The Effect of the Leakages on the Behavior of 5/3 Pneumatic Proportional Directional Control Valve

E. Sárközi, L. Földi

Abstract: In this paper a novel identified model of 5/3 pneumatic proportional directional control valve was worked out, which takes into account the leakages caused by the spool design of the valve, both in the direction of the working ports and the exhaust ports. Considering this leakages and based on measurements a novel opening characteristic of the valve was drawn (as control signal-flow rate characteristic), which is used to analyze the behavior of the valve. In central, “closed” position approx. 4.2 bar pressure was built up in connected closed vessel at the working ports, which effects not only on the behavior of the servopneumatic system, but it causes considerable leakage losses, increasing the air consumption of the already low efficiency pneumatic system.

Keywords: Servopneumatics, Position control, Pneumatic proportional directional control valve, Leakage, Mathematical model

1 INTRODUCTION

In position controlled drives the pneumatic actuators have several advantages, as they are fast, cheap, have an outstanding power-to-weight ratio, are easily maintainable and they don’t contaminate the workpiece (Földi, 2015). The challenge to the use of pneumatic drives in positioning is that due to piston friction and the characteristics of compressed gas flow their behavior is non-linear. As industrial controllers with adequate computing capacity for real-time usage became available, the pneumatic servo systems also have started to spread in positioning applications and nowadays they are good alternatives of linear drives.

A typical servo pneumatic system consists of the following parts (Fig.1.):
- pneumatic linear actuator (double acting cylinder with rod or rodless),
- proportional directional control valve,
- power supply with air service unit,
- displacement sensor and analogue pressure sensors,
- controller device.

Fig. 1. Pneumatic and electric circuit diagrams of a typical servo pneumatic system for positioning purposes (C – cylinder, Y – proportional valve, P2,P4,PT – analog pressure sensors, X – displacement encoder)

2 5/3 PNEUMATIC PROPORTIONAL DIRECTIONAL CONTROL VALVE

The proportional directional control valve is the element that makes contact through pneumatics and electronic control. The spool of the proportional valve can move into any position within it’s stroke proportionally to the control signal. So the opened cross-section of the valve is proportional with the input control signal, which is the setpoint (input) voltage (or current) signal ($U_0$) of the actuating electromagnet. With this solution not only a precise positioning can be solved, but also the flow control function in order to vary the speed of the cylinder.

Examining the physical construction of the 5/3 proportional valve it can be stated that the inlet and the outlet mass flow rates of the valve can be interpreted by the application of four orifices, which are the followings (Fig 2.):
- orifice ($A_{1,4}$) between the supply port (1) and the left side working port (4),
- orifice ($A_{4,5}$) between the left side working port (4) and the exhaust port (5).
orifice \((A_{1,2})\) between the supply port (1) and the right side working port (2),

and orifice \((A_{2,3})\) between the right side working port (2) and the right side exhaust port (3).

**NOMENCLATURE**
- \(U_v\) - control signal or setpoint voltage
- \(A\) - area of the orifice
- \(m\) - mass
- \(\dot{m}\) - mass flow rate
- \(V\) - volume
- \(w\) - velocity
- \(p_{u}\) - upstream pressure
- \(p_d\) - downstream pressure
- \(\rho\) - density
- \(\kappa\) - heat capacity ratio
- \(R\) - universal gas constant
- \(T\) - temperature
- \(q\) - flow rate

**Fig. 2. Cross-section of 5/3 proportional valve**

(FESTO, 2015)

Beyond entering and leaving pressures, cross-section (A) has got significant effect on the mass flow rate of the proportional valve. In case of proportional directional control valves the flow cross-section varies as a function of control signal. This relationship or more specifically the flow through the valve in function of input control signal is characterised with the figure 3, by the manufacturer as opening characteristic. This characteristic neglects the leakages which occur due to the spool type design of the valve, as around 5V setpoint (means closed middle position of the valve) there is no flow. In references the flow cross-section of the valve is considered due to the spool geometry (Rahmat, 2011), (Saleem, 2015), (Miyajima, 2007), (Metwally, 2013), (Messina, 2005), or a –mostly linear- \(A= f(U_v)\) is used (Yi-Chnag Tsai, 2008), (Xiang & Wikander, 2004), (Zhu, 2008), (Hamitit, 1996), or the characteristic of the manufacturer is used (Czmerk, 2015). In all three cases, the common feature is that the valve leakages are neglected, although this leakages have a very significant impact on the operation of the servopneumatic system and in terms of the air consumption.

