Static and dynamic properties of selected hydraulic pressure reducing

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Abstract. A growing demand from the users of machines and hydraulic systems has created the necessity to increase the speeds, accelerations and loads of hydraulic drives. This often results in hydraulic drives working constantly in a transition state. At the same time, the area of dynamic properties of most hydraulic elements is rather unknown for most users of power hydraulics. This paper presents the results of the preliminary research on static and dynamic properties of pressure reducing valves, both with conventional and proportional control. The research focused mainly on the comparison of dynamic properties of tested elements. By dynamic properties, the authors mean pressure settling time and its overshoot, excited by step change of the flow rate through valves. It is worth noticing that the manufacturers of conventionally controlled hydraulic valves do not include any parameters describing the dynamic features of their products. Because of the insufficient information, the constructors of hydraulic drives are unable to predict the behaviour of hydraulic drives equipped with conventional valves during transition states. The preliminary research showed that the momentary value of pressure can range widely for the pressure reducing valves. This can significantly influence on operation of a drive system. The authors propose to create procedures or norms to test the dynamic features of hydraulic valves excited by a hydraulic value (eg. step change in intensity of flow or pressure). Similar procedures were introduced in testing the proportional valves as well as servovalves, with the electric signal being the unit step function.

1. Introduction

The pressure reducing valves (hereinafter referred to as PRVs) are an essential element of every pneumatic system. In hydraulic systems, the use of PRV should be justified, because any hydraulic PRV can cause large energy losses. Among other things, for this reason, the PRV are much less common in the hydraulic systems than in the pneumatic systems. Despite the lower demand of users for hydraulic PRVs, manufacturers of elements of power hydraulics offer a quite large volume of these valves. Users can choose the direct operated PRV and pilot operated PRV. Considering the shape criterion of flow control elements, most of the PRV are created as spool valves.

Due to the control signal the typical cheap PRVs are manually operated. For modern hydraulic systems most convenient are proportional operated PRVs.

Technical data at catalogues of manually operated valves are focused on their static features. Into the catalogues of proportional valves are presented their static features and selected dynamic features, mainly their response time for unit step of electric input signal.
This paper is a result of a preliminary research of static and dynamic properties of selected PRVs focused on relationship between controlled pressure and flow rate through tested valve.

2. Goals of tests
Research of selected valves have been divided into two stages:
- testing of their p/Q characteristics,
- testing the response times of valves for step of flow rate assumed as an excitation signal.

During dynamic tests, the disturbance (for the valve as a pressure regulator is the flow rate is a disturbance) has been treated in the same way as the control signal. The value of flow rate through valve is one of important ambient conditions for it. Rapid changes of flow rate value can be observed into many real hydraulic drives and systems.

Manufacturers of manually operated PRVs almost do not give any parameters describing their dynamic features. For this reason, during the research it was necessary to adopt a physical quantity that would affect the operation of the tested valves and it would be possible to rapid change the value of this physical quantity. The flow rate meets these conditions, so assumption the flow rate as input signal was intentional because only in this way can the dynamic properties of manually operated valves with proportional valves be compared.

The following PRV types have been accepted for experimental tests:
- VM064A06VG15 made by Parker Hannifin (manually, direct operated spool valve),
- UZRB-6/22-150-Y-1 made by PONAR Wadowice (manually, direct operated spool valve),
- VMY100K06TV1P made by Parker Hannifin (proportional, pilot operated spool valve).

The diagram of a hydraulic circuit for tests is showed on figure 1. The step of flow rate was realized using a directional valve electrically operated type and two flow control valves type connected to it’s A and B ports. For the flow control valves were accepted settings as 2 dm³/min and 6 dm³/min. The directional valve was switched by a rectangular signal with a period of 2 seconds. Volume of hydraulic line between PRV and the flow control valves was approx. 130 cm³. Valves were connected using 1SC hydraulic hoses and quick couplings.

