No. 129/24, 22–32
ISSN 2657-6988 (online)
ISSN 2657-5841 (printed)
DOI: 10.26408/129.02

Submitted: 29.04.2023
Accepted: 31.05.2023
Published: 28.03.2024

ASSESSMENT OF THE OPERATION OF THE PUMP CONTROL SYSTEM USING THE PID CONTROLLER

Łukasz Betliński[1], Mostefa Mohamed-Seghir[2]*

[1,2] Gdynia Maritime University, 81-87 Morska St., 81-225 Gdynia, Poland,
Faculty of Marine Electrical Engineering

[2] ORCID 0000-0003-2814-1756, e-mail: m.mohamed-seghir@we.umg.edu.pl

* Corresponding author

Abstract: The purpose of this project was to design and construct an experimental setup enabling pump operation to be controlled and ensuring the smooth regulation of its efficiency. The closed liquid circuit is equipped with a throttling valve to slow down the flow. In addition, flow meters were used in the installation to enable the flow to be measured. Ultimately, after choking the flow, the pump could be controlled in such a way that maintained the set flow value. The PID controller fulfilling this function can be configured by changing its settings. In this way, an expiermintal setup can demonstrate the influence of individual elements of the regulator on the efficiency of regulation. This work is a continuation of further research related to the project number: 006/RID/2018/19 financed under the program Ministry of Science and Higher Education.

Keywords: control system, flowmeter, PID controller, pump control, Arduino platform.

1. INTRODUCTION

A pump is a device used to transport liquids. As a passive device, it needs to be driven, which is usually performed by an electric motor. A pump operating on automated electric drive can be subject to speed regulation, which enables it to change its operating parameters, including liquid flow.

Flow control is not often used. In the vast majority of applications, the pump is switched on when the need arises, and after starting the pump, the liquid is pumped with constant efficiency. However, there are some situations in which it is necessary to adjust the level of pump efficiency. One example of such a need can be found on ships carrying liquid cargo. When unloading the ship, the pace of pumping cargo from individual tanks is controlled in order to keep the ship stable.

One of the most commonly used methods of controlling liquid flow is throttling. It is carried out by changing the opening of the control valve, which is located on the discharge side of the pump. This is a very simple solution but not a very economical one, mainly due to the losses resulting from the increase in flow resistance. This method is used in the case of low power pumps and when the required change in the flow rate is not long-term.

The most effective way to adjust the pump's operating parameters is to adjust it by changing its rotational speed. This type of control avoids the large losses associated with throttling. Additional benefits resulting from reduced rotational speed are reduced stresses, lower bearing loads and lower vibration levels, which means that the pump is more reliable in operation [Choi, Boston and Antaki 2005; Alrheeh and Zhengfeng 2006; Yu, Zhang and Qian 2011; Jędral 2014; Gevorkov et al. 2018; Abramowicz-Gerigk et al. 2021].

When a pump is driven by an electric motor, the whole electric drive should be included in modern applications, where the motor is only a part of a more complex system. The pump is then not driven by a motor connected directly to the mains. Instead, the "intermediary" link is the power electronic converter, which determines the operation of the entire drive.

The control process is carried out using specially configured algorithms performed by microprocessor systems [Dębowski 2017; Nejad et al. 2022; Oca de et al. 2022; Su et al. 2022].

The project consists of a construction stage as well as a programming stage. Essentially, the scope of the project included:

- construction of a setup station consisting of a water system and an electrical system;
- development of a software control system performed by the Arduino board;
- an assessment of the operation of the control system and, particularly, an analysis of the operation of the PID controller with different configurations for its settings [Zhou 2022].

2. CONSTRUCTION OF EXPERIMENTAL SETUP

The experimental setup (Fig. 1) consists of a tank, pump, rota meter, two electronic flow meters and three manual valves. These elements are connected with copper pipes. The tank has two partitions dividing it into three sections. In the first one there is a hole at the bottom through which water goes to the pump. The pump has been mounted below the tank so that when water is poured into the tank, the pump is flooded. The pump pushes the water up the vertical tube. The next element in the line after the discharge port of the pump is a valve enabling the flow to be throttled. After reaching the valve, the pumped water flows through the rota meter. Above the rota meter there is a tee that divides the flow into two horizontal tubes placed one above the other. Both have an electronic flow meter installed.

