MEASURING THE PRESSURE-FLOW CHARACTERISTICS OF A PROPORTIONAL PILOT OPERATED PRESSURE RELIEF VALVE

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Abstract
The investigation of a pilot operated proportional pressure relief valve is described in this article. Different measurements are performed with a hydraulic test bench under laboratory conditions. A VT-VSPA1-1 amplifier module is used to control the current of the valve's solenoid. The characteristics of the valve are determined as a function of the pressure – command value of the amplifier – volume flow rate. The results of the measurements can provide input data for the refinement of the mathematical model of the unit, which will be set up in the future.

Keywords: *amplifier card, hydraulic pressure relief valve, static characteristics*

1. Introduction

Nowadays, hydraulic systems are represented in many areas. This is due to its high energy density; therefore, they can be found from mobile machines to industrial production lines. One of the key elements of hydraulic systems are pressure relief valves. At least one of this type of valve can be found in every hydraulic system. Pressure relief valves protect the hydraulic system from excess pressure by returning the unnecessary amount of fluid (Burhani and Hős, 2020). These valves are characterized by the so called static and dynamic characteristics. Shin dealt with the determination of static and dynamic characteristics of a two-stage pilot operated relief valve with experimentally and theoretically (Shin, 1991).

Measurements are performed to produce the static characteristics of a spool type pressure compensation valve (Vykoukal et al., 2017). The dependance of pressure drop – flow rate for different initial opening pressure values is determined. The article pointed out that measurement results can be suitable for verifying mathematical models. Dimitrov made a theoretical and experimental analysis of a pilot operated pressure relief valve (Dimitrov, 2013). The author developed a mathematical model for the pressure relief valve. Pressure-flow coefficient in other words valve constant can be determined from the static characteristic of a valve, which is practically the slope of the curve. This parameter can be used to estimate the predicted pressure change due to the change in volume flow rate through the valve.

Látrányi and Zalka investigated the static- and dynamic behavior of safety valves (Látrányi and Zalka, 1973). The safety valves are key elements of a hydraulic cycle. The expected behavior of these elements depends on their static characteristics. The equation describing the static characteristic of a direct controlled safety valve was shown in (Látrányi and Zalka, 1973).

This paper deals with the measurement of pressure-flow characteristics of a proportionally controlled, pilot operated pressure relief valve. Different measurements are performed in order to determine the properties of the valve focusing on the static characteristics of the unit relating to its operating range. The valve constants are calculated for different preset pressures.

The paper is structured as follows: Section 2 describes the hydraulic test bench containing the pressure relief valve (Rexroth Bosch Group, 2004) to be investigated, a pressure gauge, a volume flow measurement unit (KRACHT, 2020), a hydraulic power pack, a throttle valve, an amplifier card (Rexroth Bosch Group, 2013). Section 3 contains the measurements performed on the valve. The purpose of the first measurement is to determine the current of the electromagnet of the valve as a function of the command value of the amplifier card. The second measurement type provides the relationship between the command value and the pressure at constant volume flow rates. The third measurement type represents the case of valve opening due to the increased load in the pressure line of the system. Subsection 3.4. contains the determination of the static characteristics of the unit for different command values. The valve constant is determined from the measurement data. The last Section consists of concluding remarks and future plans.

2. Elements of the measurement and the test bench

The pressure relief valve is proportional, pilot operated. Therefore, the unit has a solenoid, which proportionally converts the electrical current to mechanical force. The ordering code of the unit is DBE6-11/50G24NK4M. M means that it has NBR type seals, K4 refers to the cable socket.

The valve is not equipped with integrated electronics. It has internal pilot oil drain. G24 means that the supply voltage of the electromagnet is 24 VDC. The pressure stage of the unit is up to 50 bar. The schematic drawing of the valve with the proportional solenoid denoted by EM can be seen in Figure 1.

