

## COMPARISON OF EXPERIMENTAL RESULTS WITH SIMULATION STUDIES OF "DIGITAL" HYDROSTATIC TRANSMISSION

Ahmed Zubair JAN<sup>1</sup>, Krzysztof KĘDZIA<sup>1</sup>, Paweł ŚLIWIŃSKI<sup>2</sup>

<sup>1</sup> Wrocław University of Science and Technology, POLAND, ahmed.jan@pwr.edu.pl,  
krzysztof.kedzia@pwr.edu.pl

<sup>2</sup> Gdansk University of Technology, POLAND, pawel.sliwinski@pg.edu.pl

**Abstract:** *The publication presents the results of experimental research on a "digital" hydrostatic transmission conducted at INOE 2000 IHP within the framework of the grant "Method of effective use of the digital hydraulics concept in multi-source hydrostatic drive systems". The primary goal of the research is to compare the effectiveness (efficiency) of using different methods of controlling the pump capacity and the hydraulic motor capacity in multi-source, hydrostatic drive systems and to compare the experimental results with simulation studies obtained in the MATLAB Simulink program.*

**Keywords:** *"Digital" hydrostatic transmission, modelling and simulation, experimental tests*

### 1. Introduction

Hydrostatic drives, also referred to as hydrostatic transmissions, are typically created by hydraulically connecting pumps and motors. A motor with constant displacement and a pump with variable displacement make up a standard hydrostatic gearbox. The system typically operates at maximum efficiency when the motor is operating at its highest volumetric displacement. When power is needed, hydraulic systems use fluids under pressure to convey power or perform tasks at a desired area. The history of technology has shown that fluid power is a valuable medium. It has been utilised in construction, agricultural, and aerospace equipment as well as more complicated designs like the water wheel. The following are some benefits of fluid flow over other power transmission technologies, such as electrical, pneumatically, and mechanical systems:

- Compared to its equivalents, hydraulic pumps and motors are substantially lighter and smaller than electric or petrol motors with the same horsepower.
- Due to their extreme flexibility, hydraulic hoses can send power to nearly any spot and route fluid lines around other pieces of equipment.
- Compared to a mechanical system that can generate the same amount of force, a hydraulic system is far smaller.
- A fixed gear ratio is not necessary because speeds may be readily adjusted for every operating circumstance.

The efficiency of a hydraulic system can be somewhat poor, which is a drawback. "Most mechanical systems are more efficient than hydraulic systems, even if hydraulic systems are far more efficient than electrical systems. The pump is the main part of the hydraulic system that supplies power. Axial-piston pumps, gear pumps, and vane pumps are only a few examples of the numerous varieties of pump arrangements. The most often used pumps are axial-piston pumps because they have great operating efficiency (up to 85%), can withstand high pressures, and can be controlled via variable displacement. We can further divide these pumps into two types: variable displacement and fixed displacement. For each cycle, fixed displacement pumps transport the same volume of fluid. Only when the pump's speed has been changed can the volume be altered. Pumps with variable displacement have the ability to regulate the flow without regard to the speed of the pump.

### 1.1. A "Digital" Hydrostatic Drive System Model

The "digital" pump is made up of a number of parallel arrays of constant displacement pumps (e.g. gear pumps) of various sizes. A grid of on-off valves allows the individual pumps to be switched between the load and idle states as the flow requirement varies (fig.1).

