Modelling and Simulation of Pneumatic Cylinder using Stribeck Friction

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Abstract: In modelling a pneumatic actuator it is a challenge to manage the non-linearity of the system, caused by the behavior of gas and the friction. Due to these, stick-slip may occur at low speeds as well, which is an undesirable phenomenon, as it causes the piston to move erratic. In present work we designed a model of pneumatic cylinder which applies Stribeck friction model. This model simulates properly the behavior of the cylinder not only at high speeds, but in low speed range too, as it can predict stick-slip.

Keywords: Servopneumatics, Pneumatic cylinder, Modelling, Stick-slip, Stribeck friction

1 INTRODUCTION

In position controlled drives applying pneumatic actuators is a good alternative, as they are fast, cheap, have an outstanding power-to-weight ratio and have a lot of further advantages (Földi, 2015). The challenge of using 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, these challenges can be answered with the use of a proper control algorithm.

For designing these algorithms or testing the servo system, mathematical modelling is a good solution. During the design of an appropriate model one of the key points is the applied friction model, as the friction is one source of the non-linearity of the system.

2 FRICTION MODELS OF PNEUMATIC CYLINDERS

The friction force is a resisting effect of relative motion of solid surfaces. In pneumatic cylinders it occurs between the seals of the piston and the housing. This seal is a lip type seal, with U- or V-cup shape (Figure 1.)

Fig. 1. Sectional view of double acting rodless DGPL cylinder; 1- end cap, 2- housing, 3- piston sealing (FESTO, 2012)

In pneumatic drives even in case of low speed of the piston and great external load, stick-slip may occurs. Stick-slip is an erratic movement of the piston, caused by the behavior of compressible air and friction. In references several friction models were applied. In simple friction models three elements and their combinations are used to be applied: Coulomb friction, viscous friction and static friction (Figure 2.). The simplest solution is Coulomb friction, applied as a single force in opposite direction of the movement (Saleem, 2005), (Sorli, 1999), (Taghizadeh, 2009), (Wang, 1999). The viscous friction considers the effect of the varying velocity with linear functional relationship. It is published by itself in references: (Fok, 1999), (Li, 2013), (Liu, 2013), (Qiu, 2013), the Coulomb friction combined with a viscous friction element is mentioned in (Metwally, 2013), (Rahmat, 2011). (Lin-Chen, 2003) and (Sato, 2014) uses Coulomb friction combined with stiction (static friction), and (Hamiti, 1996) combines all the three frictions in his model.

Fig. 2. Simple friction models: a) Coulomb friction, b) Coulomb friction with viscous friction, c) Coulomb+ Static+ viscous friction (Czmerk, 2015)

Beside simple friction models, there are several complex friction models as well. (Song, 1997) uses Dahl modell, (Czmerk, 2015) mentions LuGre and Stribeck models.

Fig. 3. Stribeck friction model
In our work we chose Stribeck model. Stribeck model have been chosen, which considers static and dynamic frictions, a transition between them and viscous friction in one model (Fig. 3.).

The aim of this paper is to set up a model of the double acting pneumatic cylinder, which can simulate stick-slip at low speed, using Stribeck friction model.

3 MATHEMATICAL MODEL OF PNEUMATIC CYLINDER USING STRIBECK FRICTION

To create mathematical model of double-acting pneumatic cylinder three main mathematical formulas have to be declared: the descriptive equation of the flow mass rate flowing through an orifice, the force equation and a vessel filling equation. During the deduction, the conservation laws (energy and mass), the ideal gas law and Newton 2nd law of motion were used. After some simplification, as we consider the flowing gas as ideal gas, and neglecting the effect of the temperature change, the following equation was used (Figure 4.).

Equation 1. The mass flow rate through an orifice due to the pressure difference

\[ \dot{m} = A_o \cdot p_u \cdot \frac{2 \cdot k}{(k - 1) \cdot R \cdot T} \cdot \left( \frac{p_d}{p_u} \right)^\frac{k+1}{k} - \left( \frac{p_d}{p_u} \right)^\frac{k}{k+1} \]

The mass flow rate in function of \( \frac{p_d}{p_u} \) has a maximum value at \( \left( \frac{2}{k+1} \right) = 0.528 \), so this pressure ratio is called critical pressure ratio. Below the critical pressure ratio the velocity of flow is maximal, 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.

Equation 2. The force equation of the cylinder

\[ \text{m} \cdot \ddot{x} = A_4 \cdot p_4 - A_2 \cdot p_2 - F_f - F_l \]

Equation 3. The container filling equation

\[ R \cdot T \cdot \dot{m} = V \cdot \ddot{V} + \dot{V} \cdot p \]

In the Eq. 2, the friction force is defined with the use of Stribeck friction as follows:

Equation 4. Friction force

where \( F_l = p_4 \cdot A_4 - p_2 \cdot A_2 - F_f \)

Equation 5. Stribeck friction (Fig. 3.)

4 EXPERIMENTAL APPARATUS

The pneumatic and the electric circuit diagram of the test system is presented on Figure 5. As an actuator we applied a Festo DGPL-25-450-PPV-A-KF-B double acting rodless cylinder of 450mm stroke length with recirculating ball bearing guides. The cylinder is attached to a Festo MLO-POT-0450-TLF analogue displacement encoder, which has a 0,01 mm travel resolution. The control 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. Three SDE1-D10-G2-H18 type analogue pressure sensors have been applied.

![Fig. 5. Pneumatic and electric circuit diagram of the experimental apparatus](image)

The system was controlled by an NI CompactRIO™ (cRIO 9073), a modular programmable automation controller. For data acquisition of the four 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 have been developed in LabVIEW.

6 RESULTS AND CONCLUSIONS

Based on model identification the values of the four parameters in the Stribeck friction model were:

\[
F_c = 30.5437 \text{ N} \\
F_{br} = 41.7243 \text{ N} \\
f = 22.35 \text{ Ns/m} \\
c_v = 101.25 \text{ m/s}
\]

The results of measurements and simulation with the previous parameters are shown in Figure 6-8. In the Figure 6, the stick-slip effect appears at low speed (control signal was 5V to 5.5 V, so the proportional valve was opened from closed middle position to approx. 10% forwards).

![Fig. 6. Displacement of the cylinder due to 5V to 5.5 V control signal at proportional direction valve](image)
Comparing the measured and simulated characteristics, it can be declared that model works well with the identified Stribeck friction parameters even at low speed, where stick-slip occurs.

7 SUMMARY

In modelling a pneumatic cylinder the applied friction model is a key question, as friction with the behavior of compressible gas causes non-linearity in the system and stick-slip at low speeds. There are several friction models from simple structures to complex approaches in references. In this paper our aim was to design a model of double acting rodless cylinder which can simulate properly the behavior of the pneumatic actuator even at low speed, so we chose Stribeck friction model, which considers static and dynamic friction, the transient phase between them and the viscous friction. Based on measurements and simulations, it can be declared, that Stribeck friction model works similar to the real system and with the usage of it the stick-slip phenomenon can be examined.

REFERENCES


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