LOAD CONTROL POSSIBILITIES OF EXPERIMENTAL LINEAR DRIVE

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The article describes a load drive extension for an existing laboratory experimental equipment for testing of linear drives with ball screw. The main aim is to simulate the static component of the load, and therefore the pneumatic actuator has been selected. The control elements (electro-pneumatic valves) and appropriate control strategies are also investigated. The experiment was performed with two valves exactly on the extended device and comprised of examining the behavior of the monitored system and basic capabilities of pressure-force regulation. The experiment set-up directly corresponds with the proposed use of this extension. The achieved results illustrate the ability of the load system to simulate primary the static forces. Finally, the adaptation and development are presented to improve not only the dynamic abilities of the loading system.

KEYWORDS

experiment, pressure control, control, pneumatics, ecodesign

1 INTRODUCTION

Linear drives with ball screw are an integral part of modern machine tools and are irreplaceable in terms of design in most cases [Marek 2015]. Therefore, development of this linear technology and the technology meant to increase the accuracy of the operation and energy efficiency of linear drive still continues. This is related to adapting drive topology solutions for specific production machine. The generation and reduction of vibration of machine tools is an ever researched topic [Brezina 2015] in order to increase the quality of machining. In recent years, increasing energy efficiency is becoming increasingly important. The rise of energy prices is not the only reason why customers are interested in energy-efficient equipment, but also the government's strategy for future development valid not only in the EU [Fischer 2014] – so called Eco-design.

In addition to theoretical processing of the issue, the results also must be verified by an experiment during designing new control strategy as well as structural modifications of the linear drive. The experimental devices are generally used for verification of the theoretical assumptions that allows to test new methods under various working conditions [Kamalzadeh 2007, Wang 2013]. An external load is an important factor for linear axis testing. This allows better simulation of the different working conditions on a real machine, with particular emphasis on the positioning accuracy of the linear axes [Knobloch 2015]. The load is necessary simulated by another so-called analogous actuator, which is controlled by a separate control system or is included in the control system of the linear drive.

2 LOAD TESTING OF THE BALL SCREW

The author's research and development team deals with the testing of experimental equipment with linear drive with ball screw, which was developed and implemented there for this purpose. The device serves as an educational and research model of one positioning axis which is commonly used in production machines. The equipment can be used for verification of the control algorithms focused on improving positioning accuracy and power measurements [Mohammad 2014, Huzlik 2014]. The equipment is additionally possible to equip with two motors on both sides of the ball screw. It is therefore possible to test double (redundant) actuation and compare the operational characteristics with conventional actuation. The control system is based on the Beckhoff platform. The experimental equipment is shown schematically in Fig. 1, where the construction and motor driven by Beckhoff system are grayed out. The load force is caused by load actuator with the controller, which is based on the National Instruments platform. The load system is highlighted in red in the diagram.

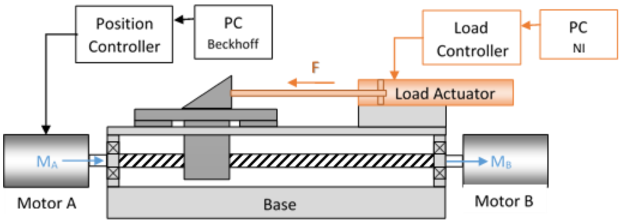

Figure 1. Scheme of the experimental equipment for testing of the linear drive with ball screw

The opportunity to test experimental equipment under specific load is important in order to verify the capability of the control system to operate the drive unit correctly under various operating conditions. The forces acting on the linear drives can be divided into two basic types – static and dynamic. Static load is caused by gravitational forces and the cutting force, typical for the machining process. More specifically, the force of the cutting process involves static and dynamic components. The static component is equal to the mean value in the direction of positioning axes. The dynamic component is formed by chip machining, each tooth with a cutting edge on the tool produces a dynamic force. These dynamic forces are often approximated by sinusoidal waveforms with frequencies in tens to hundreds Hertz. The purpose of this work is to study the means and methods for controlled load of the presented experimental equipment with a focus on static component of the load force.

