EXPERIMENTAL VERIFICATION OF PNEUMATIC ELEMENTS MATHEMATICAL MODELS IN MATLAB-SIMULINK SIMSCAPE

LUKAS DVORAK, KAMIL FOJTASEK, FILIP DYRR

VSB - Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Hydromechanics and Hydraulic Equipment, Ostrava, Czech Republic

The paper deal with a mathematical model of a pneumatic system and simulation of its behaviour. In the Matlab-Simulink Simscape program, there are models of basic elements from which it is possible to build a model of the entire system. The article describes the gradual testing of pneumatic elements mathematical models on the base of comparison with experimental data.

KEYWORDS

pneumatic system, mathematical model, simulation, experiment

1 INTRODUCTION

As already mentioned, the Matlab-Simulink Simscape contains models of a basic pneumatic elements from which a system model can be assembled. The Matlab-Simulink Simscape Help [Matlab] contains an example of a pneumatic system model consisting of a pneumatic double-acting cylinder, directional control valve, hoses and a compressed air source. After primary comparing the results of the basic pneumatic circuit behavior simulation with the results of experiment, we decided to check the models of the individual elements. Based on the comparison of simulation and experiment results, own mathematical models were built and their settings were verified.

The aim of this article is to contribute to the optimization of the mathematical modeling of pneumatic systems in the Matlab-Simulink Simscape. More accurate models make it possible to better predict the behaviour of pneumatic systems when designing them for industrial applications.

The key to optimizing the system can be power curve [Widjonarko 2019], or improvement of model creation. The procedure can be applied to standard pneumatic systems [Dvořák 2018], pneumatic systems with special types of motor, e.g. diaphragm motors [Fojtášek 2014] and rotary air motors [Dvořák 2017], which can be part of air engine of the car [Szpica 2019], or [Leontiev 2020]. Further modifications of air piston engines describes for example [Szpica 2020], or [Hanan 2022].

2 VERIFICATION OF THE INFLUENCE OF AIR PROPERTIES AND HEAT TRANSFER

During the operation of pneumatic devices thermodynamic changes occur and considering or neglecting the transfer of heat from the system to the surroundings can significantly affect the results of the simulation. Therefore, we first verified the influence of heat transfer on the calculation accuracy. A simple measuring device on which the air tank (AT) was filled through a directional valve (DV) was assembled, see schema on Fig. 1. Pressure was set by pressure regulator (PR). The volume of the air tank was 2 dm^3, heat exchange surface 0.11 m^2. The tank made of steel had weight 4.95 kg. The measured quantity was the pressure (p1) in the air tank.
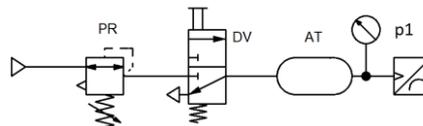

Figure 1. Air tank filling measurement scheme

Subsequently, we built a model of this system in Matlab-Simulink Simscape. Model consisted of a constant pressure source (CPS), an orifice (Or) that replaced the directional valve and a "Constant Volume Chamber" block (CVCh), see Fig. 2.
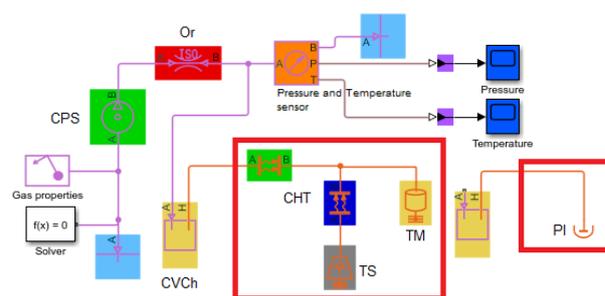