**Fig. 3. Flow rate \((q)\) of a proportional directional control valve at 6 to 5 bar as a function of the setpoint voltage \((U_w)\) (FESTO, 2015)**

Regarding the three main positions of the valve spool the functions and the sizes of the orifices are as follows:

<table>
<thead>
<tr>
<th>Valve position, setpoint signal</th>
<th>Theoretical operation, sizes of the orifices</th>
<th>Real operation, sizes of the orifices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle, closed position, (U_v=5V)</td>
<td>all four orifices are completely closed, (A_1 = 0 \text{ mm}^2)</td>
<td>leakages on all four orifices, (A_1 \neq 0 \text{ mm}^2)</td>
</tr>
<tr>
<td>Forward, (U_v=5V)</td>
<td>(A_{1,2}=f(U_v), A_{1,3}=0 \text{ mm}^2, A_{2,3}=0 \text{ mm}^2)</td>
<td>(A_{1,2}=f(U_v), A_{1,3}=0 \text{ mm}^2, A_{2,3}=0 \text{ mm}^2)</td>
</tr>
<tr>
<td>Backward, (U_v&gt;5V)</td>
<td>(A_{1,2}=0 \text{ mm}^2, A_{1,3}=0 \text{ mm}^2, A_{2,3}=0 \text{ mm}^2)</td>
<td>leakages on all four orifices, (A_1 \neq 0 \text{ mm}^2)</td>
</tr>
</tbody>
</table>

The aim of this paper is to to set up a model of the 5/3 proportional pneumatic valve which takes into account the leakages of the valve and to evaluate the valve’s behavior with the use of this model.

3 MATHEMATICAL MODEL OF 5/3 PNEUMATIC PROPORTIONAL DIRECTIONAL VALVE

To create mathematical model of the proportional valve, the descriptive equation of the flow mass rate flowing through an orifice on account of pressure differential should be known, that is a form of equation of \(\dot{m} = \rho \cdot w \cdot A\), concerning to ideal gases.

The following equation can be derived from the basic relationships (eq. 1):
The mass flow rate in function of \( \frac{P_d}{P_u} \) has a maximum value at \( 0.528 \), so this pressure ratio is called critical pressure ratio. Below the critical pressure ratio the velocity of flow is maximum, and this velocity is the speed of the sound at exhausting temperature. Above the critical pressure ratio the velocity of flow is lower than the speed of sound, the value of it depends on the actual pressure ratio.

To examine the valve, the charging of fixed volume vessels connected to the working ports of the valve has to be modelled as well. Therefore the ideal gas equation is used:

\[
m \cdot R \cdot T = p \cdot V \tag{2}
\]

After derivation and rearrangement the variation of pressure:

\[
p = \frac{\dot{m} \cdot R \cdot T}{V}, \tag{3}
\]

and after its integration the pressure in the containers can be calculated.

The block oriented model of the 5/3 proportional directional control valve contains four orifices \((A_{4,5}, A_{1,4}, A_{1,2}, ..., A_{2,5})\). The model calculates the mass flow rates of these orifices based on the (1) in function of upstream and downstream pressure and the area of the orifice. The area of the orifices depends on the control signal, their function relationships is interpreted according to Figure 3 by the manufacturer. As in our model we would like to consider the leakages too, we have created and used a modified characteristic. This modified characteristic has got two parameters, first one is the minimal area of the orifice of the working ports at closed central position of the valve \((A_{\text{minP}} \text{ [m}\text{]}^2\)), at 1-2 and 1-4 channels), and the other parameter is a ratio of this minimal area of orifices at working ports to the minimal area of orifices at the exhaust ports \((\text{orf}_{\text{PR}}, \%\)). (We assumed that the valve is symmetrical, so in pairs – working ports and exhaust ports - the minimal areas of the orifices are identical at the two sides of the valve.) Hereinafter the exact values of the parameters and the real opening characteristic were determined by measurements and model identification.