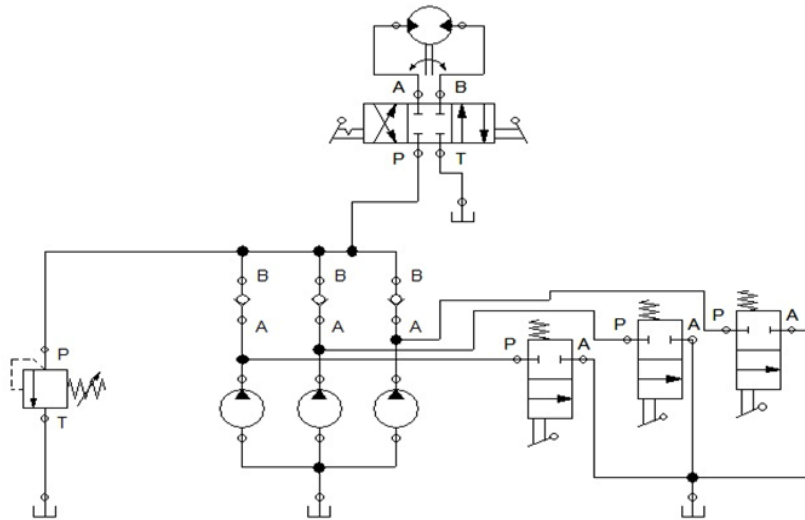


Fig. 1. Schema of "digital" hydraulic circuit

## 2. Scientific Goal of The Project

The scientific goal of this project is to compare the effectiveness (efficiency) of using different methods of controlling the pump flow rate and hydraulic motor capacity in multi-source, hydrostatic drive systems. Currently, the point is to compare a traditional hydrostatic system composed of multi-piston, axial hydrostatic unit with a "digital" hydrostatic transmission that allows for changing the liquid flow rate in the system with an appropriate displacement pumps (4 gear pumps on one shaft of an electric motor).

After comparing the results, it will be possible to answer the questions:

1. Will replacing a pump with the ability to change the flow rate (e.g. multi-piston axial pump with a tilting disc) and proportional control (implemented using a proportional valve) with a system consisting of a "digital" hydraulic transmission meet the requirements for the power supply units and control used for the construction of multi-source hydrostatic drive systems?
2. What will be the energy efficiency above the change described?
3. Will the dynamic parameters of the hydraulic system subjected to such modifications meet the requirements for multi-source systems?
4. What types of savings will result from this modified arrangement?
5. What will be the impact of replacing a typical hydraulic system with a system built according to the concept of "digital hydraulics" in the area of efficiency, reliability, safety and ecology (carbon footprint, emissions of harmful substances, e.g. in the case of using an internal combustion engine: carbon dioxide, nitrogen oxides, particulate matter)?

### 2.1 Technical Data of the Experimental Testing Pumping System

- Three – phase induction motor power ..... 11 kW;
- 3-phase supply voltage ..... 380 V 50 Hz;

- Motor speed ..... 1475 rev/min;
- Variable speed drive ..... Altivar 71; 15 kW;
- Motor speed adjustment range ..... 10÷50 Hz ;
- Max. flow .....  $Q = 45 \text{ l/min}$  ;
- Max. pressure .....  $f(Q): 100\div 200 \text{ bar}$ ;
- Pumps displacement ..... 2, 4, 8, 16  $\text{cm}^3 / \text{rev}$ .

## 2.2 Technical Means Used During Experimental Test

### Fluid working environment:

- Working fluid: HP 46 hydraulic oil;
- Filter fineness: 10m;
- Maximum temperature of the working fluid:  $40 \pm 5^\circ\text{C}$ .

### Equipment used:

- Flow transducer accuracy class 2.0;
- Speed transducer accuracy class 1.0;
- Torque meter accuracy class 1.0;
- Thermometer 0 to  $100^\circ\text{C}$ , accuracy class 2.0;
- Pressure transducer 0 to 160 bar;
- Power supply 24 V / 10A.