Figure 2. Block diagram of the air tank filling model

Port H on the "Constant Volume Chamber" block (CVCh) allows heat transfer to be calculated. "Convective Heat Transfer" blocks (CHT) that represent the inner and outer surface of the tank (in Fig. 2 green and blue blocks) must be connected to port H. Furthermore, it is necessary to connect "Thermal Mass" (TM), where it is possible to define the mass and specific heat of the tank. The ambient temperature is defined in the "Temperature Source" block (TS). If we don´t consider the transfer of heat to the surroundings, the "Perfect Isolator" (PI) is connected to port H as shown on the right in Fig. 2. Fig. 3 shows a comparison of pressure curves in the tank. The blue curve presents the results of the simulation without considering heat transfer. A steeper pressure rise compared to the experiment is evident. The red curve presents the results of the simulation with consideration of heat transfer. In this case, the simulation results show a good agreement with the experiment. The heat transfer coefficient value, which must be entered in the "Convective Heat Transfer" block, was determined based on a comparison with the experiment: for heat transfer from compressed air to the tank wall 80 $W·m^{-2}·K^{-1}$ and for transfer from the wall to the surroundings 20 $W·m^{-2}·K^{-1}$.
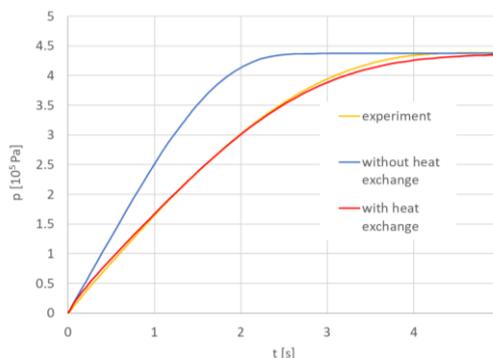

Figure 3. Pressure curve when filling the air tank

Based on the comparison, it is clear, that it is necessary to consider heat transfer to the surroundings. This especially applies to elements such as hoses and pneumatic cylinders.

In the "Gas Properties" block the properties of dry air are set by default. If necessary, the properties of any gas can be set here. For air, it is possible to choose between "Perfect" gas, "Semiperfect" (temperature parametrization of parameters) and "Real" (pressure-temperature parameterization). We decided to test the differences in calculations for the mentioned choices. For comparison, the filling of the air tank described above was chosen. Only slight differences were observed between the results. It was decided that "Real" gas would continue to be used. Later it was found that in the case of calculating more complex systems the calculation collapses and it was necessary to change the properties to "Perfect" gas.

3   PIPELINE MODEL VERIFICATION

The next element we decided to check was the "Pipe". According to Matlab-Simulink Simscape Help [Matlab] "the block accounts for viscous friction losses and convective heat transfer with the pipe wall". The model therefore represents resistance to movement, but does not take into account the capacity of the pipeline, i.e. resistance to deformation. This could significantly affect the results of the simulation of dynamic events in the case of larger pipe sizes. Resistance to movement depends on the length and diameter of the pipe and the roughness of the walls. Default value of Internal surface absolute roughness is $15 \cdot 10^{-6}$ m. Polyurethane hoses are often used to connect pneumatic elements, so we measured the roughness of their walls. The measured roughness value is $0.4 \cdot 10^{-6}$ m. This value was then used in all system models.

This was followed by checking the response of the mathematical model to a sudden change in pressure. To verify the model a measuring device similar to the previous case was assembled. Instead of an air tank, a hose (Ho) was included in the system. The pressure at the beginning (p1) and at the end (p2) of the hose after opening the valve was measured, the scheme is in Fig. 4.
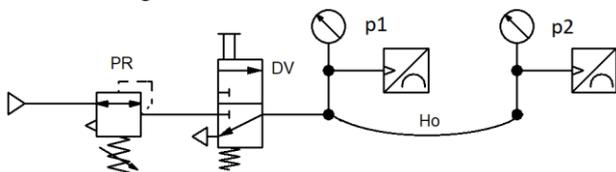

Figure 4. Scheme of measuring step change in pressure

Hoses with an inner diameter of 2.5, 4 and 5 mm and a length of 1, 3 and 6 m were used during the measurement. Simulation was performed for all hoses. The results especially for larger hoses were not good. Therefore, the "Constant Volume Chamber" (CVCh) block was added to the "Pipe" block (Pi). Of course, heat transfer to the surroundings is also considered. The entire pipeline model is shown in Fig. 5.
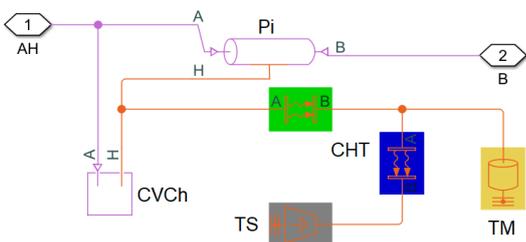