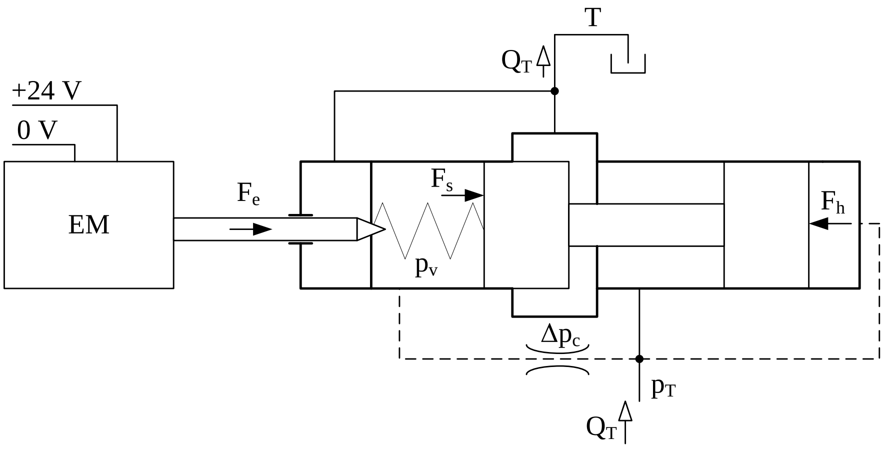

Figure 1. *Schematic of the pressure relief valve*

A hydraulic force F_h from system pressure will act to the right side of the spool of the main valve. Due to a spring, and a pressure p_v, which is equal to p_T when the valve is closed, spring force F_s and the hydraulic force will act at the opposite side of the spool:

$$F_s + p_v A_{sp} > p_T A_{sp}, \tag{1}$$

where A_{sp} is the area of cross-section of the spool. Then the spool is in its end position on the right, i.e., the valve is closed. When the system pressure reaches the preset value, the pilot puppet can move left, since the solenoid force F_e is less than the hydraulic force, which comes from the pressure p_v. The pilot oil drains internally therefore, it is connected to the drain connector of the main valve.

The following relation between the forces acting on the main valve at the moment of opening can be written:

$$F_s + p_v A_{sp} < p_T A_{sp}, \tag{2}$$

where $p_v = p_T - \Delta p_c$ since there will be a pressure drop Δp_c as the result of the flow started through a choke. The spool of the main valve moves left until the force equilibrium will occur of which Figure 1 shows a possible example.

In order to control the current of the proportional pressure relief valve, an external control electronic board is essential. VT-VSPA1-1 valve amplifier is used to produce the adequate currents for the valve. It is suitable to control direct and pilot operated pressure valves without feedback of the position (Rexroth Bosch Group, 2013). The module has features, e.g., ramp up/down generator, differential input with switchable voltage or current option etc.

The connection between the proportional valve and the amplifier card can be seen in Figure 2 in accordance with (Rexroth Bosch Group, 2013). The pins 22ac and 20ac are used to connect the solenoid of the pressure relief valve. The command value 12ac of the card varies between 0 and +9 V, which can be adjusted with a potentiometer. The amplifier module can modify the current of the solenoid depending on the value of the input command value. The opening pressure of the valve can be adjusted by changing the command value. A voltage meter is connected to check the value of the command signal.

