Control Performance of an Energy-Efficient Hydrotronic Transmission

PhD. Student Eng. **Alexandru-Polifron CHIRIȚĂ**[1,2*], PhD. Eng. **Radu Iulian RĂDOI**[1],
PhD. Student Eng. **Bogdan Alexandru TUDOR**[1], PhD. Student Eng. **Ștefan-Mihai ȘEFU**[1],
Res. Assist. **Ana-Maria POPESCU**[1]

[1] National Institute of Research & Development for Optoelectronics / INOE 2000 - Subsidiary Hydraulics and Pneumatics Research Institute / IHP, Bucharest, Romania

[2] Technical University of Civil Engineering of Bucharest (UTCB), Faculty of Technological Equipment

* chirita.ihp@fluidas.ro

Abstract: *The article presents the virtual experimentation of a closed circuit hydrotronic transmission that aims at the precise control of an angular displacement with the help of a semi-rotary hydraulic actuator, experimentation performed by using Simcenter Amesim numerical simulation software. Such position control systems are often used in industry; such a system is suitable and can be used to control the pitch angle of the blades of a wind turbine.*
The article deals extensively with the control capabilities of a hydrotronic transmission. Combining high-performance hydraulic components with sensors and a PID controller - components of a hydrotronic transmission - the result is an energy-efficient transmission, with outstanding control capabilities.

Keywords: *Closed circuit, hydrotronic transmission, control performance, energy efficiency, simulation*

1. Introduction

Hydrostatic transmissions can have several methods of transmitting engine power to the actuator by using hydraulic fluid [1, 2]. Mobile machinery use closed - circuit hydrostatic transmissions [3-5] with variable displacement axial piston pumps. Hydraulic fluid leaks that occur at the pump and other system components are compensated by a low-pressure charge pump. Closed - circuit pumps have simple or more efficient and complex servo systems for displacement control. Pump displacement control is done by changing the angle of inclination of the swash plate by means of a piston and levers. The simplest variants have a mechanical control loop with mechanical feedback via levers, and the most advanced ones use PID servo controllers and angular position transducers. Controllers with adaptive feedback are used for certain applications that require high precision, e.g. machine tools or robots.
Some examples of hydraulic drive applications for angular load positioning can be found in Figure 1(a), which shows a servo-hydraulic system that controls rudder movement on tugboats. The rudder operator needs assistance in controlling and moving of it. This system has no feedback for the rudder angle and engaging the propulsion of the boat can take the operator by surprise in certain situations. In figure 1(b) one can see a servo-hydraulic rotary actuator with position control by means of a neurobilogically motivated algorithm [6]. A version of the brain emotional learning based intelligent controller (BELBIC), a bio-inspired algorithm based upon a computational model of emotional learning that occurs in the amygdala, is utilized for position controlling a rotary electro-hydraulic servo system. Figure 1(c) shows a four-way valve controlled motor with position feedback [7]. The hydraulic actuator consists of a rotary hydraulic motor that is controlled with a servo valve and an angular position controller. Figure 1(d) shows a McKibben muscles hydraulic control system for a robotic arm [8]. The authors investigated three different controllers developed for a loaded robotic arm actuated with hydraulic oil. The results of investigations showed that a simple proportional-integral controller has significant phase lag and attenuation at the higher frequencies tested. Inclusion of the feedforward term almost completely eliminates these.
Closed circuit transmissions, compared to open circuit transmissions, have faster response time, are more precise and have a smaller mass because the oil tank has a very small volume.
In the present paper, the authors investigated, through numerical simulation, the control performance of an energy efficient hydrotronic transmission, which controls an oscillating hydraulic motor.