a) General view of valves connection



b) The view of electric motor with pumps

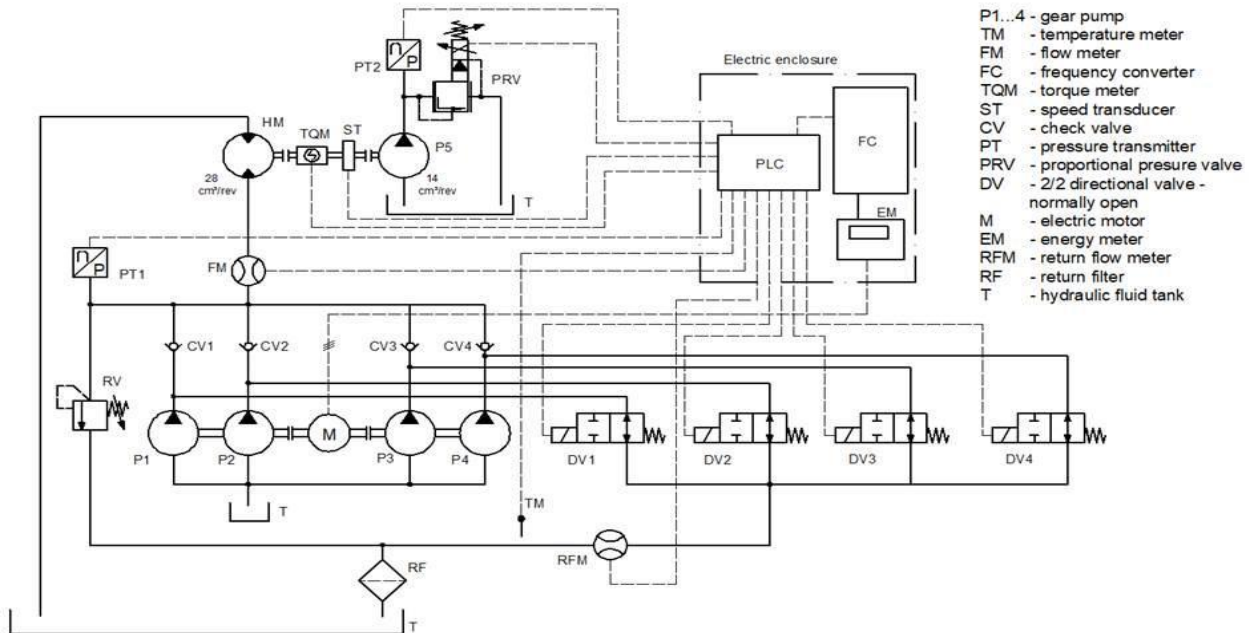


c) The view of hydraulic motor with load

Fig. 2. Experimental Equipment

### 2.3 Hydraulic Schematic Diagram of Experimental Testing Stand

Figure 3 displays the “digital” hydraulic schema used in the experiment.



**Fig. 3.** Schema of “digital” hydrostatic transmission testing stand

### 2.4 Equipment Characteristics

| No. | Equipment                       | Product type        | Manufacturer       | Charateristics   |
|-----|---------------------------------|---------------------|--------------------|--|
| 1   | Pressure transducer             | S-10                | Wika               | - Supply 10...30 VDC<br>- Range 0...400 bar<br>- Output sig. 4...20 mA   |
| 2   | Flow transducer 1 (output flow) | EVS3100             | Hydac              | - Supply 10...30 VDC<br>- Pmax. 400 bar<br>- Range 6...60 l/min<br>- Output sig. 4...20 mA   |
| 3   | Flow transducer 2 (return flow) | VT1541VADNSOA4      | Sika               | - Supply 4.5...24 VDC<br>- Range 2...40 l/min<br>- pulses/liter 915<br>- Pmax. 300 bar<br>- Meas. instrument TD 32500<br>- Output sig. 4...20 mA |
| 4   | Temperature trans.              | TSOCB1              | Comeco             | - Range 0...100 °C<br>- Output sig. 4...20 mA  |
| 5   | Torque transducer               | DR-2493             | Lorenz messtechnik | - Supply 12...28 VDC<br>- Range 500 Nm<br>- Output sig. ± 10 V   |
| 6   | Speed transducer                | 8.A020.3132.0360    | Kubler             | - Supply 10...30VDC, 150 mA<br>- 360 pulses/rev  |
| 7   | Solenoid controlled valve       | HK EMDV 10 NO1 24DC | Hansa Flex         | - MN10<br>- Rated flow 30 l/min<br>- Pmax. 350 bar   |

### 3. Traditional Hydrostatic Transmission Simulation Model

The simulation model's creation aims to analyze the hydrostatic transmission (fig. 4), specifically the flow through the overflow valve during start up ( $Q_z$ ) in relation to valve opening pressure ( $p_o$ ), hydraulic motor angular velocity ( $\omega_s$ ), hydraulic pump side pressure ( $p_p$ ), and hydraulic motor side pressure ( $p_s$ ). The aim of simulation research is an answer whether the "digital" hydraulics can be used in a multi-source hydrostatic drive system? Are their parameters similar to the classic hydrostatic transmission?