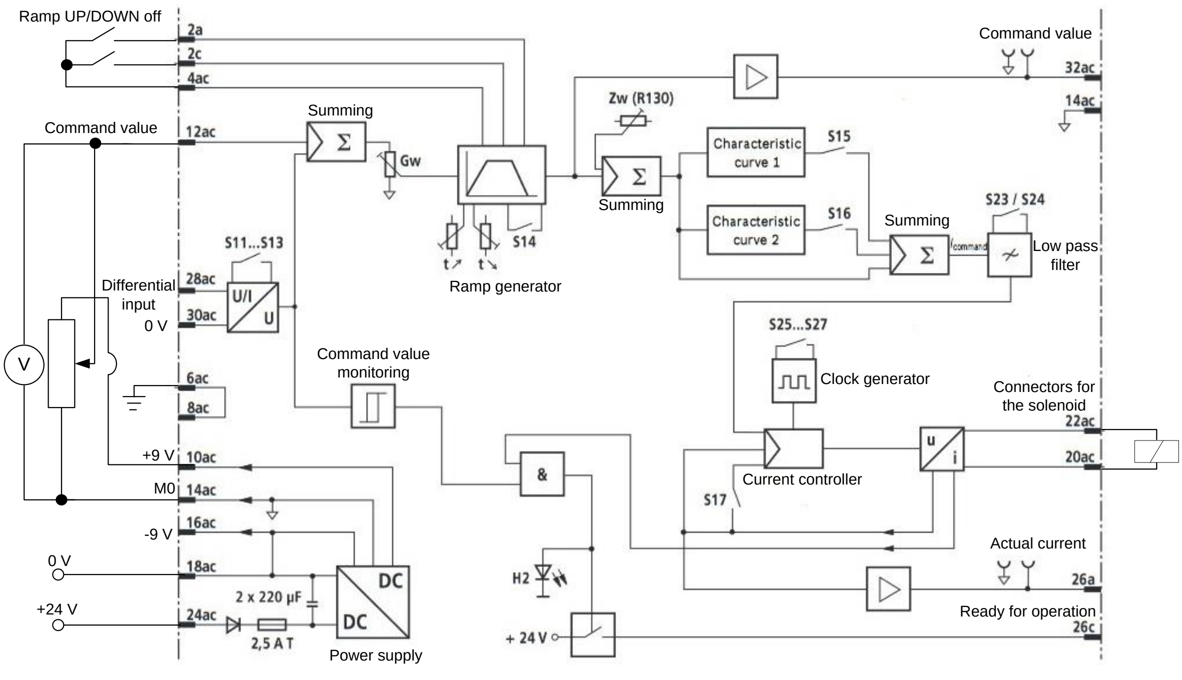

Figure 2. *The elements of the proportional amplifier module and its wiring for the measurement*

For measurements, a Kracht gear type flow measurement unit is used, which ordering number is VC 0.4 F1 PV, where 0.4 is the nominal size, F is the sealing type (FKM), PV means that the connection type is plate mounting, and the electronics has not equipped with pre-amplifier. The maximum allowable pressure is 480 bar. A pressure gauge will be used with a measurement range of 0–100 bar. The hydraulic circuit of the test bench is shown in Figure 3. A throttle valve is used in order to simulate the effect of load change.

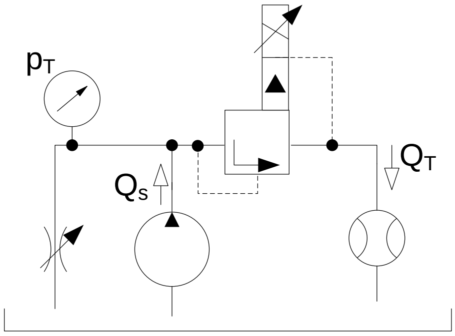

Figure 3. *The hydraulic circuit of the measurements*

The photo of the test bench can be seen in Figure 4. The notations are the following: 1) amplifier unit with its connection pins, 2) power distributor, 3) proportional pressure relief valve, 4) throttle valve, 5) hydraulic pressure- and return lines, 6) voltmeter, 7) pressure gauge, 8) multimeter, 9) flow measurement device.

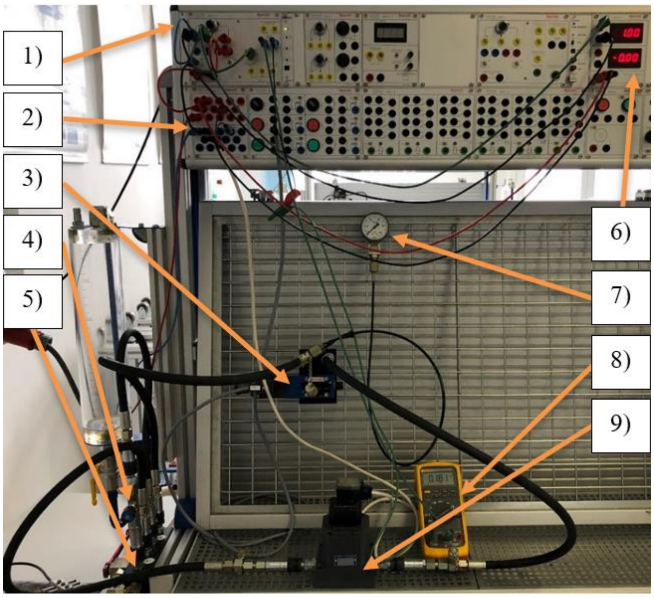

Figure 4. *Proportional valve unit under laboratory test*

The hydraulic tank is filled with AVIA fluid RSL hydraulic oil, which has 22 viscosity class. The kinematic viscosity at T = 40 °C is $\nu = 23.3\ mm^2/s$, the viscosity index VI is 94.

3. Measurements performed on the pressure relief valve

Four different types of measurements are performed in order to determine the properties of the hydraulic system and the valve.

3.1. Current of the spool as a function of command value

The first measurement focused on the determination of the current of the solenoid of the pressure relief valve. The amplifier unit gets different command values, and with a digital multimeter, the currents are measured.

The relationship between the current and command values can be seen in Figure 5. It is noted that there is a linear relationship between the two quantities. If we increase the command value, more current will flow through the solenoid of the valve, therefore it will exert more force on the spool of the valve, i.e., a higher system pressure can be set with it. In the case of the maximum command value only a current of nearly 800 mA can be measured, since the switch marked S17 (see Figure 2) is activated, therefore the half of the 1.6 A maximum current value can be achieved.