In addition, in the lower tube, the flow can be throttled using a manual valve. The circuit closes where the vertical tubes direct the water to the second and third compartments of the tank. Water can be drained from the system using the drain valve located in the lowest position between the tank and the pump.

The pump used in the project is a small-sized centrifugal pump in a compact design with a DC motor, which is powered by a voltage of 24 V. The maximum power of the device declared by the manufacturer is 60 W. The electric motor of this pump is brushless, which means that its construction is devoid of a mechanical commutator.

Not only does the fully built and programmed system not only enable control in an open system; it also meets the formal requirements permitting it to be called an automatic control system (closed system) (Fig. 2).

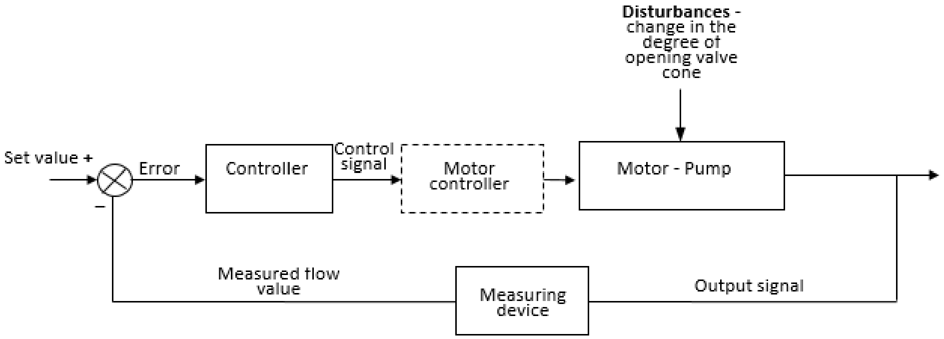

Fig. 2. Structural diagram of the automatic control system

3. SYSTEM OPERATION ANALYSIS

3.1. Open-loop control

The graph (Fig. 3) shows that the measured flow values do not resemble a continuous function. In other words, the set of values of this function is discrete. The "steps" of the flow chart are separated by a value of approximately 0.5 L/min. Therefore, the resulting flow regulation can hardly be called fully stepless or smooth. The reason for the staircase visible in the graph is not in the pump control system, but is due to the discreteness of the flow meter.

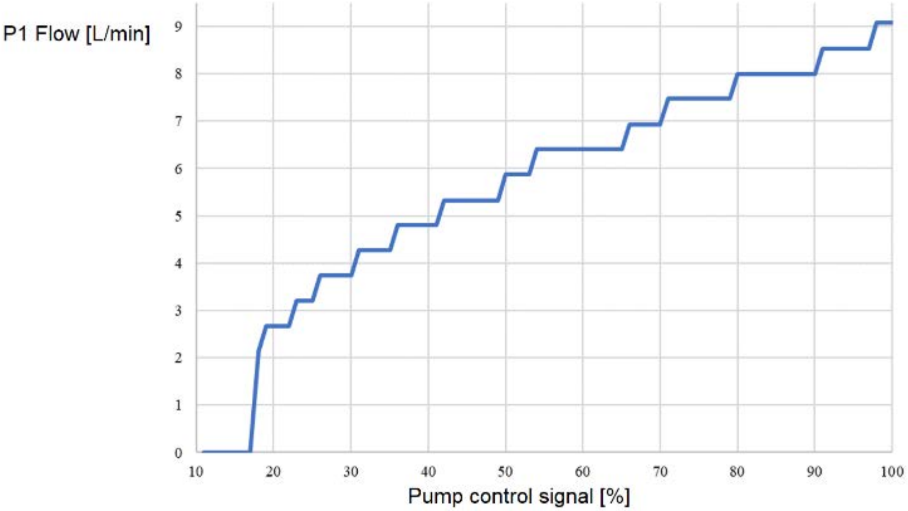

Fig. 3. Dependence of the P1 flow on the pump control signal [%] for the conditions of the water system: valve Z1 open, valve Z2 closed