The choice of an actuator for controlled loading is crucial in the design phase, because it defines the characteristics and control methods. Three different conventional drives can be used. The linear electromagnetic actuator can be easily controlled to a constant force and therefore be able to adjust the load profile during the test. Its main disadvantage is its high price, compared with the achievable static forces. Additionally, in the case of static forces the load actuator is heated and an excessive transmission of heat to the test drive is possible. Despite the relatively good dynamic properties of the drive, it is not capable of simulating the dynamic forces typical for the cutting process. The second possibility is a hydraulic actuator [Shi 2015], which can otherwise be used as load balancing. A parallel connection of the hydraulic actuator and ball screw driver is often used to reduce energy consumption and to increase the dynamics of production machines. The third possibility is a pneumatic actuator [Driver 2013], which is structurally similar to the hydraulic actuator, but it provides a higher degree of flexibility. Moreover, it is less demanding on the completion and operation. Many authors [Driver 2013, Taghizadeh 2009, Mehmood 2010, Taghizadeh 2008] are currently interested in the possibilities of controlling the pressure in pneumatic cylinders specifically because of the low prices and high energy density of this drive. These results suggest that the pneumatic actuators are applicable in many applications where other types of actuators has been previously used.

3 ANALYSIS OF THE BALL SCREW LOADING

Based on previous findings and also taking into account available resources, the pneumatic actuator is selected as the load driver. However, there are several variants – valves, which can control the position or force of the pneumatic cylinder.

3.1 Proportional pressure control valve

Use of a proportional pressure control valve is the simplest option. These devices operate on the basis on a linear 3/2 valve and measuring the pressure feedback. The control is implemented inside the device, and it usually is not possible to modify any of its parameters. Another problem are the dynamics of these valves. Due to the typical use of these devices, their dynamic is not fast enough for loading linear drive.

3.2 Fast switching 3/2 valve

A possibility of using the classic switching valves for positioning is presented by the authors [Taghizadeh 2009, Hodgson 2012] and many others. The basic idea is to minimize the number of actuators. In the extreme case it is possible to use only a single 3/2 valve which greatly reduces drive cost. However, the main problem of this solution is the number of valve switching per second. Based on the test, the authors report approximately 200 switching per second. The life of the valve then drops to the level of 500 hours. Even then the solution is acceptable for laboratory conditions. The authors use fast switching valves with switching speed under 1ms. Feedback control system is called sliding mode controller, which is based on the idea of fuzzy controller. Conclusion of the research indicates that three control states are minimum in order to be able to control the system. However, more preferable results are achieved with seven different control states that include information from both the encoder and the pressure sensor in the chamber of the cylinder.

3.3 Valve with spool controlled position

Papers [Driver 2013, Situm 2013] contains nearly identical pneumatic system, but the valve with spool position control is used. This valve contains an internal control loop that controls the position of the spool. This regulates the amount of air that flows through the valve. Work is concentrated on controlling the system with knowledge of the dynamic model. This, much like the sliding mode control approach, typically achieves better control results of pneumatic systems than conventional linear controllers. This is due to the nonlinear behavior typical for pneumatic systems. The paper [Driver 2013] is based on a unique algorithm of estimating the pressure in the chamber of the cylinder. With this estimate very respectable results in the force control of pneumatic cylinders is achieved.

3.4 Proportional 3/2 valve

Valves with special construction can also be used. E.g. 3/2 valve used for controlling the pressure in braking and similar systems. The valve has properties similar to the valve with controlled spool, however, the supply voltage is applied directly to the coil. Due to this control, it is possible to bypass spool controller and control the entire control structure of the system with minimal delay. Next advantage of this valve is the lower price when compared to the valve with controlled position spool The disadvantage of this particular valve is minor leakage of air through the valve to the vent, which due to its own design. For this reason, the valve use is limited for some applications. .

3.5 Evaluation

The pneumatic actuator has the potential of sufficiently precise load control, as herein reference demonstrate. While at the same time some flexibility is allowed which is advantageous for the proposed application. It may be recalled, that the aim of the paper is to simulate static components of load. Therefore, the pneumatic actuator is chosen as the proposal for the devices for controlled loading of the linear drive with the ball screw. Additional factor in actuator selecting is the current availability of the needed components and equipment for implementation of the load actuator at the workplace.

Also, the pneumatic circuit, the position of pressure sensors, pneumatic resistance in routes and another parameters are play similarly important role. It is therefore desirable to minimize flow delays between the valves – the pressure sensors and to minimize pneumatic resistance of the cylinder inlet.