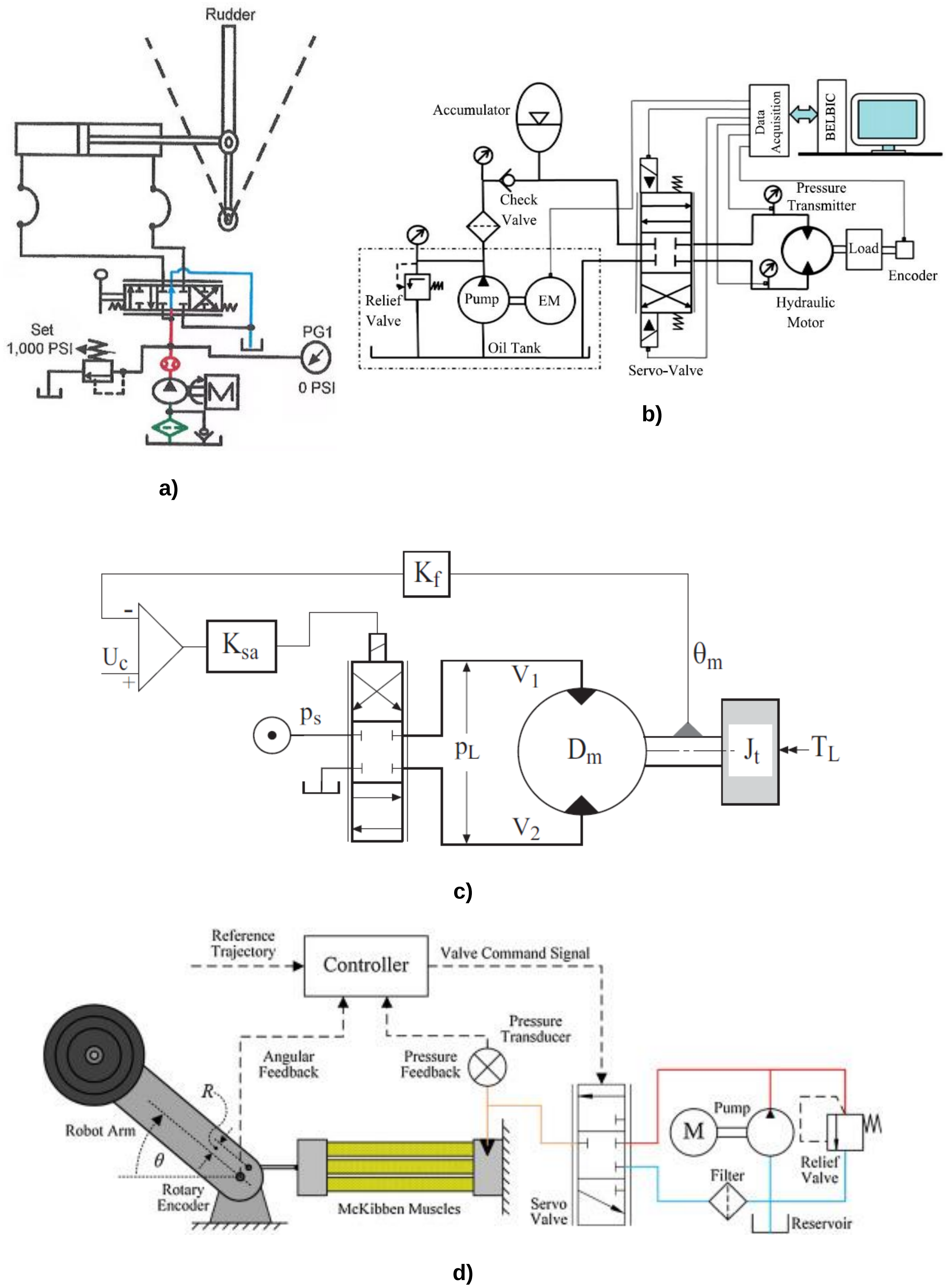

Fig. 1. Angular displacement control systems (a, b, c and d)

2. Material and method

For the analysis of control performances and efficiency of the hydrotronic transmission, the simulation model in **Figure 2** has been developed with the help of Simcenter Amesim numerical simulation software. The simulation network shows a closed circuit transmission, which aims to precisely control an angle in the range of 0.01 - 179.99 degrees.