The dependence of the P1 flow on the pump control signal for the same water system conditions is also shown in Figure 4. This graph illustrates that the current steady state of the pump depends on its previous state. When the control signal is increased, the pump starts pumping only after exceeding 17%. However, when the the control signal is reduced, the pump stops pumping when the control signal drops below 13%. The reason for this phenomenon is this: at start-up, the torque generated by the motor must overcome the resistance torque, which is a prerequisite for the motor shaft to start rotating. Thus, when the motor is already in motion, applying a control signal lower than the one at which it started to rotate does not cause the motor to stop.

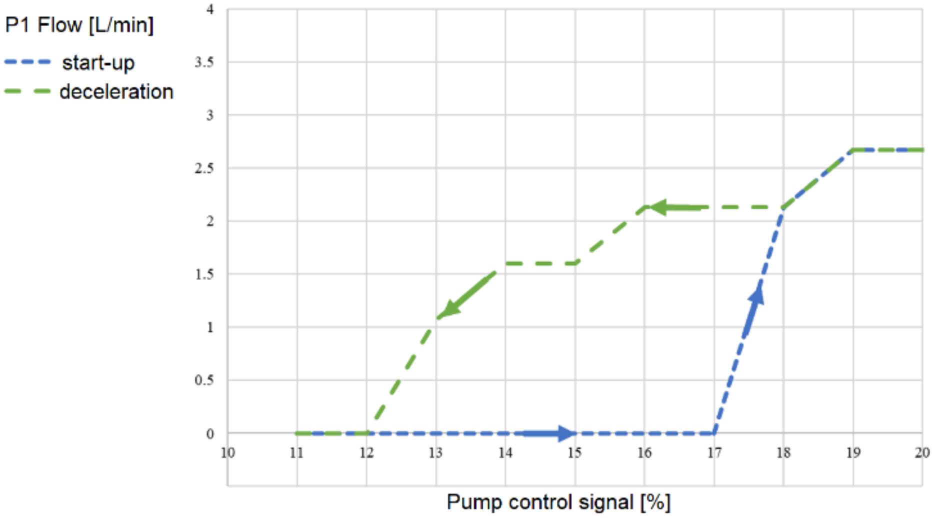

Fig. 4. Two dependences of the P1 flow on the pump control signal: during engine start-up and during engine deceleration

The next dependencies were tested under the conditions of the water system, when both valves Z1 and Z2 remained open. In this way, it is possible to study the dependency of the P1 flow and P2 flow on the pump control signal. Both of these dependencies have been placed on one graph (Fig. 5).

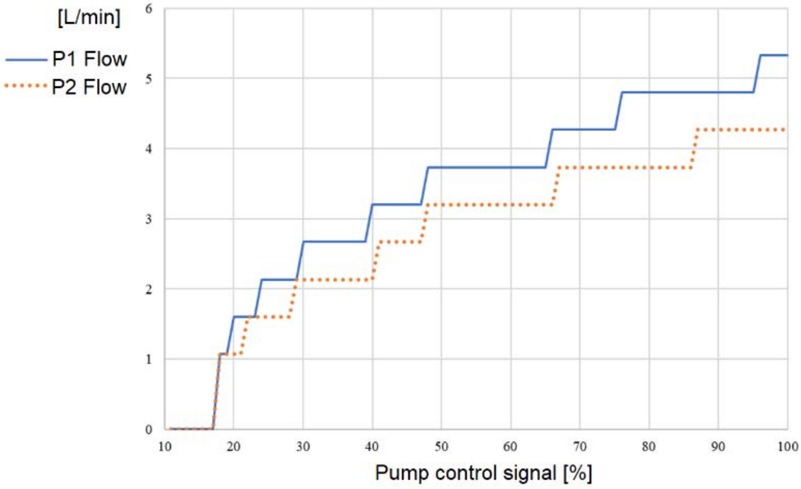

Fig. 5. Dependence of P1 flow and P2 flow on the pump control signal [%] for the conditions of the water system: valve Z1 open, valve Z2 open

It can be observed that the P1 flow remains greater than the P2 flow over the entire range of the control signal. The reason for this is a valve installed in the branch where the P2 flow is measured. This contributes to the increase of flow resistance, even when it is fully open, as a result of the construction of the ball valve used in the water system.