The main parameters of the hydraulic power unit for testing circuit were as follow:
- pressure value on pressure line: 90 bar,
- flow rate of a gear pump: 8,4 dm³/min,
- hydraulic liquid: HM 46,
- temperature range of h.l.: 40 ÷ 45 °C

The measuring system was consisted of:
- Portable measuring and data logging device type HMG3010,
- Pressure transducers type HDA 4748-H-0250
- Flowmeter type EVS 3108-H-0020
- Temperature transducer type ETS 4148–H–006

The waveforms of recorded values were sampled using the 1 kHz frequency in 10 seconds during the tests of response time of valves. During tests of p/Q characteristics was assumed the sampling frequency as 100 Hz.

DOE (Design of experiment)
The p/Q characteristic curves were tested for three reduced pressure settings for each valve, namely: 25, 50 and 75 bar. The response time tests were accomplished for same reduced pressure settings and step of flow rate between 2dm³/min and 6dm³/min.
3. Results of static tests of PRVs characteristic curves
On figure 2 is presented recorded example characteristic curve of tested PRV (namely PRV type UZRB-6/22-150-Y-1 with pressure setting as 50 bar). The main static properties of PRVs are:
• slope of p/Q characteristic curve,
• maximum hysteresis error of p/Q characteristic curve.
Method of determination above parameters is shown on figure 2. Total results of research of static properties of tested PRVs are presented at table 1.
Figure 2. The example p/Q characteristic curve of one of the few tested PVRs.

Table 1. Static properties of tested PRVs.

| Type of PRV      | Producer    | Type of operating | Output pressure setting [bar] | Slope of p/Q curve [bar] | Hysteresis error [bar] | [%] | [%] |
|------------------|-------------|-------------------|-------------------------------|--------------------------|------------------------|-----|-----|
| VM064A06VG15     | Parker Hannifin | direct, manual, operated | 25, 50, 75 | 3.2, 4.3, 5.4 | 20.00, 5.9, 7.6 | < 0.1, 0.6, < 0.1 | < 0.1, 1.20, < 0.13 |
| UZRB-6/22-150-Y-1 | PONAR Wadowice | direct, manual, operated | 25, 50, 75 | 1.6, 5.9, 7.6 | 6.40, 11.80, 10.13 | 2.1, 0.7, 0.7 | 8.40, 1.40, 0.93 |
| VMY100K06TV1     | Parker Hannifin | proportional valve, pilot, operated | 25, 50, 75 | 1.2, 4.6 | 2.40, 6.13 | 1.1, 0.5 | 2.20, 0.67 |

4. Discussion of static tests results
The advantage of both direct operated PRVs is low values of hysteresis error. It is proof of low friction forces on their spools. Deviations of hysteresis errors values are similar to accuracy of pressure transducer (typically ≤ 0.25% FS, what is around 0.6 bar). Only for the pilot operated, proportional PRV was observed significant hysteresis error at output pressure setting as 25 bar. Basically, the hysteresis error is not important for the tested valves.

The slope of p/Q performance curve of each PRV can be explained as effect of varying spring force acting on the spool of the PRV (figure 3). Changes in the spring force are the result of changes in the position of the valve spool. In various operating conditions (flow through the valve, supply pressure, reduced output pressure) the valve opening and thus the position of the spool must be different.
Figure 3. Schema of a 3-way spool pressure reducing valve for two cases: a - high pressure drop between P-port and output port or small flow rate through valve, b - low pressure drop between P-port and output port or high flow rate through valve.

If the flow rate through the valve is changed from 0 up 8 dm$^3$/min, it can be expected that the largest change in the valve opening will occur for the case of the minimum pressure drop between P-port and output port. In this way, it can be explained that the largest slopes of the p/Q characteristics of the tested valves was observed for a setting of reduced pressure as 75 bar.

The normalised values of slopes of p/Q curves are shown on table 2. The given values of normalized slopes of p/Q curves are only approximate and have been determined in order to compare the tested valves. The true normalized slopes may be less due to the non-linearity of the p / Q characteristic curves of PRVs.

| Type of PRV    | Nominal flow rate [dm$^3$/min] | Nominal pressure [bar] | Average slope of p/Q curve [bar*min/dm$^3$] | Pressure differences for full range of flow rate [bar] | Normalised slope of p/Q curve [%] |
|---------------|---------------------------------|------------------------|---------------------------------------------|------------------------------------------------|----------------------------------|
| VM064A06VG15  | 25                              | 64                     | 0.54                                        | 13.44                                             | 21.0%                            |
| UZRB-6/22-150-Y-1 | 30                             | 150                    | 0.77                                        | 23.13                                             | 15.4%                            |
| VMY100K06TV1  | 40                              | 100                    | 0.31                                        | 12.33                                             | 12.3%                            |