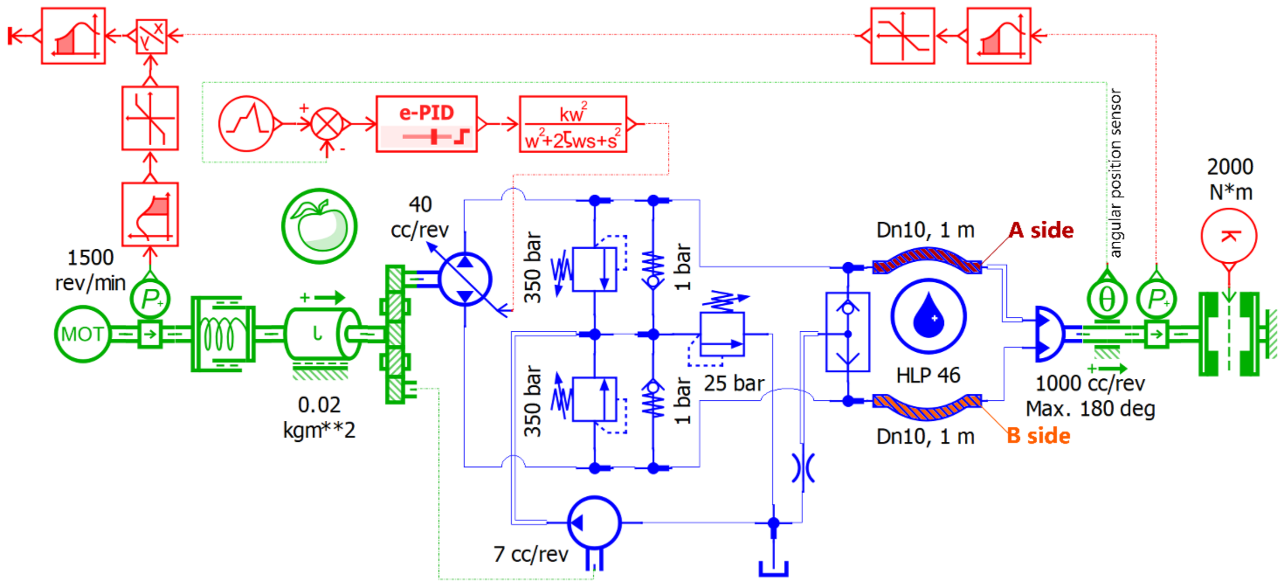

Fig. 2. Simulation network - hydrotronic transmission

Operation and structure of the transmission: an electric motor, with a speed of 1500 rev / min, supplies the two hydraulic pumps, the main one with a variable capacity of 40 cc / rev and the auxiliary one with a capacity of 7 cc / rev. Between the electric motor and the two hydraulic pumps there is a power transducer, a shaft whose model takes into account rigidity, damping, inertia and friction, and a mechanical connector that allows a single motor to operate the two pumps. The hydraulic actuator is a semi-rotary one; it has a capacity of 1000 cc / rev, can achieve an angular displacement between 0.01 - 179.99 degrees, and can develop a large continuous torque. Between the main pump and the semi-rotary actuator there are the specific components of a closed circuit transmission: two pressure valves acting as safety valves set at 350 bar, the check valves that allow for part of the auxiliary pump flow rate to reach the suction port of main pump, a pressure relief valve for the auxiliary pump that discharges the remaining flow to the cooler and tank, two hydraulic hoses Dn16 with a length of 1 m and a group of two components, a selector valve and a throttle that discharges part of the flow rate of the high-pressure side to simulate volumetric losses. Connected to the shaft of the semi-rotary actuator, there are an angle transducer, a power transducer with which the energy efficiency of the transmission is calculated, and a coupling that creates a resistant torque with a constant value of 2000 Nm. The pump capacity is controlled by a PID controller with self-tuning function; between the PID controller and the pump capacity control mechanism there is a filter that limits the frequency and amplitude of the signal; this filter limits the signal frequency with high amplitudes to a maximum of 5.5 Hz, and if the frequency increases, the amplitude of the signal decreases, the maximum frequency for small amplitudes of the signal being 25 Hz. Initial simulation data: start time 0 s – end time 5 s, print interval 0.001 s, tolerance 1e-05 s.

3. Results

Following the experimentation of closed circuit hydrotronic transmission with the help of numerical simulation, a couple of graphs resulted, as presented below.
Figure 3 shows the time variation of flow rates and pressures in the system. This shows the

variation of the main pump flow rate, the volumetric losses of the transmission (3 l/min, at a pressure of 250 bar), the pressures of the two sides with distinct values and variations.