Figure 5. Block diagram of the pipeline model

In the case of simulating systems with long pipelines, it is convenient to use a so-called "Segmented Pipe", as is common for hydraulic systems, see e.g. [Hružík 2017]. But the Matlab-Simulink Simscape library for pneumatic systems does not include the segment pipe. That's why we created our own model. The pipeline simulation subsystem was divided into 10 equal parts and the individual blocks were assembled as seen in the cut-out in Fig. 6.
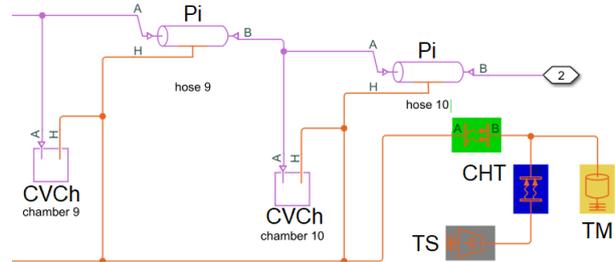

Figure 6. Block diagram of the segment pipeline

The pressure step change simulation results of all mentioned models for different pipelines were compared with the experiment. Fig. 7 shows an example of the pressure curve at the end of a pipe with a diameter of 4 mm and a length of 3 m. The figure shows the pressure curve for the model "Pipe" (simulation - R), "Pipe" with "Constant Volume Chamber" (simulation - RD) and "Segment pipe" (simulation - RD seg).
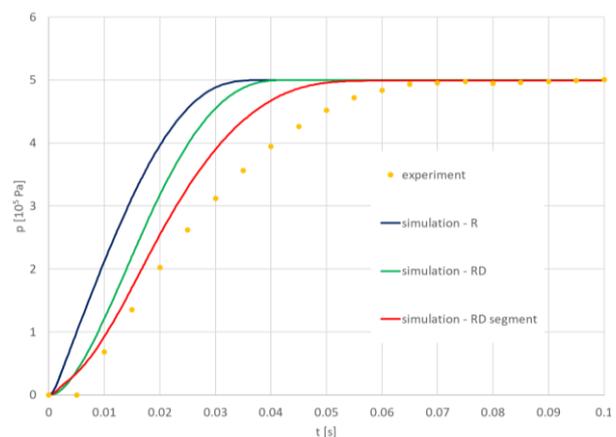

Figure 7. Pressure curves at the end of the pipe

A comparison of the simulation and experiment results shows that for hoses longer than 1 m it is advisable to use a model that also respects the pipe capacity. For pipelines longer than 3 m, the segment pipeline model must be used. It should be noted that the "Segmented pipe" disproportionately increases the time for simulating the behavior of more complex systems.

4   PNEUMATIC CYLINDER MODEL

The pneumatic cylinder model needs to be assembled from several elements. They are primarily two "Translation Mechanical Converter" blocks, one representing the piston chamber (TMC1) and the other the piston rod chamber (TMC2). The input values of these blocks are mainly the area of the piston, the initial pressure in the chamber and the dead volume. The stroke of the cylinder must be defined using the "Translation Hard Stop" block (THS). This block also includes damping in the end positions, but it is not very suitable for the cylinder model. The default value setting causes the piston to oscillate in both end positions. Therefore, it is necessary to