### 4 EXPERIMENTAL APPARATUS

The pneumatic and the electric circuit diagram of the test system is presented on Figure 4. The examined valve is an MPYE-5-1/8-LF-010-B 5/3 pneumatic proportional directional control valve. It is a normally closed, directly actuated valve with position-controlled spool. The nominal size is 4 mm, the standard nominal flow rate is 350 l/min, the setpoint value range is 0 to 10 V DC, the critical frequency is 100 Hz of the valve. We applied three SDE1-D10-G2-H18 type analog pressure sensors. The system was controlled by an NI CompactRIO™ (cRIO 9073), a modular programmable automation controller.

![Fig. 4. Pneumatic and electric circuit diagram of the experimental apparatus](image-url)
For data acquisition of the three sensors and the control signal we used an NI USB-611 DAQ instrument. Both the controller and the DAQ equipment were connected to a measuring PC, where the control VI and the measuring VI were running, both developed in LabVIEW.

5 MODEL IDENTIFICATION

To determine the parameters of the model \( A_{\text{min}\_P}, \text{orf}_{P/R} \) model identification was performed. During this firstly we have measured the time response of the system to various control signal \( (p_{2\_m}(t)=f(U_c); p_{4\_m}(t)=f(U_c)) \), then we have created these functions by running the model \( (p_{2\_s}(t)=f(U_c); p_{4\_s}(t)=f(U_c)) \). Finally, to do the model identification, we have set up an objective function:

\[
\text{Obj}_\text{func}(A_{\text{min}\_P}, \text{orf}_{P/R}) = \left[ \int_0^T (p_{4\_s}(t) - p_{4\_m}(t))dt \right] + \left[ \int_0^T (p_{2\_s}(t) - p_{2\_m}(t))dt \right] \Rightarrow \min
\]

where:

\( A_{\text{min}\_P} \) - minimal size of the orifice between the supply port (1) and both the working ports (2 and 4) at closed \( (U_v = 5 \text{ V}) \) valve,

\( \text{orf}_{P/R} = A_{\text{min}\_P} / A_{\text{min}\_R} \) - area ratio of the working ports’ and the exhaust ports’ minimal size,

\( s \) - index of the simulated values,

\( m \) - index of the measured values.

6 RESULTS AND CONCLUSIONS

The result of the model identification:

\( A_{\text{min}\_P} = 4.3e^{-8} \text{ [m}^2\text{]} \)

\( \text{orf}_{P/R} = 1.6843 \text{ [-]} \)

The modified opening characteristic is shown on Figure 5. In this picture the leakage caused by the not complete sealing of spool can be observed around 5V control signal.

![Fig. 5. Modified control signal-flow rate characteristics of 5/3 proportional direction control valve](image-url)
Figure 6. and 7. show the pressures at the working ports (so the loading of the tanks) at constant 5V control signal. Based on the figures it can be stated that the identified model works truthfully, measured and calculated values coincide well. It is also can be declared that the real behavior of the valve is significantly different from the leakage-free behavior. In case of 5V control signal in both output working sides the pressure were above 4 bar (3 bar gauge-pressure) in steady state, which basically affects on the operation of the servo system using a proportional directional control valve.

![Fig. 6. Loading of connected vessel at (2) working port at 5V control signal (closed valve)](image)

7 CONCLUSION
The proportional directional control valve is a key element of servopneumatic systems, it connects pneumatics and electronics. In position controlled servopneumatic drives the most commonly used valve type is the 5/3 proportional directional control valve with spool design, in which the spool moves proportionally to the control input signal. The leakages caused by the spool type design of the valve is used to be neglected during the modelling and system testing. In our work we have created a novel identified model of the 5/3 pneumatic proportional valve that takes into account these leakages as well. Analyzing the behavior of the valve it is concluded that leakages fundamentally effect on the behavior of the whole servopneumatic system. In center position of the valve (closed position) there was 4.2 bar pressure (3.2 bar gauge-pressure) built-up in the connected vessels. This means for the servo system that the cylinder will be this much biased from both sides in steady state. This phenomenon also causes significant losses in the system, which increases operational costs of the already low efficient pneumatic system. 
REFERENCES


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