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The characteristics of pneumatic piston drive

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Abstract. The article presents a study on the rodless pneumatic piston actuator. Mathematical model of the pneumatic actuator, static and dynamic characteristics are obtained and compared with the real drive characteristics.

1 Introduction

One of the primary actuators used in industry is a pneumatic drive. Due to its construction and used working medium, the drive is characterized by high dynamics of movements, resistance to overload and not very high positioning accuracy. Easy to use and high speed drive systems, especially in performing simple two state movements made pneumatic drive essential in every mass production factory. More advanced use of pneumatic drives is construction of pneumatic manipulator, which requires a much more detailed study of drive parameters, and control systems that will take into account many factors such as compressibility of working medium, friction, various cross-sections of the drive and connectors. As shown in the work of P. A. Laski[1,2], developing appropriate trajectory of pneumatic manipulator requires more advanced control system such as Fuzzy-logic controller[3].

2 Mathematical model

A common mathematical model of pneumatic piston drive is a model based on energy balance, which can be represented as follows:

$$Q_i = Q_o + dL + dU + Q_T \tag{1}$$

Where: : Q_i – flowing energy, Q_o – outflowing energy, dL – work done by the actuator, U – changes of internal energy, Q_T – energy flow to the environment.

Assuming that the temperature in the chambers is uniform, and that the working medium is a gas which meets the ideal gas law, it can be derived differential equation determining the changes of pressure in a single chamber:

$$\dot{p} = \frac{1}{V}\left(kRT_i\dot{m}_i - kRT\dot{m}_o - kp\dot{V} - \frac{pV}{T}\dot{T} - (k-1)\alpha\pi\left(Dx + 0,25D^2\right)\Delta \mathrm{T} \right) \tag{2}$$

Where heat capacity ratio $k = c_p / \mathrm{c}_v$, the gas constant $R = c_p - c_v$, D – diameter of the piston, x – the current position of the piston, ΔT – the temperature difference between the actuator and the environment.

Changes in temperature inside the chamber is obtained from the ideal gas equation differentiation:

$$\frac{dT}{dt} = T\left(\frac{1}{p}\frac{dp}{dt} + \frac{1}{x}\frac{dx}{dt} - \frac{\dot{m}RT}{pV} \right) \tag{3}$$

On the piston acts forces resulting from the pressure difference between the chambers as well as the friction:

$$\frac{d^2x}{dt^2} = \frac{1}{m}\left[A\left(p_1 - p_2\right) - F_T \right] \tag{4}$$

m – mass of piston, *A* – surface on which pressure is acting, p_1 – pressure in chamber, F_t – friction forces.

2.1 Friction

Friction is one of the most inlfuential force occurring in the piston pneumatic drives, we can distinguish the static friction - important at the beginning of the movement, and dynamic friction that occurs during the entire drive operation. Moreover compressibility of the working medium causes a phenomenon known as stick-slip, which makes piston moves in a stepped manner when at low velocity (Figure 1).

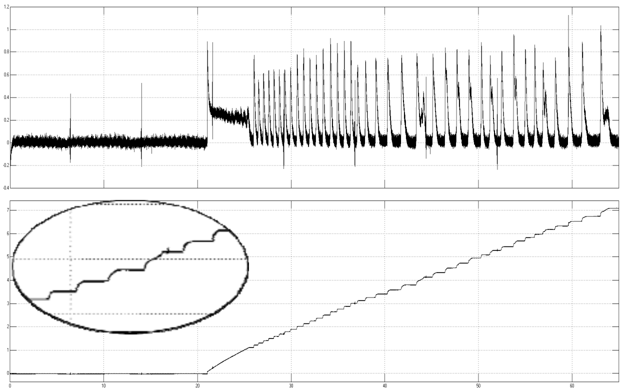

Fig. 1. Real pneumatic piston drive with stick – slip effect. Top picture – velocity, bottom – position, approximate velocity 9.34 mm/s.

There are several basic models of friction which are used to simulate behaviour of pneumatic actuators, one

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of them is a Lund – Grenoble model[4]. Equations describing LG model:

$$\frac{dz}{dt} = v - \sigma_0 \cdot \frac{|v|}{g(v)} \cdot z \qquad g(v) = F_c + (F_s - F) \cdot e^{-(v/v_s)^2}$$

$$F_f = \sigma_0 z + \sigma_1 \dot{z} + F_v v \tag{5}$$

z – average deviation bristles, v – velocity of the piston, σ_0 – stiffness of bristles, σ_1 – damping, F_v – viscous friction, F_c – Coulomb force, F_s – stiction force. This model reflects the behaviour of friction in the pneumatic drives very well, and also allows to simulate the stick – slip phenomenon, which for a very low speed of the piston makes positioning accurate very difficult.