#### 3.1 The Mathematical and Numerical Data of the Model:

a) Torque equation for hydraulic motors (1):

$$q_s p_s = M_0 + R_0 \omega_s + I \frac{d\omega_s}{dt} \quad (1)$$

The initial state:  $\omega_s(0)=0$ , circumstances of the boundaries: for  $q_s p_s \leq M_0$  and  $\omega_s=0$ ,  $\frac{d\omega_s}{dt}=0$

b) Equation for pump flow (2):

$$q_p \omega_p = G_p p_p + G_r(t) \sqrt{p_p - p_s} + Q_z + \frac{V_p}{E_c} \cdot \frac{dp_p}{dt} \quad (2)$$

$$p_p(0) = \left[ \frac{q_p \omega_p}{G_r} \right]^2$$

Conditions at the beginning:

c) Equation of flow for distribution valves (3):

$$G_r(t) \sqrt{p_p - p_s} = q_s \omega_s + G_s p_s + \frac{V_s}{E_c} \cdot \frac{dp_s}{dt} \quad (3)$$

Conditions at the beginning:  $p_s(0) = 0$

d) Flow from an overflow valve  $Q_z$  formula (4), (5):

A non-inertial valve:

$$\begin{aligned} \text{For } p_p < p_o: \quad Q_z &= 0 \\ \text{For } p_p > p_o, \quad Q_z &= K (p_p - p_o) \end{aligned} \quad (4)$$

The inertial valve:

$$T_z \frac{dQ_z}{dt} = K_z (p_p - p_o) - Q_z \quad (5)$$

Data:

$q_p \omega_p = 723 \cdot 10^{-6} [\text{m}^3/\text{s}]$ ,  $E_c = 1.5 \cdot 10^9 [\text{N}/\text{m}^2]$ ,  $p_o = 19 \cdot 10^6 [\text{N}/\text{m}^2]$ ,  $q_s = 4.76 \cdot 10^{-6} [\text{m}^3/\text{rad}]$ ,  $R_0 = 0.03 [\text{Nm}/\text{s}]$ ,  $G_p = G_s = 5.4 \cdot 10^{-12} [\text{m}^4/\text{s}/\text{kg}]$ ,  $T_z = 0.2 [\text{s}]$ ,  $V_p = 150 \cdot 10^{-6} [\text{m}^3]$ ,  $V_s = 230 \cdot 10^{-6} [\text{m}^3]$ ,  $K_z = 0.52 \cdot 10^{-9} [\text{m}^5/\text{Ns}]$ ,  $I_0 = 54 \cdot 10^{-4} [\text{Nm}/\text{s}^2]$ ,  $M_0 = 60 [\text{Nm}]$ ,  $G_r = 7.23 \cdot 10^{-7} [\text{m}^4/\text{N}^{0.5}]$ .