set the damping constants to higher values, as shown in the lower part of Figure 8. The friction of the piston must also be included in the model using the "Translation Friction" block (TF). The frictional resistance parameters are expressed as a percentage of the theoretical cylinder force at a given working pressure, as shown in the upper part of Fig. 8. The cylinder model needs to be further supplemented with blocks for calculating heat transfer and blocks representing force and mass load (externally, see Fig. 9).
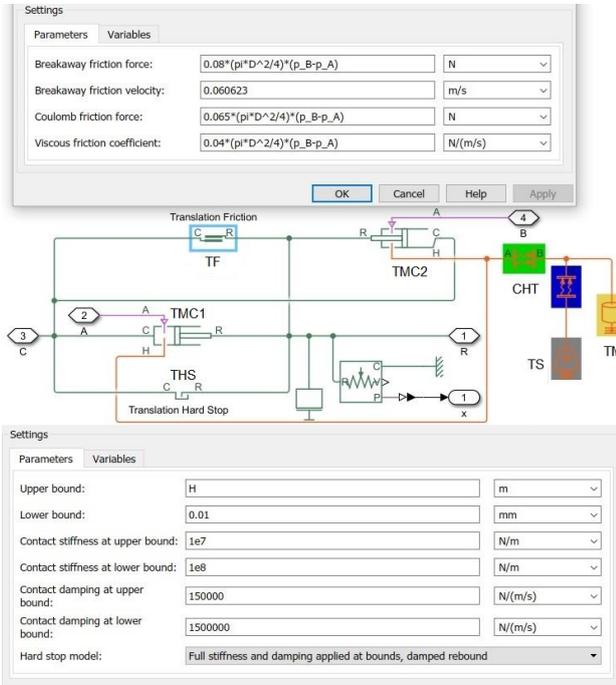

Figure 8. Block diagram of the pneumatic cylinder model

5   VERIFICATION OF PNEUMATIC SYSTEM MODEL RESULTS

After verifying the basic elements, a model of the basic pneumatic system was assembled. It consists of a source of constant pressure of 0.7 MPa, a pressure regulator that serves to set the working pressure, a directional control valve, hoses and a pneumatic cylinder. The system model is further supplemented with blocks for setting of simulation parameters, gas properties, reference values, visualization of output values, etc. The block diagram of system is shown in Fig. 9.

At this point it is necessary to mention the directional control valve and reduction valve model. Models included in the Matlab-Simulink Simscape library were used to simulate these two elements. The directional control valve model is composed of four "Variable Orifice ISO 6358" blocks. The valve size can be specified using sonic conductance C and critical pressure b, which is the most accurate description of the element. The same is the case with the reducing valve model. The values of C and b were not available in this case, so the size was defined using the flow coefficient Cv.

The diagram of the real circuit is shown in Fig. 10. To verify the simulation results a test equipment was assembled. It consists of a frame to which a pneumatic cylinder is attached. The piston rod is connected to the moving part of the frame. A load can be placed on it. The frame can be tilted to a horizontal position, which allows simulating mass movement in a vertical or horizontal direction.
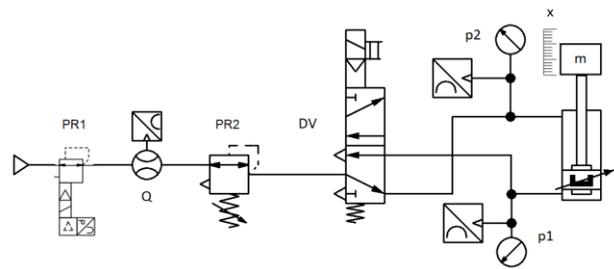