4 THEORETICAL ANALYSIS OF THE PRESSURE REGULATOR

The force control of the pneumatic actuator can be realized by using a force sensor connected to the piston rod or pressure sensor at cylinder inlet, which is also needed. Ignoring the effects of friction in the cylinder, then the pressure in the cylinder chamber is directly proportional to the force and can be expressed as [Driver 2013]:

$$\mathrm{F} = \mathrm{p_a A_a} - \mathrm{p_b A_b} - \mathrm{p_{atm} A_r} \tag{1}$$

Where P_a and P_b are absolute pressures in a chamber and P_{atm} is the atmospheric pressure, A_a and A_b are effective surface of each side of the piston and A_r is the area of the rod. The friction in the cylinder can be ignored if the friction force is considerably minor to the force caused by the piston. This of course depends on usage. However, this can be difficult to predict without direct information about power or position and therefore it is only possible to perform the verification of possible omission.

The pressure change is dependent on the position change of the piston and of the piston and the cylinder filling by control valve. The pressure change depending on the piston position, which is primarily dependent on the position of the loaded actuator, can be expressed as [Wang 1999]:

$$\acute{p}_a = -k p_a \left(\frac{x_a}{\acute{x}_a}\right) \tag{2}$$

Where P_a is the pressure in the chamber, x is the position of the piston and k the thermal constant. Similar equation can be written for the pressure change in the chamber b. However, in both cases it is necessary to consider that the position x is calculated from the edge of the each chamber. Position x_a is zero when the volume of the chamber is equal to zero.

Pressure change depending on the filling can be described as:

$$\acute{p}_a = \frac{kR\acute{T}_s}{A_a x_a} w f\left(\frac{p_0}{p_a}\right) \tag{3}$$

Where R is air constant, T_s is the temperature of the source air, w is the control signal, $f\left(\frac{p_0}{p_a}\right)$ is the function describing the mass flow rate as the function of pressure, where P_0 is the source pressure if the chamber is filled, or atmospheric pressure when the chamber is left open. The function $f\left(\frac{p_0}{p_a}\right)$ can in some cases be expressed analytically, provided we know sufficiently precisely controlled valve geometry [Wang 1999], or experimentally [Driver 2013, Taghizadeh 2008].

Based on this description, the model control strategy can be applied. This usually achieves improved control parameters than the traditional linear controllers. However, knowledge of the piston position is necessary for this use. This position is unknown given the current control system of the linear drive in its current state. Nevertheless, the Beckhoff control system of the linear drive allows for limited communication with other platforms using the ADS communication, which can be used to obtain the position value of the drive. However, the acquisition and transmission of data over a network is unfortunately affected by a nonnegligible delay of 5-8ms. This is due to the API available for LabVIEW. For this reason, the system usage is functionally limited and a more preferable solution would be to transfer the control of the linear drive on one platform together with the load controller.

5 LOAD CONTROL EXPERIMENT

To verify the applicability, several experiments were performed with the available devices. Specifically, SMC IPV-1050-31F2N-Q proportional valve with internal pressure control was tested. The second valve is designed as proportional 3/2 valve for the use in brake systems in the automotive industry. The pneumatic scheme is shown in Fig. 2.

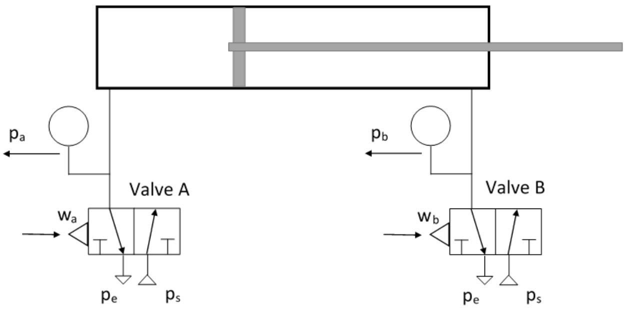

Figure 2. Pneumatic scheme of the load system

The experimental linear drive with the device for loading is shown in Fig. 4. The experiment conditions directly correspond to the expected use. Thus, the pressure in the chamber of the pneumatic cylinder is regulated at constant value during the volume change of the chamber, or the position change of the piston. The tested cylinder has diameter of 50mm and length of 500 mm. The test sequence was the shift from the position of 100 mm to 400 mm with maximum speed of 50-250 mm/s, acceleration of 3,000 mm/s and with a one-second waiting on each end. The sequences were performed at different pressures in range of 0.3-2 bars.