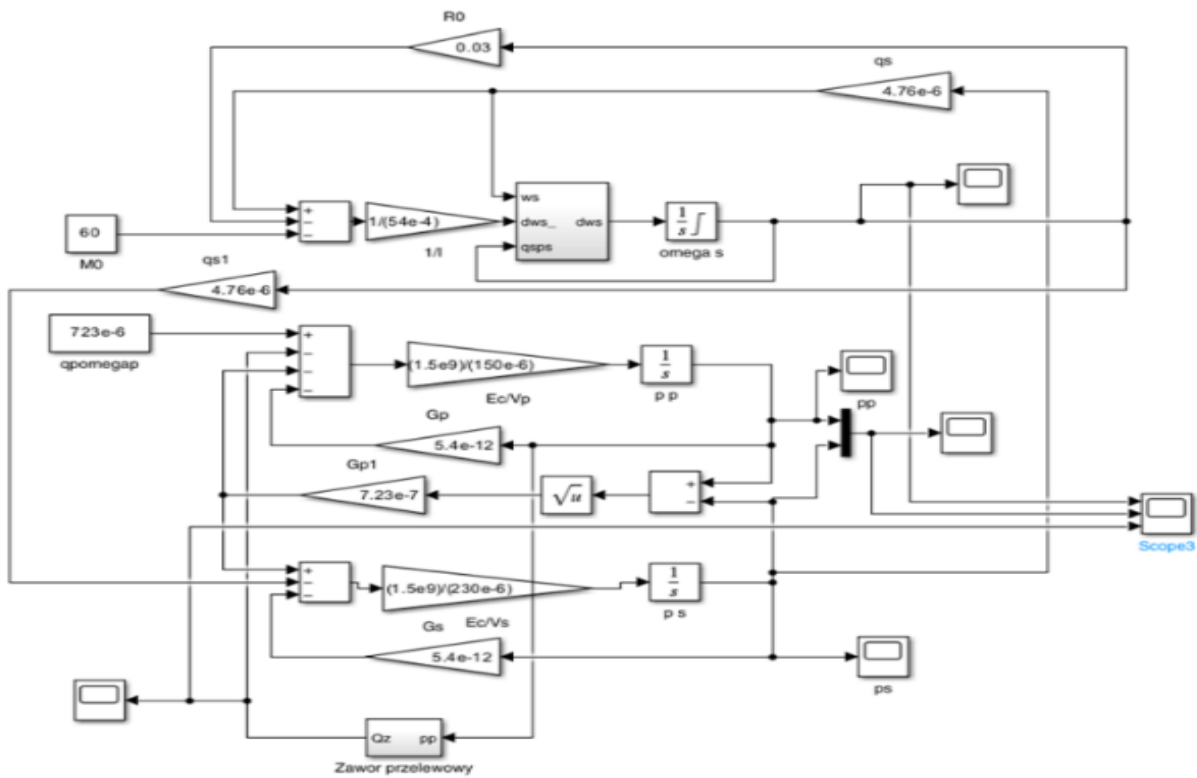


Fig. 4. Schema of simulation model

### 3. Comparison of simulation and experimental data

Figures 5 and 6 present the results of experimental studies carried out at the HYDRAULICS AND PNEUMATICS RESEARCH INSTITUTE in Bucharest, within the project "Method of effective use of the "digital" hydraulics concept in multi-source hydrostatic drive systems" (50SD/0065/24).