Figure 10. Scheme of the basic pneumatic circuit
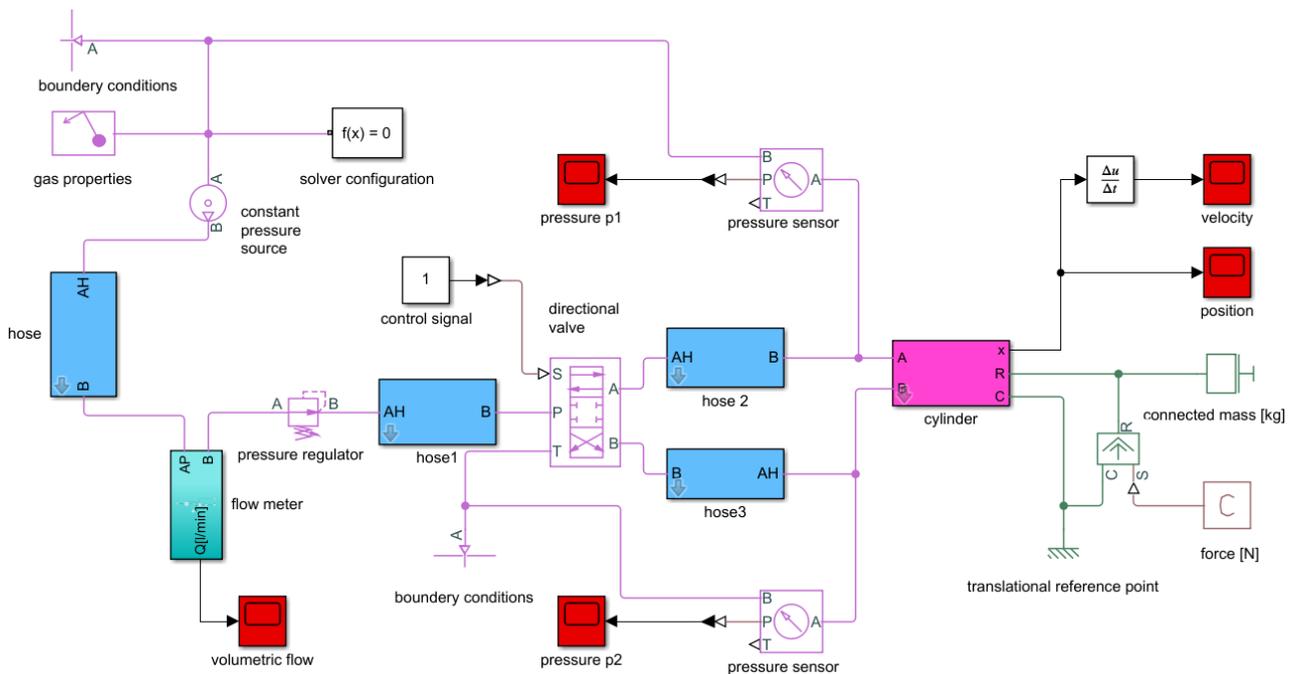

Figure 9. Block diagram of the pneumatic system model

A piston rod position sensor is fixed to the frame. Using the Hydrotechnik M5060 measuring system, the speed is calculated from the position. Furthermore, the pressure in the piston and piston rod chamber and the flow rate at the inlet to the system are measured. Fig. 11 shows photo of the entire device.

Since a constant pressure source of 0.7 MPa is used in the simulation, this was realised during the measurement with a proportional pressure regulator (in Fig. 10 - PR1) Festo VPPE-3-1-1/8-10-010-E1.

The working pressure in the system was set by a pressure regulator (PR2) from SMC EAW2000-F01D, nominal flow rate Q_n=550 dm³·min⁻¹ (Cv=0.56). To control the cylinder, a 5/2 directional control valve (DV) SMC SY3220-5LOU-M5Q was included in the system. It´s sonic conductance C=0.54 dm³·s⁻¹·bar⁻¹ and critical pressure ratio b=0.42 ware obtained by measurement.

A pneumatic cylinder according to the ISO 15552 standard with a piston diameter of 32 mm, a piston rod diameter of 12 mm and a stroke of 500 mm was chosen as the working element. The connection of the elements was realized by hoses with an inner diameter of 4 mm and a length of 1 m.
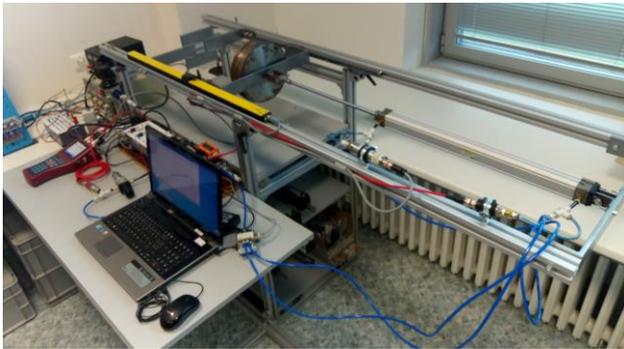

Figure 11. Test equipment - horizontal position

Fig. 12 and 13 show a comparison of stroke (position) and piston speed and pressure in the cylinder chambers. This is a case of moving a load weighing of 23 kg in the horizontal direction at a working pressure of 0.4 MPa. A further comparison is shown in Fig. 14 and 15. In this case it is a vertical movement, i.e. lifting a weight of 23 kg at a working pressure of 0.6 MPa. The graphs show a fairly good agreement between the results of the simulation and the experiment. It was similar in other cases, however, the simulations will need to be verified by a series of further experiments with other cylinders and directional control valves.