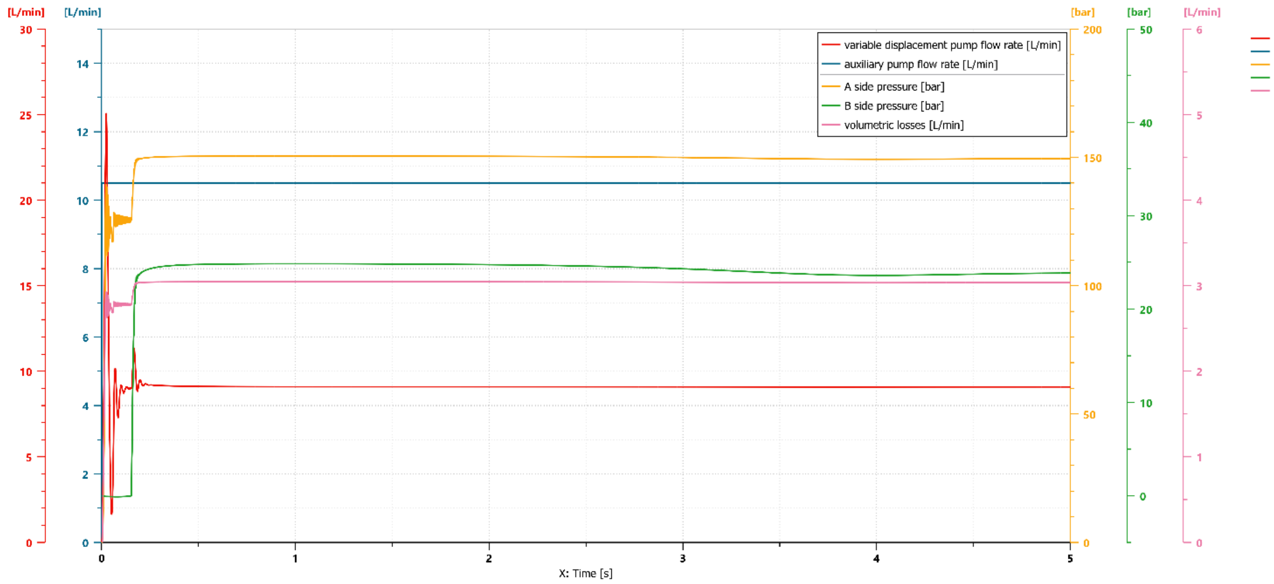

Fig. 3. Time variation of system pressures and flow rates

On the detail in **Figure 4**, one can see that due to the inertia of the hydraulic actuator and the compressibility of the system, a depression occurs (close to the limit of cavitation) on the suction port of the main pump for a short period of time; it is compensated in 0.15 s by the auxiliary pump flow rate passing through the check valve.

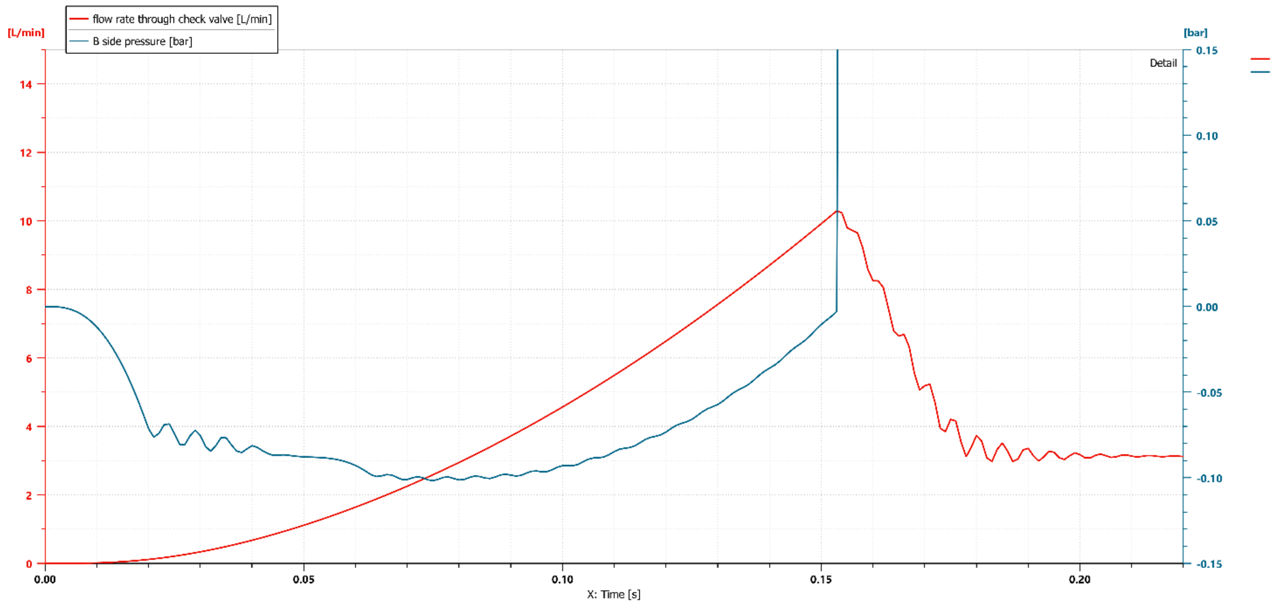

Fig. 4. Detail - Main pump suction port pressure variation and compensation flow rate

Figure 5 shows the PID controller output signal and the pump tilt angle. One can notice that the swash plate position stabilizes in 0.23 s, and the signal from the output of the PID controller is considerably attenuated.
Figure 6 shows the graph with the frequency response of the PID output and the swash plate positioning. The magnitude of swash plate positioning drops sharply over the 25 Hz frequency. The obtained performances are similar to those specified in the catalogs of the manufacturers of closed circuit hydraulic pumps.