5. Results of dynamic tests of PRVs characteristic curves
The dynamic properties of tested PRVs were evaluated on the basis of its response to step excitation. An example of the waveforms of the recorded quantities (reduced pressure, flow rate, electric signal controlling the auxiliary directional valve) during the test of the reduction valve is shown in figure 4.
Figure 4. The recorded waveforms of quantity reduced pressure, flow rate and switching signal of flow for PRV type VM064A06VG15 at 50 bar pressure setting: a) falling flow rate, b) rising flow rate.

Total results of research of static properties of tested PRVs are presented at table 3.
Table 3. Dynamic properties of tested PRVs.

| Type of PRV | Flow rate step | Setting of pressure [bar] | Average settling time T_s [s] | Standard deviation of T_s [s] | Minimum pressure [bar] | Peak pressure [bar] | Peak-to-peak pressure [bar] | P-t-p/pav [%] |
|-------------|----------------|----------------------------|-------------------------------|-------------------------------|------------------------|-------------------|---------------------------|---------------|
| VM064A0     | falling        | 25                         | 0.136                         | 0.0347                        | 12.17                  | 31.93             | 19.77                     | 76.3%         |
|             | rising         |                            | 0.137                         | 0.0006                        | 3.90                   | 32.03             | 28.13                     | 108.6%        |
| 6VG15       | falling        | 50                         | 0.081                         | 0.0006                        | 33.43                  | 57.37             | 23.93                     | 47.1%         |
|             | rising         |                            | 0.112                         | 0.0000                        | 19.07                  | 57.40             | 38.33                     | 75.4%         |
|             | falling        | 75                         | 0.064                         | 0.0025                        | 61.63                  | 83.20             | 21.57                     | 28.1%         |
|             | rising         |                            | 0.106                         | 0.0006                        | 34.63                  | 84.20             | 49.57                     | 64.6%         |
| UZRB-6/22-150-Y-1 | falling        | 25                         | 0.224                         | 0.0220                        | 21.17                  | 32.33             | 11.17                     | 42.4%         |
|             | rising         |                            | 0.184                         | 0.0020                        | 13.07                  | 34.43             | 21.37                     | 81.1%         |
|             | falling        | 50                         | 0.159                         | 0.0010                        | 35.80                  | 60.47             | 24.67                     | 48.0%         |
|             | rising         |                            | 0.114                         | 0.0006                        | 27.00                  | 59.27             | 32.27                     | 62.8%         |
|             | falling        | 75                         | 0.053                         | 0.0006                        | 61.20                  | 85.57             | 24.37                     | 31.6%         |
|             | rising         |                            | 0.102                         | 0.0006                        | 41.43                  | 84.97             | 43.53                     | 56.5%         |
| VMY100K     | falling        | 25                         | 0.189                         | 0.0550                        | 23.30                  | 32.30             | 9.00                      | 35.2%         |
|             | rising         |                            | 0.175                         | 0.0189                        | 11.53                  | 32.70             | 21.17                     | 82.7%         |
| 06TV1P      | falling        | 50                         | 0.191                         | 0.0211                        | 40.10                  | 63.63             | 23.53                     | 45.6%         |
|             | rising         |                            | 0.105                         | 0.0064                        | 25.63                  | 57.87             | 32.23                     | 62.4%         |
|             | falling        | 75                         | 0.063                         | 0.0000                        | 62.90                  | 85.17             | 22.27                     | 29.0%         |
|             | rising         |                            | 0.104                         | 0.0006                        | 42.00                  | 82.33             | 40.33                     | 52.6%         |

All tested valves are characterized by a high response speed. The main disadvantage of the tested valves can be perceived as high peak-to-peak pressure values. Particularly high peak-to-peak values of pressure and low values of minimum pressure were occurred for the abrupt increase in flow through the tested valves. Probably it was caused by too low flow rate of the pump supplying the tested valves (gear pump flow rate was approx. 8.4 dm³/min). It follows that in the case of sudden changes in the flow through the reducing valve, an auxiliary flow source should be added to its pressure line (eg gas-loaded hydraulic accumulator).