6   CONCLUSIONS

The experiment has an irreplaceable role in improving simulation models. Therefore, it is necessary to further verify the models of the pneumatic system and we plan to focus especially on the model of pneumatic damping in the end positions of the cylinders.
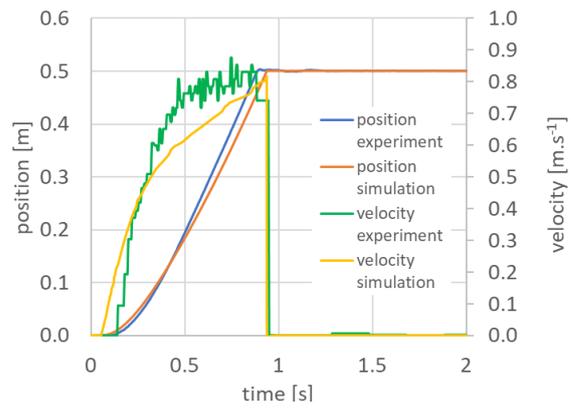

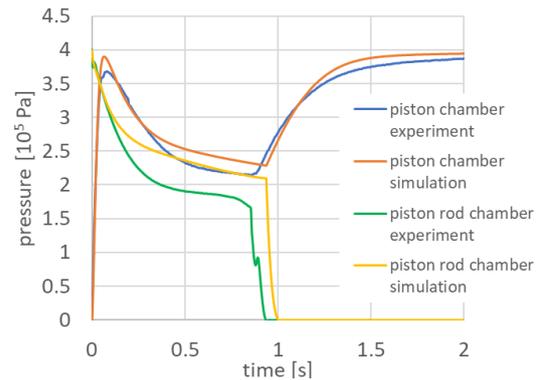**Figure 12.** Course of piston stroke and speed - horizontal movement

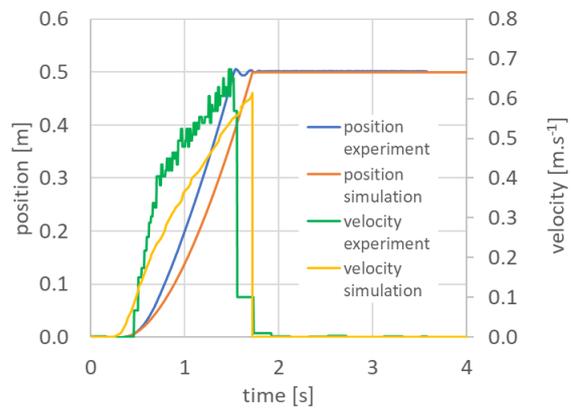**Figure 13.** Course of pressure in the cylinder chambers - horizontal movement

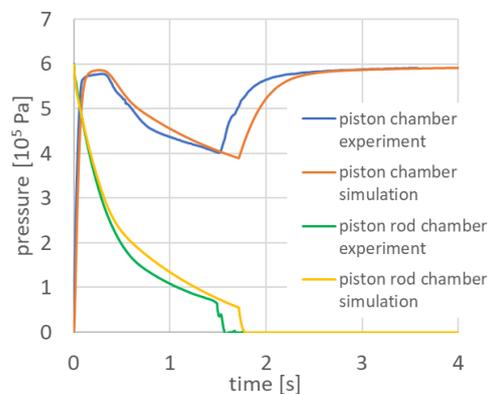**Figure 14.** Course of piston stroke and speed - vertical movement

Figure 15. Course of pressure in the cylinder chambers - vertical movement

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CONTACTS:

Ing. Lukas Dvorak, Ph.D.
VSB-Technical University of Ostrava, Faculty of Mechanical Engineering, Departament of Hydromechanics and Hydraulic Equipment
17. listopadu 2172/15, 708 00 Ostrava-Poruba
+420 597 324 314, lukas.dvorak@vsb.cz