3.2. Closed-loop control

In order to assess the effectiveness of the programmed regulators, a special type of experiment was developed. This can be carried out in the constructed water system. The basis for comparing different variants of regulators was primarily the setting time obtained in repeated series of the same experiment.

The experiment consists of three main parts, and each of these parts involves introducing a different disturbance to the control object, which is the flow measured by the P1 flow meter. The next steps of the experiment are described below.

Part I:

- Experiments should be started in open-loop control mode. Use the potentiometer to set the pump control signal to 90%.
- The Z2 valve remains fully closed, while the Z1 valve should throttle the flow to such a degree that the read P1 flow is 3.20 L/min.
- At this point, switch on the selected regulator. The set value for the regulator will be the P1 flow measured when the regulator is switched on (i.e. when the red or blue button is pressed). The set point is then displayed on the first line of the display.

- After switching on the regulator, fully open Valve Z1 with a quick movement. This will cause a sudden increase in flow, which can be seen on both the flow meter and the P1 flow meter reading.
- After introducing a disturbance to the controlled object, the regulator starts working by reducing the value of the control signal accordingly: its percentage value can be observed on the display. The algorithm also detects the introduction of a disturbance, which can be recognised on the display by the flashing of the set point and the start of the timer.
- The timer stops counting when the algorithm detects that the P1 flow value has reached the preset value.
- At this point, you can write down the displayed regulation time reached by the tested regulator.

Part II of the experiment begins immediately after Part I:

- The set point for the tested regulator is still 3.2 L/min. Valve Z1 remains fully open.
- The introduction of the second disturbance consists in the sudden opening of Valve Z2.
- The display shows a decrease in the P1 flow and an increase in the P2 flow.
- The controller begins to increase the control signal accordingly, and the timer begins to measure the setting time.
- After reaching the set value, similarly to the first part, the timer stops. Record the obtained setting time.

Part III of the experiment is carried out immediately after Part II:

- The last disturbance is the opposite of the disturbance from the previous part of the experiment: Valve Z2 should be completely closed with a decisive movement.
- The display shows a decrease in the P2 flow and an increase in the P1 flow.
- As in the previous parts of the experiment, the display shows the setting time reached by the regulator.

The experiment was carried out in a system with a PID controller with gain parameters equal to Kp = 5, Ki = 25, Kd = 10. For the individual parts of the experiment, the setting time for Parts I, II and III was 3.8 s, f 3.8 s andPart III 3.2 s respectively.

Graph (Fig. 6), with two y-axis scales, shows the time course of the measured value and the time course of the pump control signal.

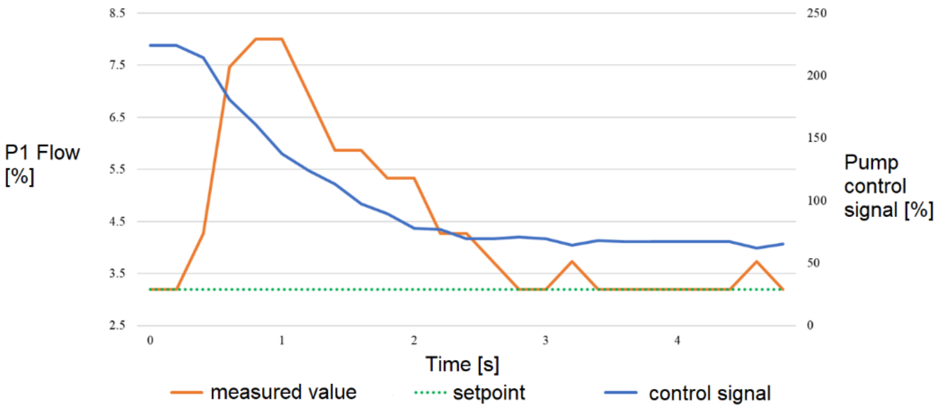

Fig. 6. The reaction of the PID controller with gain parameters equal to Kp = 5, Ki = 25, Kd = 10 obtained in part I of the experiment