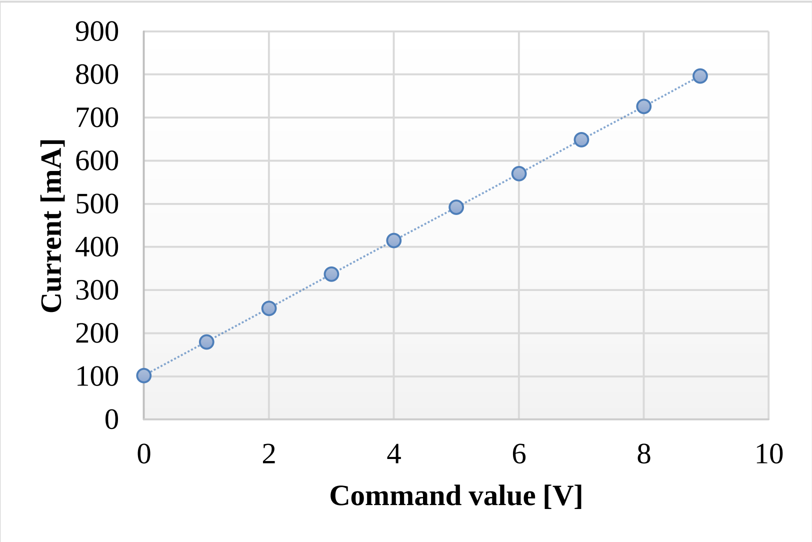

Figure 5. *Command value vs current of the valve's solenoid*

3.2. Command value versus pressure characteristic

The flow rate through the pressure relief valve is kept at a constant value with the help of the throttle valve simulating the load. Pressure measurement is performed in the function of increasing the command signal. The obtained results are illustrated in Figure 6 for two flow values: 3 dm^3/min and 5 dm^3/min, respectively.

It can be observed that approximately from a control signal of 4 V, the system pressure gradually increases. The reason for this is that the greater the command value results a greater magnetic force, against which the valve can open. At a higher flow rate, the pressures will be higher, this can be traced back to the size of flow area, since at a higher flow rate, the flow area size is larger, thus the compression of the spring is greater, i.e., a higher spring force is required, and the equilibrium in forces is only achieved at a higher pressure.

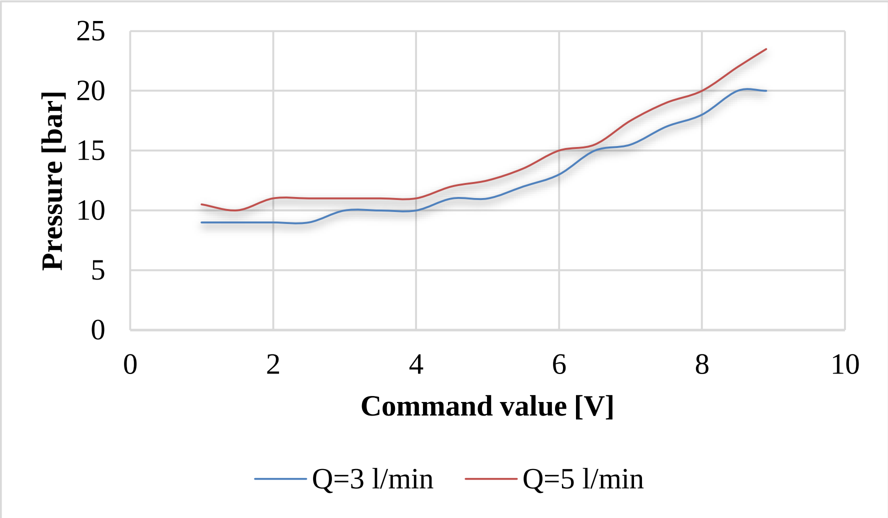

Figure 6. *Command value vs pressure at constant flow rates*

3.3. Relationship between pressure-flow rate-command value with closed throttle valve

In the following measurement, the throttle valve simulating the load is completely closed, therefore the hydraulic oil can only flow back into the tank through the pressure relief valve. By increasing the command value from 1 V to 8.9 V, the magnitude of the available system pressures and the values of the flow rates returning through the pressure relief valve are determined.

By performing the measurement, the behavior of the pressure relief valve integrated in the given hydraulic system can be seen, if the valve has to open due to the increased load in the pressure line of the system.