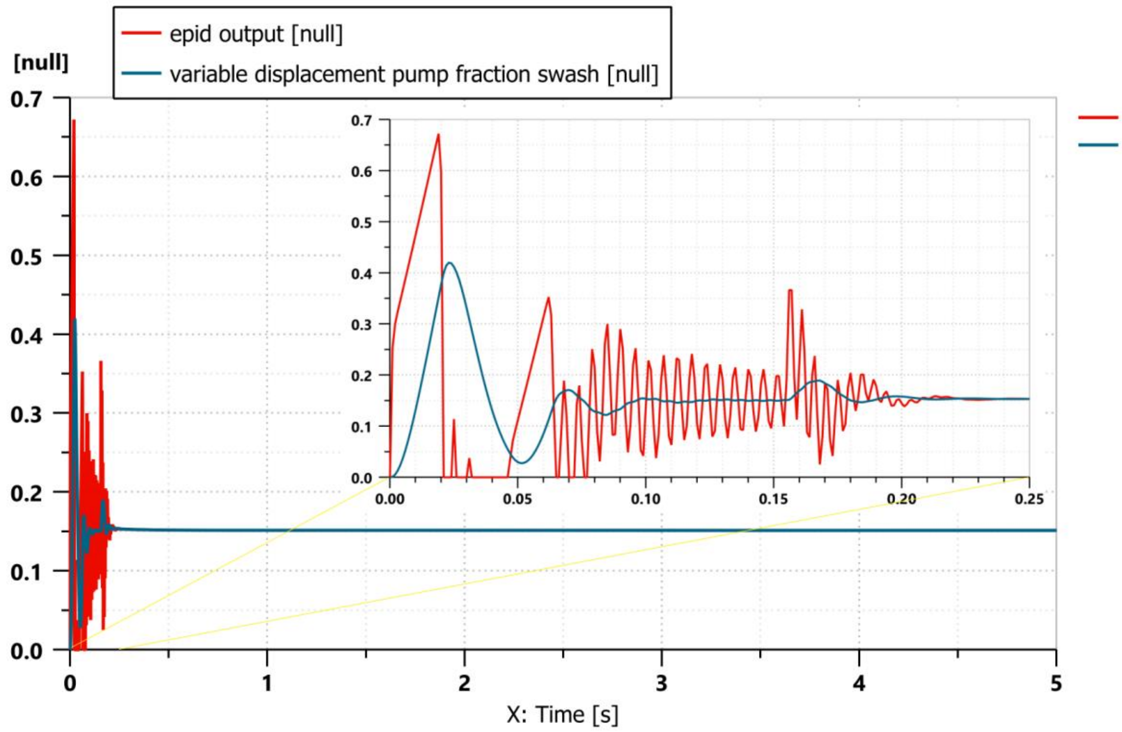

Fig. 5. Time variation of the PID controller output and the pump fraction swash

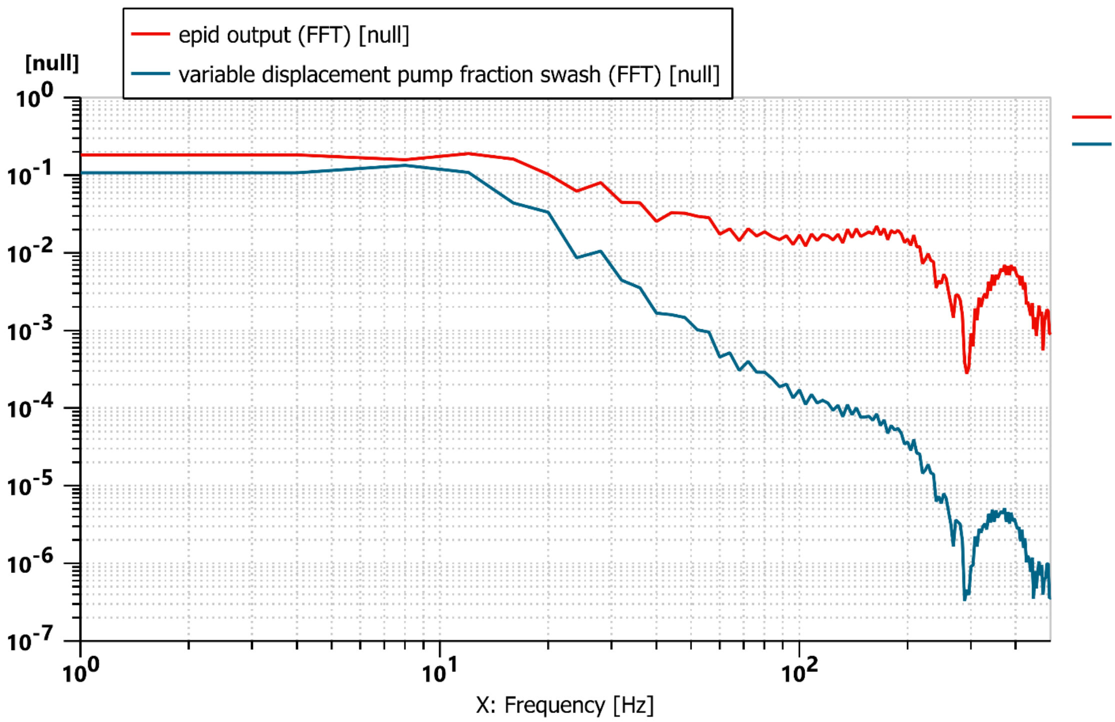

Fig. 6. Frequency spectrum of the PID controller output signal comparative to pump fraction swash

In the graph in **Figure 7**, one can see that the rotation of the hydraulic actuator shaft is opposed by a resistant torque with a constant value. After a while, the actuator speed stabilizes and the actuator achieves the prescribed angular displacement.