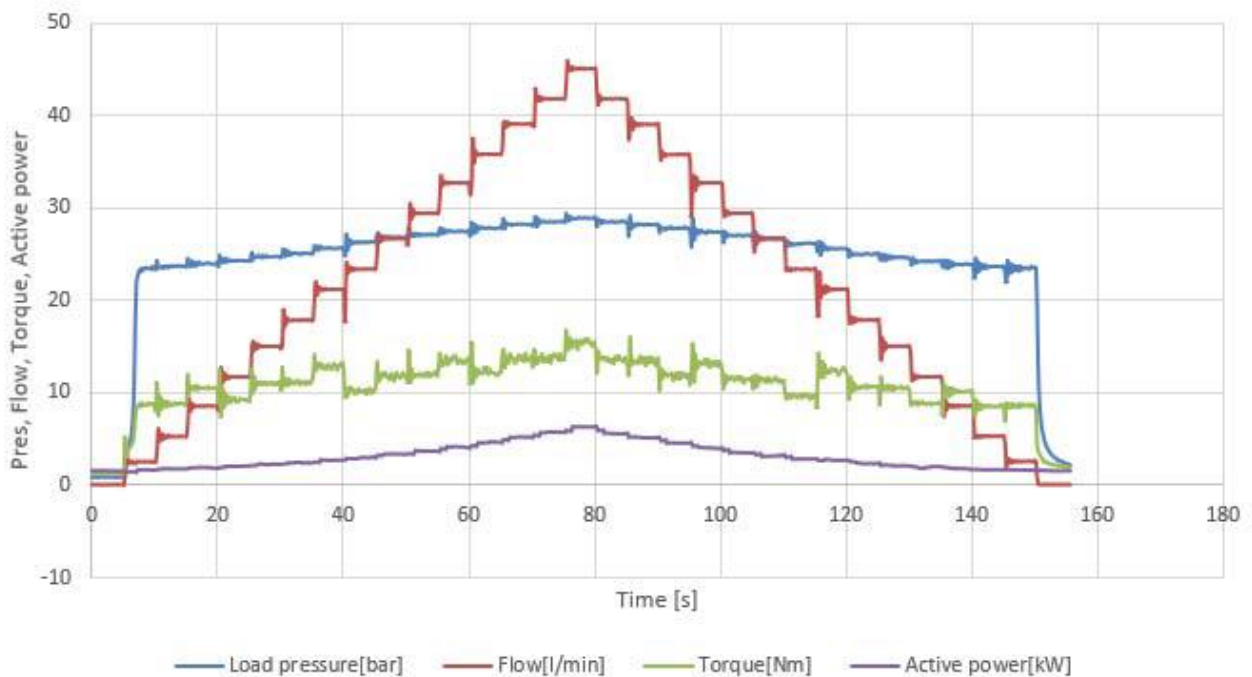


Fig. 5. Experimental research results

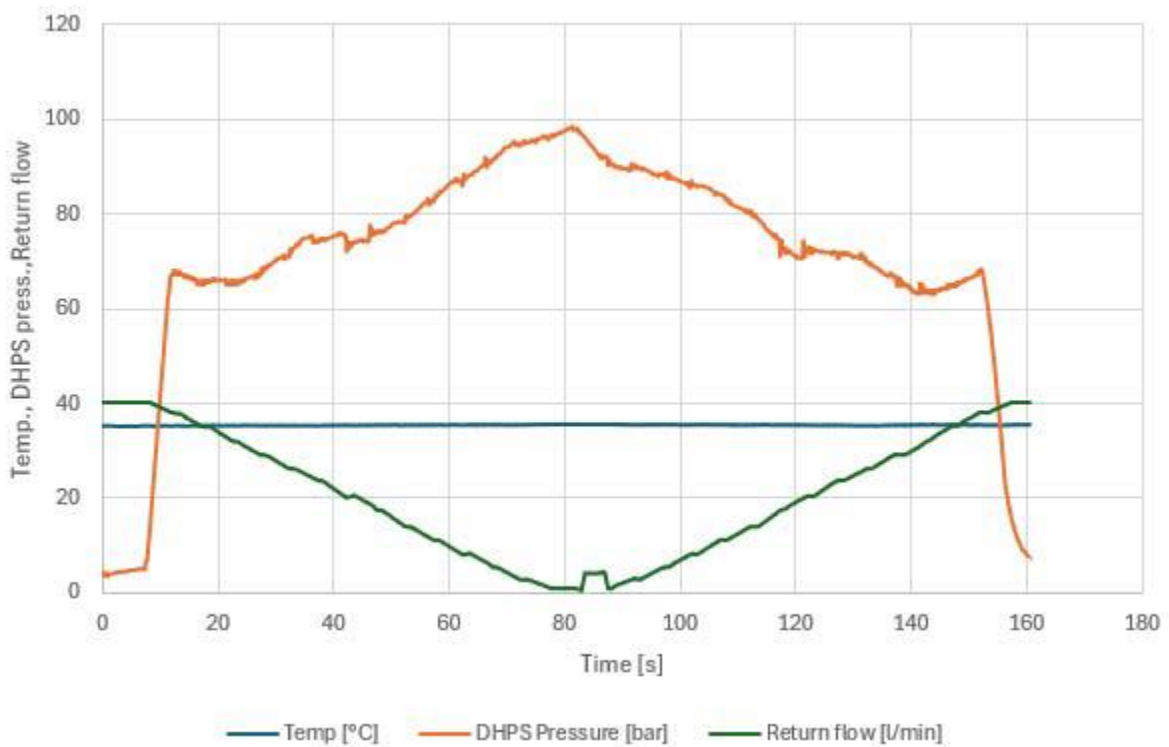


Fig. 6. Experimental research results

The simulation model built and the research results obtained from it initially confirm its correctness (figure 7 and 8). No statistical analysis has been carried out so far to compare the simulation and experimental results. This will be the subject of subsequent publications.