In order to examine the influence of individual elements of the regulator on the efficiency of the regulation, a series of experiments were carried out in which the gain parameters Kp, Ki, Kd were used (Tab. 1). Each parameter configuration was repeated three times, and then the arithmetic mean of the setting time measurements from the individual parts of the experiment was calculated. It was assumed that the controller efficiency indicator was the sum of three arithmetic means on the basis of which the individual configurations of the PID controller could be compared.

Table 1. The influence of the gain of the parameters of the individual PID controller elements on the setting time obtained in repeated series of the experiment

Gain of the parameter			**Setting time**			**Sum $\overline{t_I}$ + $\overline{t_{II}}$ + $\overline{t_{III}}$ [s]**
Kp	**Ki**	**Kd**	**t_I [s]**	**t_{II} [s]**	**t_{III} [s]**	
0	10	0	8.2	7.2	5.6	20.9
			8.2	7.0	5.6	
			8.8	7.0	5,6	
			$\overline{t_I}$ = 8.2	$\overline{t_{II}}$ = 7.1	$\overline{t_{III}}$ = 5.6	
5	10	0	10	7.4	5.8	23.3
			10	7.2	6.6	
			9.8	6.8	6.2	
			$\overline{t_I}$ = 9.9	$\overline{t_{II}}$ = 7.1	$\overline{t_{III}}$ = 6.2	

cont. Table 1

0	10	5	8.4	6.8	6.0	21.2
			8.6	7.0	5.8	
			8.2	7.0	5.8	
			$\overline{t_{I}}$ = 8.4	$\overline{t_{II}}$ = 6.9	$\overline{t_{III}}$ = 5.9	
0	15	0	5.6	5.0	4.0	15.2
			5.6	4.8	4.6	
			6.2	5.6	4.2	
			$\overline{t_{I}}$ = 5.8	$\overline{t_{II}}$ = 5.1	$\overline{t_{III}}$ = 4.3	
0	20	0	4.4	4.2	3.2	12.9
			4.8	4.6	4.0	
			4.8	4.4	4.4	
			$\overline{t_{I}}$ = 4.7	$\overline{t_{II}}$ = 4.4	$\overline{t_{III}}$ = 3.9	
0	25	0	4.0	3.6	3.4	11.7
			4.0	4.2	4.8	
			4.6	3.4	3.2	
			$\overline{t_{I}}$ = 4.2	$\overline{t_{II}}$ = 3.7	$\overline{t_{III}}$ = 3.8	
0	30	0	6.2	3.4	4.0	12.6
			4.6	2.8	4.2	
			5.8	3.2	3.6	
			$\overline{t_{I}}$ = 5.5	$\overline{t_{II}}$ = 3.1	$\overline{t_{III}}$ = 3.9	
2	25	0	4.2	3.6	2.8	10.6
			3.8	3.6	3.2	
			3.4	4.2	3	
			$\overline{t_{I}}$ = 3.8	$\overline{t_{II}}$ = 3.8	$\overline{t_{III}}$ = 3	
4	25	0	3.8	3.8	3	10.7
			4.2	3.6	3.2	
			4.4	3.6	2.6	
			$\overline{t_{I}}$ = 4.1	$\overline{t_{II}}$ = 3.7	$\overline{t_{III}}$ = 2.9	
2	25	5	4.6	4.0	3.2	10.8
			3.6	4.0	3.4	
			3.8	3.4	2.6	
			$\overline{t_{I}}$ = 3.9	$\overline{t_{II}}$ = 3.8	$\overline{t_{III}}$ = 2.1	
2	25	10	4.2	4.0	3.0	11
			3.8	3.4	3.4	
			4.6	3.8	2.8	
			$\overline{t_{I}}$ = 3.9	$\overline{t_{II}}$ = 3.8	$\overline{t_{III}}$ = 2.1	

On the basis of the above series of experiments, it can be concluded that the integrating element influences the efficiency of regulation to the greatest extent. The shortest setting time for the integral-only controller was obtained when the gain parameter Ki was set to 25 (11.7 s). Activation of the proportional gain made it possible to reduce time by a maximum of 10% when the gain parameter Kp was 2 (10.6 s). In none of the tested configurations was it observed that the activation of the D component had improved the efficiency of the regulation.