Table 1

Command value vs pressure and flow rate at closed throttle valve

Command value [V]	Pressure [bar]	Flow rate [dm^3/min]
1	14	7.48
2	14	7.47
3	15	7.46
4	15	7.44
5	17	7.41
6	19	7.37
7	21	7.3
8	25	7.25
8.9	26	7.2

3.4. Determination of the static characteristics for different preset pressures

The static characteristics of the valve regarding the operating range are determined shown in Figure 7 for four different command values. It can be seen that the flow rate increase through the valve results an increase of system pressure, since the change of spring force in the main valve.

In order to determine the expected change in pressure due to the increase of the flow rate for different command values, the valve constant should be calculated. The relationship between pressure and flow rate for the measurements can be considered quasi linear, therefore the value of the valve constant can be written as:

$$K_{5V} = \frac{\Delta p}{\Delta Q} = \frac{13\ \text{bar} - 9\ \text{bar}}{6\,\frac{\text{dm}^3}{\text{min}} - 2\,\frac{\text{dm}^3}{\text{min}}} = 1\,\frac{\text{bar}}{\text{dm}^3\text{min}^{-1}}, \tag{3}$$

where ΔQ is the change of the flow rate, Δp is the pressure drop for the command value CV = 5 V. For the other command values the valve constants are the following:

- K_{6V} = 1.25 bar/dm^{3}min^{-1},
- K_{7V} = 1.375 bar/dm^{3}min^{-1},
- K_{8V} = 1.375 bar/dm^{3}min^{-1}.

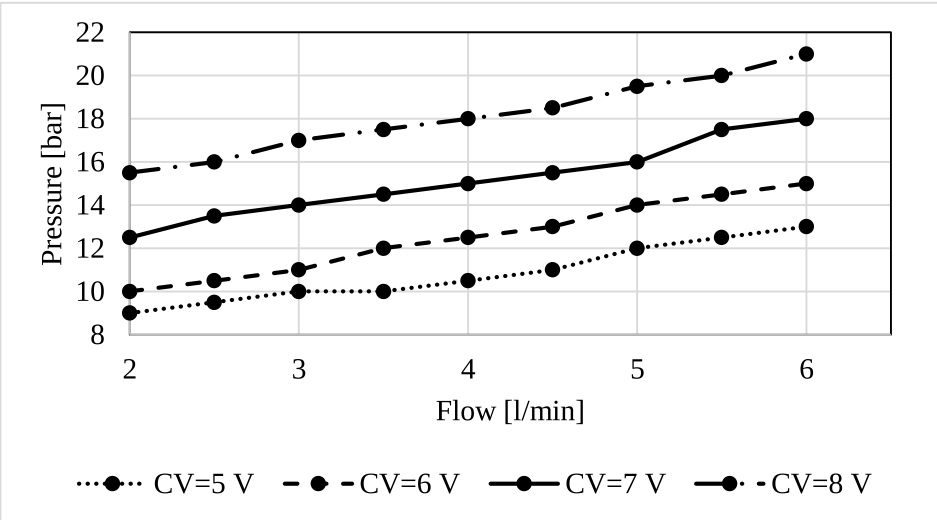

Figure 7. *Change in pressure as a function of flow rate*

By calculating the valve constant, it becomes possible to determine in advance how much pressure change can be expected in the system when a given command signal is used besides a change in volume flow rate. It can be observed that in the case of a larger command signal, the value of the valve constant will be larger.

The measurement results are greatly influenced by the temperature of the hydraulic oil, which has an effect on the viscosity of the medium. The measurements were performed at an oil temperature of 28 °C.

The accuracy of the measurements is affected by the manometer used. The available instrument is analog and has a scale division of 5 bar. In order to avoid parallax error, the pressure values were read perpendicular to the pointer of the pressure gauge.

4. Conclusions

The article dealt with the determination of the characteristics of a hydraulic, proportional pilot operated pressure relief valve via different measurements. A hydraulic test bench was set up to perform the measurements.

Depending on the command value, the magnitude of the current flowing through the coil of the valve was determined. Based on the characteristic, the relationship between the two quantities is linear, as can be seen in the datasheet of the amplifier unit. The pressure changes caused by the variation in the command value were determined at constant volume flow rates on the pressure relief valve. Since increasing the command value causes a greater electromagnetic force, against which the spool of the valve must open. With the throttle valve in closed state, the volume flows through the relief valve and the available system pressures were determined as a function of the command value. In the last measurement type, the static characteristics of the valve were determined for different command values. Then, due to the quasi-linear relationship, the slopes of the curves were determined, i.e., the valve constants were calculated. The valve constant specifies that how much change in pressure will result if the change of flow rate through the valve is occurred.

In the future, the mathematical model of the pressure relief valve will be determined, in which the measurement data will help to refine it.

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