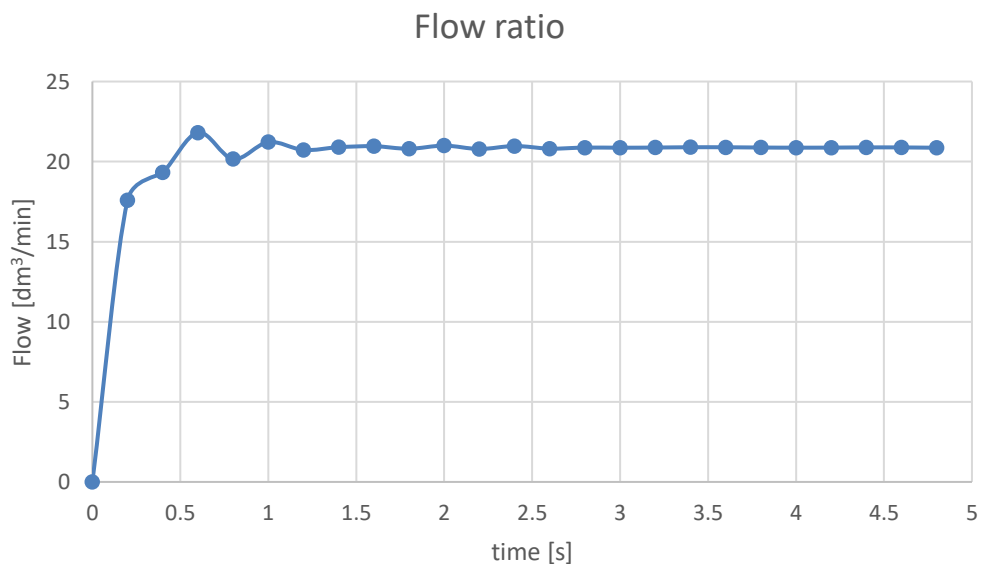


Fig. 7. Experimental research results for 20 dm<sup>3</sup>/min flow

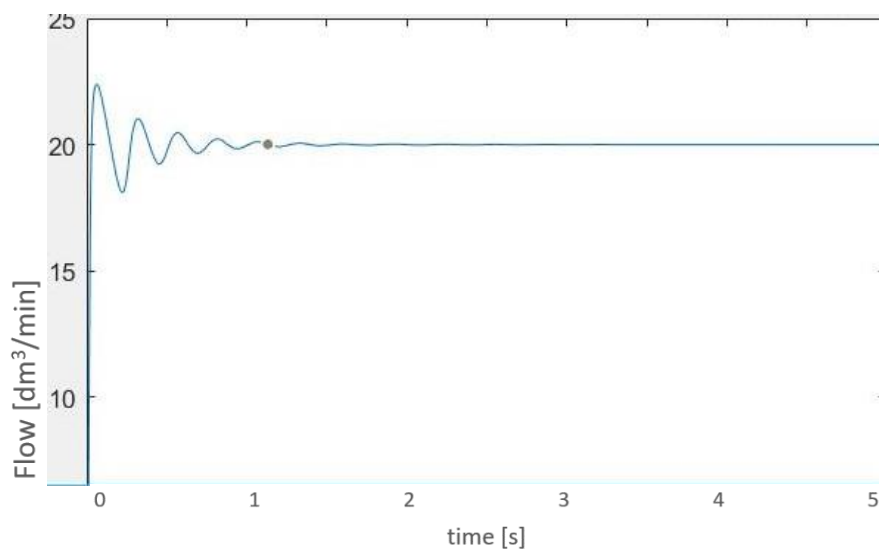


Fig. 8. Simulation research results for 20 dm<sup>3</sup>/min flow

#### 4. Conclusions

The publication presents the preliminary results of the comparison of experimental studies of the "digital" hydrostatic transmission, conducted at INOE 2000 IHP as part of the grant "Method of effective use of the concept of digital hydraulics in multi-source hydrostatic drive systems" with its simulation model. Due to the too short time between obtaining the results of the experimental studies and the deadline for sending the full text of the paper, only symbolic comparison of the simulation model with the experimental studies is included. An extended comparison of the effectiveness (efficiency) of using different methods of controlling the pump capacity and the hydraulic motor capacity in multi-source, hydrostatic drive systems and a comparison of the experimental results with simulation studies obtained in the Matlab Simulink program will be the subject of future publications.