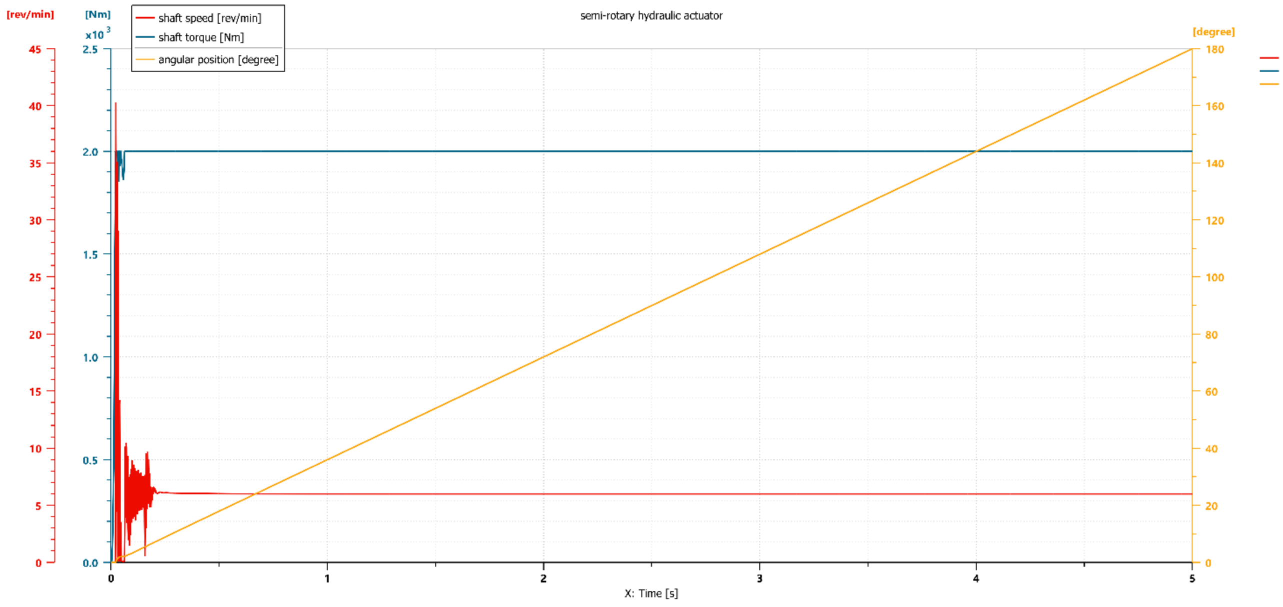

Fig. 7. Time variation of the parameters of the semi-rotary hydraulic actuator

The graph in **Figure 8** shows the external parameters of the PID controller. The graph shows a good tracking of the prescribed value, except for the first second. Moreover, on the same chart one can see the overall control error values.