5.1 *Tested valves*

The proportional valve with internal regulation only requires the determination of the value of the desired pressure. This was determined by voltage from an external source. No control parameters can be changed or read.

Control system for the proportional 3/2 valve is based on the platform NI cRIO9164 with I/O module NI9475 and NI9215. NI9475 is digital output module with possibilities of direct DC motors connection or coils switching. The valve has been powered by PWM generated by FPGA. Pressure sensor Keller PR-33x is used as the feedback sensor connected via the analog input module NI9215. The scheme of the system is drawn in Fig. 3. Based on the basic test of the capabilities of the valve and limitation of using two different platforms, linear PID controller has been implemented. The sampling frequency is 1 kHz, as well as the PWM frequency. PWM resolution is up to 1024 values.

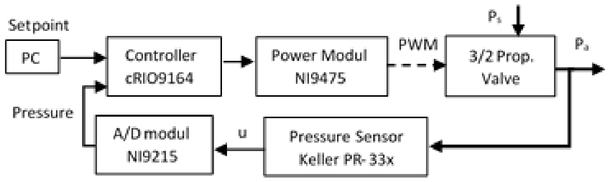

Figure 3. Proportional valve control system scheme

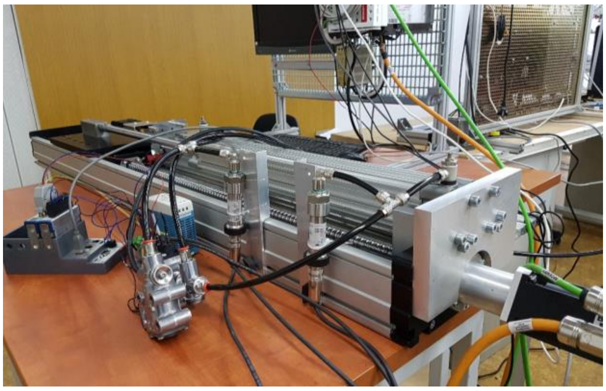

Figure 4. Device for testing of the ball screw drive

6 TEST RESULTS

The controller was tuned using the Ziegler-Nichols method with a view to minimize the RMS value of the pressure during the test sequence. The results comparing the pressure progress during the test sequence are shown in Fig. 5 and 6, where are desired values 2bar - red, 2.05bar - black.

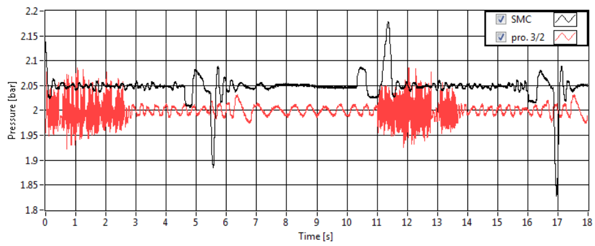

Figure 5. Max speed of 50mm/s

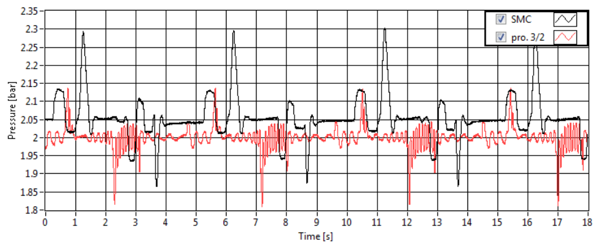

Figure 6. Max speed of 150mm/s

Additional tests indicated that with increasing pressure and speed of the piston the proportional 3/2 valve reaches significantly lower RMS deviations, up to the half of the original value. Moreover, the control system with proportional 3/2 valve reacts much faster to pressure change as can be seen in Fig. 5 and 6.

The results show that the SMC proportional valve is no longer able to achieve higher dynamic pressure stabilization. Whereas the implemented control system with proportional valve 3/2 already achieved more satisfactory results, and has the potential to achieve further improvement in stabilization of pressure, assuming the use of model-based control strategy.