4. CONCLUSIONS

The weakest link in the built control system turned out to be the electronic flow meters, which return discrete values of the measured flow to the control system. Improving the accuracy of this element of the system would have the greatest benefit on the quality of regulation.

Not only does the fully built and programmed system enable control in an open loop; it also meets the formal requirements permitting it to be called an automatic control system. A series of experiments testing various configurations of regulators was carried out on the system. By manipulating the PID controller settings, the impact of its individual elements on the level of control efficiency was tested on a real object.

The experimental setup used in the proposed exercise can successfully assist the user in getting acquainted with the subject of control and regulation on a real control object.

5. ACKNOWLEDGEMENTS

Funding: The project is financed within the framework of a programme by the Ministry of Science and Higher Education called “Regionalna Inicjatywa Doskonałości” in the years 2019–2022 (project number: 006/RID/2018/19; the amount of financing provided is: 11,870,000 PLN).

REFERENCES

Abramowicz-Gerigk, T., Burciu, Z., Jachowski, J., Kreft, O., Majewski, D., Stachurska, B., Sulisz, W., Szmytkiewicz, P., 2021, *Experimental Method for the Measurements and Numerical Investigations of Force Generated on the Rotating Cylinder under Water Flow,* Sensors, vol. 21.

Alrheeh, M., Zhengfeng, J., 2006, *Automatic Control of Water Pumping Stations,* 1st International Symposium on Digital Manufacture, vol. 1–3, Wuhan Univ Technology Press, Wuhan, China, pp. 147–149.

Choi, S., Boston, J.R., Antaki, J.F., 2005, *An Investigation of the Pump Operating Characteristics as a Novel Control Index for LVAD Control*, Int. J. Control Autom. Syst., vol. 3, pp. 100–108.

Dębowski, A., *Automatyka. Napęd elektryczny*, Wydawnictwo Naukowe PWN, Warszawa 2017.

Gevorkov, L., Rassolkin, A., Kallaste, A., Vaimann, T., 2018, S*imulink Based Model for Flow Control of a Centrifugal Pumping System*, 25th International Workshop on Electric Drives: Optimization in Control of Electric Drives, Ieee, New York, USA.

Jędral, W., 2014, *Pompy wirowe*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa.

Nejad, H.D., Nazari, M., Nazari, M., Mardan, M.M.S., Mohammadzadeh, A., Vu, M.T., Mosavi, A., 2022, *Fuzzy State-Dependent Riccati Equation (FSDRE) Control of the Reverse Osmosis Desalination System With Photovoltaic Power Supply*, Ieee Access, vol. 10, pp. 95 585–95 603.

Oca de, E.Y.-M., Maya-Rodriguez, M.C., Tolentino-Eslava, R., Lozano-Hernandez, Y., 2022, *A Real-Time Stable Neuro-Controller to Reduce the Energy Consumption in a Centrifugal Pump Under Disturbances*, Rev. Iberoam. Autom. E Inform. Ind., vol. 19, pp. 265–273.

Su, X., Xie, Y., Sun, L., Jiang, B., 2022, *Constant Force Control of Centrifugal Pump Housing Robot Grinding Based on Pneumatic Servo System*, Appl. Sci.-Basel, vol. 12.

Yu, J., Zhang, T., Qian, J., 2011, *Efficiency Testing Methods for Centrifugal Pumps, [in:] Electrical Motor Products: International Energy-Efficiency Standards and Testing Methods*, Woodhead Publ. Ltd, Cambridge, pp. 125–130.

Zhou, Y., 2022, *A Summary of PID Control Algorithms Based on AI-Enabled Embedded Systems*, Secur. Commun. Netw.