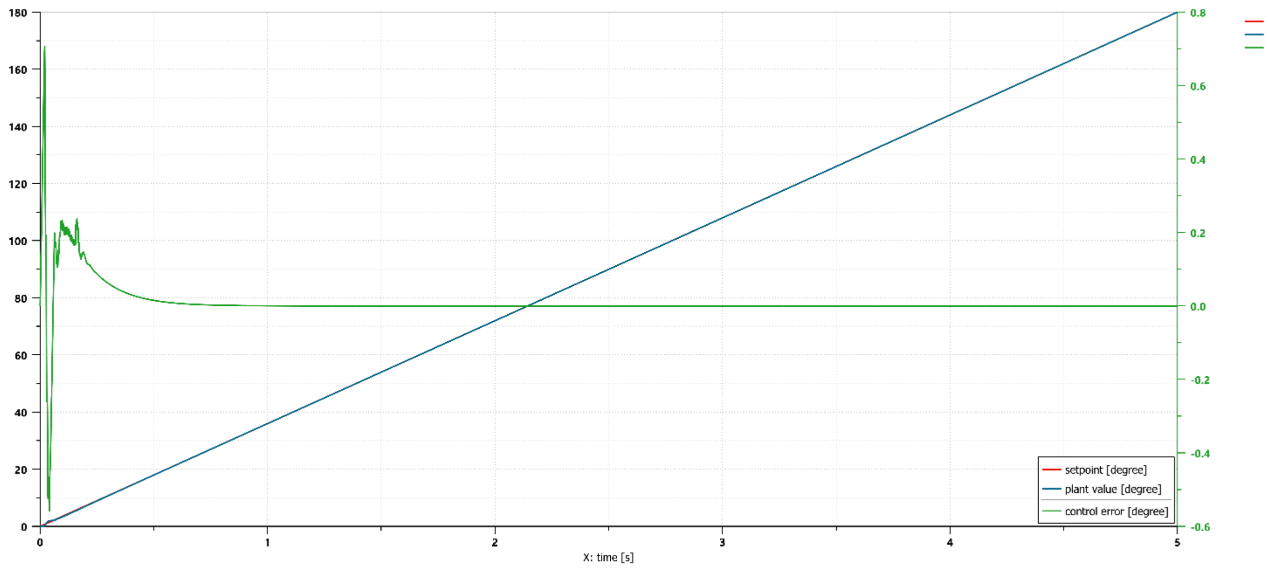

Fig. 8. Time variation of the parameters of the PID controller

Figure 9 shows in detail the variation of the external parameters of the PID controller; in the first quarter of a second of the simulation, the positioning error takes maximum values of 0.7 degrees. The prescribed value is shown in red (setpoint), and the angular displacement in blue (plant value); the large differences between these curves (0.8 degrees) are due to the elasticity of the system, the compressibility of the hydraulic fluid that has a composition of 0.2% gas and the inertia of moving components and fluid. After a very short time, 0.25 s, the value of the positioning error drops below 0.1 degrees and its value continues to decrease.
Figure 10 is intended to show an overview of the angle control error, on which one can see that the error after one second has a value very close to 0.