It seems that the settling time is influenced by the pressure setting, if the setting increases, the settling time is shorter. This assumption can be confirmed or disproved using statistical tests.

Statistical analysis of significance of differences between the settling times as the first, has been realised the Fisher test for equality of settling time variances at different pressure settings. It was necessary for correct realising the next step of statistical analysis, namely Student t-test for equality of average values of settling time. Both tests were realized using MS Excel, and they results (probabilities for hypothesis, that the tested variables values are equal) are presented on tables 4 and 5.
Table 4. Results of F-test for equality of two variances (bold – non equal).

| Valve type /Q | Pressure settings [bar] | P  | Valve type /Q | Pressure settings [bar] | P  | Valve type /Q | Pressure settings [bar] | P  |
|---------------|--------------------------|----|---------------|--------------------------|----|---------------|--------------------------|----|
| VM064A06      | 25 vs 50                 | 0.0006 | UZRB-6/22-150-Y-1 | Q↓ | 25 vs 50 | 0.0041 | VMY100K06TV1P | Q↓ | 25 vs 50 | 0.2562 |
|               | 50 vs 75                 | 0.1  |               |                          |    |               |                          |    |
|               | 25 vs 75                 | 0.0105 |               |                          |    |               |                          |    |
|               | 25 vs 50                 | 1    | UZRB-6/22-150-Y-1 | Q↑ | 50 vs 75 | 0.1538 | VMY100K06TV1P | Q↑ | 50 vs 75 | 0.0164 |
|               | 50 vs 75                 | 1    |               |                          |    |               |                          |    |
|               | 25 vs 75                 | 1    |               |                          |    |               |                          |    |

Table 5. Results of t-test for equal means (bold – non equal).

| Valve type /Q | Pressure settings [bar] | P  | Valve type /Q | Pressure settings [bar] | P  | Valve type /Q | Pressure settings [bar] | P  |
|---------------|--------------------------|----|---------------|--------------------------|----|---------------|--------------------------|----|
| VM064A06      | 25 vs 50                 | 0.1121 | UZRB-6/22-150-Y-1 | Q↓ | 25 vs 50 | 0.0354 | VMY100K06TV1P | Q↓ | 25 vs 50 | 0.9486 |
|               | 50 vs 75                 | 0.0003 |               |                          |    |               |                          |    |
|               | 25 vs 75                 | 0.0681 |               |                          |    |               |                          |    |
|               | 25 vs 50                 | 0.0000 |               |                          |    |               |                          |    |
|               | 50 vs 75                 | 0.0003 |               |                          |    |               |                          |    |
|               | 25 vs 75                 | 0.0000 |               |                          |    |               |                          |    |

The results of the statistical tests suggest that for direct operated PRVs there may be a relationship between the pressure setting and the settling time for the flow rate step. For pilot operated PRV this relationship looks as worse.

6. Conclusions
The values in table 2 indicate that for the user, the main problem associated with PRVs using is the high pressure difference for different flow rates through the valve. The hysteresis errors can be neglected (of course only for fully serviceable valves). The response times of tested PRVs should be fully satisfying for almost all users. Using a flow rate step function as excitation, the new steady-state of pressure was achieved in a flash (usually faster than in 0.2 seconds). It should be emphasized that producers of manually operated hydraulic valves do not show any data describing their dynamic features. The results of the research included in this paper may inform users that the dynamic features of valves are no less important than their static characteristics.

The user, for whom it is important that a constant pressure value can be maintained in a wide range of flow rates instead of reducing valves, the working one should use a pressure regulation system. The reducing valve as simple mechanical regulator does not provide high accuracy of output signal.

The outcome of the research indicates that it is possible to test dynamic features of any hydraulic valves with a hydraulic exciter (via step change in flow or pressure). Manufacturers of hydraulic
valves, together with standard-setting bodies (such as CETOP), ought to put across procedures for testing the features of dynamic valves for hydraulic excitation. This will provide the users with more complete information regarding these products which may be used in simulation tests within the process of developing new power hydraulic systems which will, in turn, decrease the need for validation testing.

7. References
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