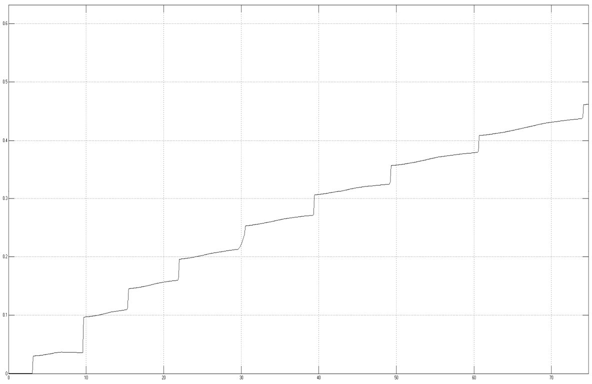

Fig. 2. Simulation of pneumatic piston drive model with Lund – Grenoble friction model (stick-slip effect).

Another much simpler approach that allows to simulate friction in pneumatic drives is a combination of Coulomb model and Stribeck curve. Usage of such a simulation model is shown on the Figure 3.

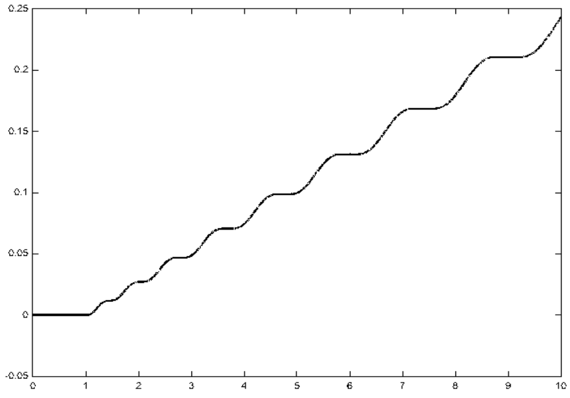

Fig. 3. Simulation of pneumatic drive model for slow movement with combined Stribeck and Coulomb friction.

2.1 Measurements

In order to present certain characteristics of the pneumatic actuator, the test rig consisting of a linear servo and pneumatic drive combined with a force sensor was developed.

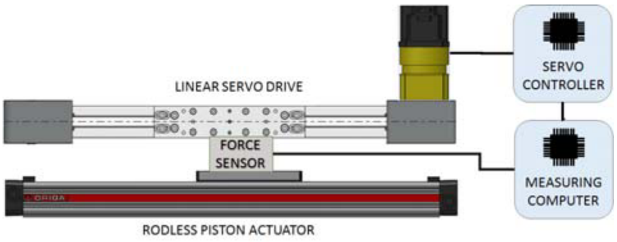

Fig. 4. Test rig for friction measurements.

The measurement process takes place automatically by increasing the speed from 1 to 450 mm / s and continuous readings measurements from the force sensor. Every single cycle generates about 5 000 measurements of friction force. In order to reduce the impact of movement changes on the measurements, 5% of the initial values are ignored and the others are subjected to moving average filter with a period equal to 5. Figure 4 shows a part of measurement cycle on which we can see changes in friction force shortly after the start of the movement.

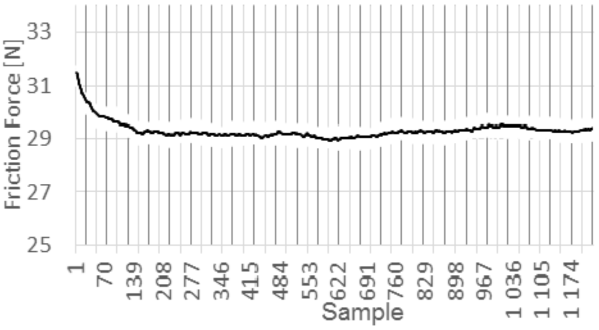

Fig. 5. Friction measurement cycle for the 2 mm/s speed.

As we can notice, the friction value is the largest right after the change of movement direction of the piston, is above all due to the construction of a seal, and a static friction value - which is highly dependent on the stopping time.

From one measurement cycle we obtain a mean value of the force. All cycles form a graph showing the relationship of the friction and velocity (Figure 5).

