEE.

38. Achten, P., van den Brink, T., Potma, J., Schellekens, M., & Vael, G. (2009, June). A four-quadrant hydraulic transformer for hybrid vehicles. In 11th Scandinavian International Conference on Fluid Power, Linköping, Sweden.

39. Luo, X., Sun, H., & Wang, J. (2011, June). An energy efficient pneumatic-electrical system and control strategy development. In American Control Conference (ACC), 2011 (pp. 4743-4748). IEEE.