#### Acknowledgments

The authors would like to thank the director of INOE 2000- IHP PhD. Eng. Catalin Dumitrescu, as well as chief of Department PhD. Eng. Radu Radoi and Dipl. Eng. Bogdan Tudor for their help, kindness and support in carrying out the experimental studies cited in the article.

#### References

- [1] Seyfferth, W., A.J. Maghzal, and J. Angeles. "Nonlinear modeling and parameter identification of harmonic drive robotic transmissions." Paper presented at the 1995 IEEE International Conference on Robotics and Automation, Nagoya, Aichi, Japan, May 21-27, 1995.
- [2] Tuttle, T. D., and W. P. Seering. "A nonlinear model of a harmonic drive gear transmission." *IEEE Transactions on Robotics and Automation* 12, no. 3 (June 1996): 368–374.
- [3] Kircanski, N.M., and A.A. Goldenberg. "An experimental study of nonlinear stiffness, hysteresis, and friction effects in robot joints with harmonic drives and torque sensors." *The International Journal of Robotics Research* 16, no. 2 (1997): 214–239.
- [4] Kaminaga, H., T. Amari, Y. Niwa, and Y. Nakamura. "Electro-hydrostatic actuators with series dissipative property and their application to power assist devices." Paper presented at the IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob 2010), Tokyo, Japan, September 26-29, 2010.
- [5] Kaminaga, H., T. Amari, Y. Katayama, J. Ono, Y. Shimoyama, and Y. Nakamura. "Backdrivability analysis of Electro-Hydrostatic Actuator and series dissipative actuation model." Paper presented at the 2010 IEEE International Conference on Robotics and Automation, Anchorage, AK, USA, May 3-7, 2010.
- [6] Jan, A. Z., K. Kędzia, and D. Prostański. "A new approach in hydrostatic drives: "Digital" pumps." Paper presented at the International Scientific-Technical Conference on Hydraulic and Pneumatic Drives and



- Controls, NSHP 2023, Piechowice, Poland, October 11-13, 2023. *Lecture Notes in Mechanical Engineering - Advances in Hydraulic and Pneumatic Drives and Control 2023 (2024)*: 58-70.
- [7] Dąbek, K., P. Osiński, and K. Kędzia. "Preliminary tests for the use of hydrostatic transmission with oscillating energy flow." Paper presented at the International Scientific-Technical Conference on Hydraulic and Pneumatic Drives and Controls, NSHP 2023, Piechowice, Poland, October 11-13, 2023. *Lecture Notes in Mechanical Engineering - Advances in Hydraulic and Pneumatic Drives and Control 2023 (2024)*: 184-195.
- [8] Kędzia, K. *Determinant of load cycle variation of a multi-source hydrostatic drive system*. 2nd edition revised and supplemented / *Wyznacznik zmienności cyklu obciążenia wieloźródłowego hydrostatycznego układu napędowego*. Wydanie II poprawione i uzupełnione. Wrocław, Publishing House of Wrocław University of Science and Technology, 2023.
- [9] Jan, A. Z., P. Śliwiński, and K. Kędzia. "Digital hydraulics circuit based on PWM function for controlling hydraulic actuator position." Paper presented at the 26th International Conference on Hydraulics and Pneumatics HERVEX 2022, Băile Govora, Romania, November 9-10, 2022.
- [10] Kędzia, K. "A method of determining optimal parameters for the secondary energy source of a multisource hydrostatic drive system in machines working in closed spaces." *Energies* 15, no. 14 (2022): 5132.
- [11] Domagała, Z., K. Kędzia, and M. Stosiak. "The use of innovative solutions improving selected energy or environmental indices of hydrostatic drives." Paper presented at the Innovative Mining Technologies: IMTech 2019 Scientific and Technical Conference, Szczyrk, Poland, October 14-16, 2019. *IOP Conference Series: Materials Science and Engineering – Part 2* 679 (2019): 012016.