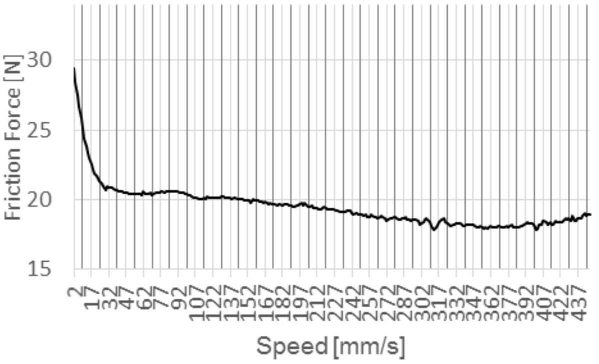

Fig. 6. The results of measuring the friction force as a function of speed.

As can be seen from the measurements, for small values of speed the resistance of the drive is the biggest. As well, it is difficult to see on the figure a point of Stribeck speed directly. This may be caused by: the surface quality of the cylinder [5], impurities, worn seals or even corrosion.

To check the impact of pneumatic actuator seals on motion resistance, the friction force measurements for the different speed of the piston subjected to varying pressure value was made.

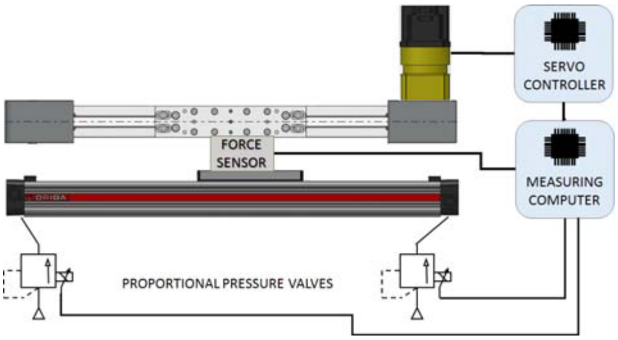

Fig. 7. Test rig for the friction force of pneumatic drive under pressure measurements.

The piston velocity was changed in the range of 1 - 500 mm / sec, and the pressure from 0.1 to 1.5 Bar which was fed to both chambers. Unfiltered measurement results shown in Fig 6.

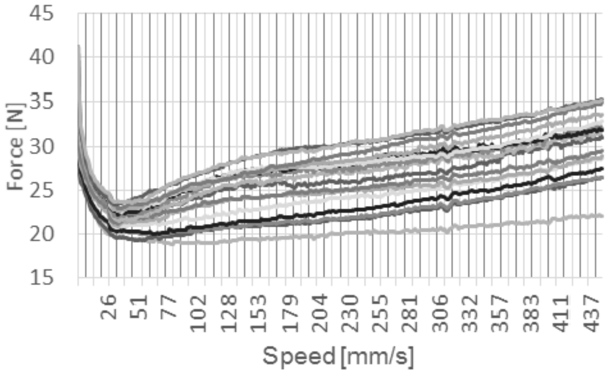

Fig. 8. The results of measuring the friction force as a function of speed for a pressure from 0.1 to 1.5 Bar. Lower line is lower pressure.

It can be seen that as the pressure increases the characteristics of the friction force are more like Stribeck curve. As a result of drive seal deformation, for low velocities, the friction value increases with increasing pressure.

3 Conclusions

The study showed that the pneumatic actuator is a very complex and sensitive to many physical elements. The performance of this drive is affected by many factors such as changes in temperature, working fluid properties, and especially the velocity of piston and how long the drive is stopped. While simple applications are not so demanding, so far attempts to precise positioning can be challenging. However, if the control of manipulator consisting of a pneumatic drive would take place along a predefined trajectory it is possible to use the predictive control based on complex mathematical model which takes into account the impact of known physical factors.

The current study was conducted in one cycle without stopping, we can say for sure that due to such action drive characteristics can maintain a specific trend directly resulting from continuous operation. Even short-term stop of the drive during the test causes a complete change of drive characteristics, an example of such middle-stop presents Figure 9.

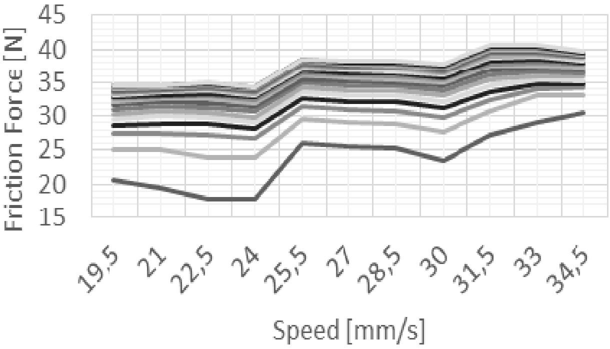

Fig. 9. Changes of friction forces during 15-seconds stops.