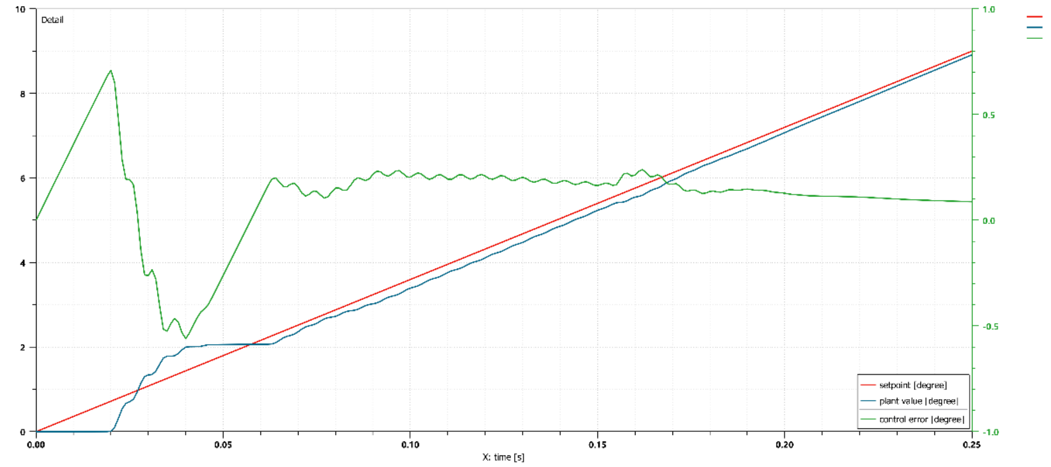

Fig. 9. Detail - Time variation of the parameters of the PID controller

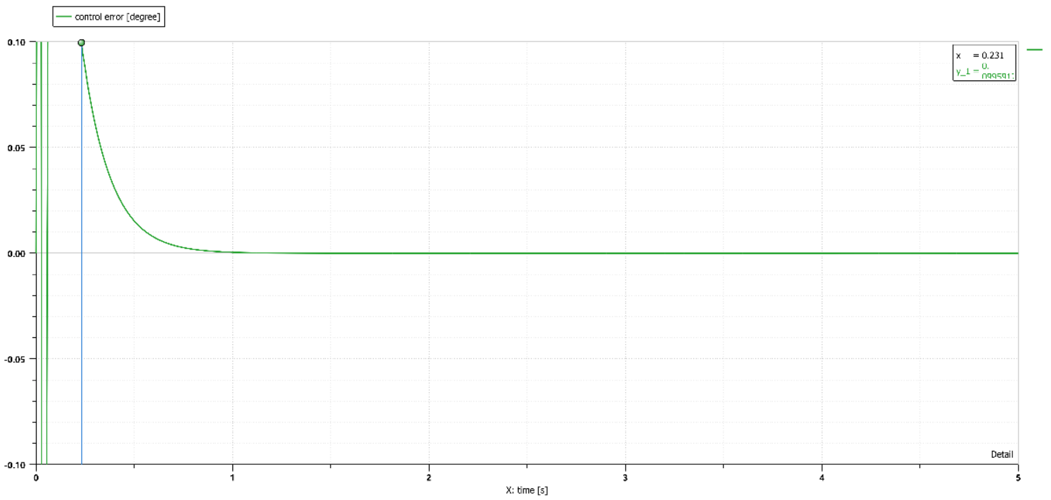

Fig. 10. Detail - Time variation of the control error

The transmission efficiency is shown in **Figure 11**; it has a value of 0.75, which is a very good value for a closed circuit transmission. The 0.2 s delay is caused by the moving average.

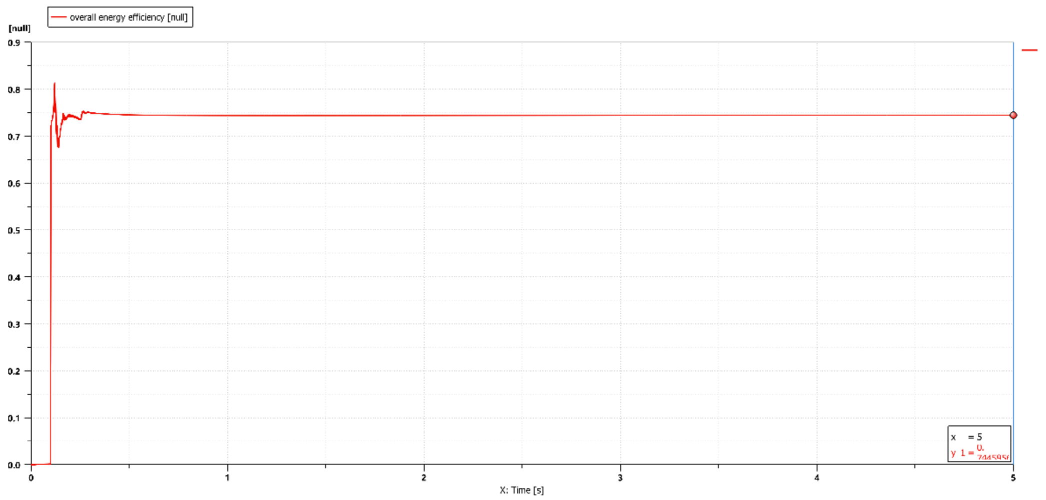

Fig. 11. Time variation of the overall energy efficiency of the closed circuit hydrotronic transmission

4. Conclusions

Using high-performance and energy-efficient hydraulic pumps and motors, in combination with sensors and electronic control systems - components of a hydrotronic system - transmissions with particularly precise control characteristics can be achieved.
Closed circuit transmissions, as opposed to open circuit transmissions, have the following advantages:

- higher control capabilities
- faster response times, especially when changing the direction of displacement
- usually, these transmissions are more compact and are used on mobile machines, because the oil tank capacity is small, consequently, the value of power and mass ratio is higher;

and the following disadvantages:

- if the cooler is not sized / chosen correctly, the transmission will overheat, and after the viscosity of the hydraulic fluid will fall below the permissible limits, the transmission will no longer work as expected by the user
- in the case when the transmission works in difficult conditions (the moment of inertia related to the load and the torque that opposes the displacement have high values or the hydraulic lines have too long lengths), simultaneously with the case when the compensation pump has a too low flow rate, all this leads to the occurrence of cavitation at the suction port of the main pump.

The central topic of this research, that is, closed loop hydrostatic transmissions, is the object of the study of the doctoral thesis of the main author; the simulation model is designed to be scalable so that transmissions with powers between a few hundred watts and a few MW can be simulated.

Acknowledgments

This paper has been funded by the Romanian Ministry of Research and Innovation under NUCLEU Programme, Financial Agreement no. 18N/08.02.2019, Ad. doc. no. 13/14.04.2021, Project code PN19-18.01.01, Project acronym: OPTRONICA VI, Theme 2 - Advanced research on the development of synergistic frontier architectures used in solving global challenges and increasing knowledge-based competitiveness, Phase 3, titled “Developing advanced methods, stands, equipment and teaching materials in order to enlarge specific knowledge in the fields of hydrotronic, pneumotronic and digital hydraulic components and systems”. European funding has also been granted, under Competitiveness Operational Programme POC 2014-2020, call POC-A1-A.1.1.3-H-2016, Financial agreement no. 253/02.06.2020, signed between INOE 2000 and the Ministry of Education and Research for the project titled “Horizon 2020 Support Center for European project management and European promotion PREPARE”, MYSMIS2014 code 107874.

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