A particular impact on results (Figure 9) has work of the seals, which are often intentionally designed in two directions: reducing friction or reduction of leakage. Currently, technology of various kinds of seals is widely developed, which may result in the use of more complex sealing systems with reduced influence on the drive work[7-12]. Also, the use of new methods to improve the surface properties cooperating with the seal, could significantly improve the operating parameters [13]. The complexity of pneumatic drive cylinder quality, can be connected not only to the manufacturing method, but also to verification methods of desired cylinder parameters [13,14]. Another element affecting the operation of the drive is the size of connectors [15] and length of pneumatic lines whereby improper selection significantly reduces the maximum speed or dynamics of the piston.

After analysing most of factors affecting action of pneumatic piston drive, it can be concluded that for a complete description of phenomena occurring in drive, it is required to carry out a more detailed study which will take into account the measurements of friction for various durations of stopping the piston, in the function of operating pressure. In addition, measurements must be taken for a wider range of pressure connected asymmetrically, which much more corresponds to a typical drive operation. This measurement due to occurring moments that influence the non-uniform deformation of the sealing should be based also on the method of affixing the drive to the measuring system.

References

1. P. A. Laski, J. E. Takosoglu, S. Blasiak. *Design of a 3-DOF tripod electro-pneumatic parallel manipulator*. Robotics and Autonomous Systems Vol. 72, pp. 59-70, (2015)
2. P. A. Laski, J. E. Takosoglu, S. Blasiak. *Delta type closed kinematics chain with pneumatic muscle actuator manipulator*. In Fuis, V (Ed.), *ENGINEERING MECHANICS 2014* (pp. 360–363). (2014).
3. J. E. Takosoglu, P. A. Laski, S. Blasiak. *A fuzzy logic controller for the positioning control of an electro-pneumatic servo-drive*. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering Vol. 226, no. 10: pp. 1335-1343, (2012)
4. Olsson, H. *Control Systems with Friction*. Department of Automatic Control, Lund Institute of Technology, (1996).
5. L. Nowakowski, E. Miko, M. Skrzyniarz, *The analysis of the zone for initiating the cutting process of x37crmov51 steel* , Engineering Mechanics (2016).
6. L. Nowakowski, M. Wijas, *The Evaluation of the process of surface regeneration after laser cladding and face milling*, Engineering Mechanics (2016).
7. S. Blasiak, J. E. Takosoglu, P. A. Laski. *Heat transfer and thermal deformations in non-contacting face seals*. Journal of Thermal Science and Technology Vol. 9, no. 2, (2014)
8. S. Blasiak, P. A. Laski, J. E. Takosoglu. *Parametric analysis of heat transfer in non-contacting face seals*. International Journal Of Heat And Mass Transfer, Vol.57, Issue 1, pp. 22-31, (2013)
9. S. Blasiak. *The two dimensional thermohydrodynamic analysis of a lubrication in non-contacting face seals*. Journal of Thermal Science and Technology, *10*(1), JTST0016 (2015).
10. S. Blasiak. *An analytical approach to heat transfer and thermal distortions in non-contacting face seals*. International Journal of Heat and Mass Transfer, *81*, 90–102. (2015).
11. S. Blasiak., A. Pawinska, *Direct and inverse heat transfer in non-contacting face seals*. International Journal of Heat and Mass Transfer, *90*, 710–718. (2015).
12. S. Blasiak., A. V. Zahorulko, *A parametric and dynamic analysis of non-contacting gas face seals with modified surfaces*. Tribology International, 94, 126–137. (2016).
13. D. Janecki, J. Zwierzchowski, L. Cedro, *A problem of optimal cylindricity profile matching,* Bulletin Of The Polish Academy Of Sciences-Technical Sciences Vol: 63, Pages: 771-779 (2015)
14. D. Janecki, J. Zwierzchowski, *The bird-cage method used for measuring cylindricity. A problem of optimal profile matching,* XIX IMEKO World Congress: Fundamental And Applied Metrology, Proceedings Pages: 1784-1789 (2009).
15. S. Blasiak, J. E. Takosoglu, P. A. Laski. *Optimizing the flow rate in a pneumatic directional control valve*. Proceedings of 20th International Conference on Engineering Mechanics 2014, Brno University of Technology, Czech Republic, pp. 96-99, (2014)