7 CONCLUSION

The paper presents the proposal of the suitable actuator and control strategy for load system of the experimental linear drive with focusing on simulation of static components of load. Based on the research, the pneumatic actuator which is able to achieve sufficient precision, dynamics and low cost of implementation was selected. The model-based control strategy is the most appropriate for controlling the pneumatic actuator, since it provides the best results due to the nonlinear behavior of pneumatic systems. Model-based control strategy requires knowledge of the piston position in real-time. In the case of the separate control system controlling the pressure in the pneumatic cylinder, the information regarding the piston position is problematic to obtain. It is ideal to include load controller and positioning controller of linear drive in a single system.

The experiments performed with pneumatic valves demonstrate limited ability of proportional pressure control valves. These are limited primarily by low dynamics and highly limited access to regulation. The second tested system based on proportional 3/2 valve is used for the implementation of a system for controlled loading of the experimental linear drive, which in principle allows to extend the control structure to model-based control strategy. This idea will be investigated in future research focused on improving the simulation of the static force component.

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REFERENCES

[Brezina 2015] Brezina, T., at al. Improvement of heavy machine tool dynamics by passive dynamic vibration absorber, MM Science Journal, December 2015, vol. 2015, no. 04, pp. 838–845, DOI: 10.17973/MMSJ.2015_12_201545, ISSN 18031269

[Driver 2013] Driver, T. at al. Pressure Estimation-Based Robust Force Control of Pneumatic Actuators, Int. J. Fluid Power, Jan. 2013., vol. 14, no. 1, pp. 37–45, ISSN 1439-9776

[Fischer 2014] Fischer, C. Preparatory Study to establish the Ecodesign Working Plan implementing Directive Draft Task 1 Report Document information Or, no. October 2014, pp. 1–48

[Hodgson 2012] Hodgson, S. at al. Improved tracking and switching performance of an electro-pneumatic positioning system, Mechatronics, Feb. 2012, vol. 22, no. 1, pp. 1–12, ISSN 09574158

[Huzlik 2014] Huzlik, R. at al. Device for Measuring of Active Power and Energy at Machine Tools, in Mechatronics 2013, Cham: Springer International Publishing, 2014, pp. 503–509, ISBN 978-3-319-02294-9

[Kamalzadeh 2007] Kamalzadeh, A. at al. Compensation of Axial Vibrations in Ball Screw Drives, CIRP Ann. - Manuf. Technol., 2007, vol. 56, no. 1, pp. 373–378, ISSN 00078506

[Knobloch 2015] Knobloch, J. at al. Error motion analysis of machine spindle under load, MM Science Journal, December 2015, vol. 2015, no. 04, pp. 744–747, DOI: 10.17973/MMSJ.2015_12_201554, ISSN 18031269

[Marek 2015] MAREK, J. “Designing process,” in Design of CNC Machine Tools, Praha: MM publishing, 2015, pp. 24–34. ISBN 978-80-260-8637-6

[Mehmood 2010] Mehmood, A. at al. Nonlinear Modeling of the VNT Pneumatic Actuator with Aero-dynamic Force, IFAC Proc., 2010, Vol., vol. 43, no. 7, pp. 518–523, ISSN 14746670

[Mohammad 2014] Mohammad, A. E. K. at al. Reduction of Electrical Energy Consumed by Feed-Drive Systems Using Sliding-Mode Control With a Nonlinear Sliding Surface, IEEE Trans. Ind. Electron., Jun. 2014, vol. 61, no. 6, pp. 2875–2882, ISSN 0278-0046

[Shi 2015] Shi, H. at al. Coordination control for parallel actuation of hydraulic power assisted ball screw drive system, in 2015 IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), pp. 1010–1014, ISBN 978-1-4799-1979-6

[Situm 2013] Situm, Z. Control of a pneumatic drive using electronic pressure valves, Trans. Inst. Meas. Control, Dec. 2013, vol. 35, no. 8, pp. 1085–1093, ISSN 0142-3312

[Taghizadeh 2008] Taghizadeh, M. at al. A Linearization Approach in Control of PWM-Driven Servo-Pneumatic Systems, in 2008 40th Southeastern Symposium on System Theory (SSST), pp. 395–399, ISBN 978-1-4244-1806-0

[Taghizadeh 2009] Taghizadeh, M. at al. Improving dynamic performances of PWM-driven servo-pneumatic systems via a novel pneumatic circuit, ISA Trans., Oct. 2009, vol. 48, no. 4, pp. 512–518, ISSN 00190578

[Wang 1999] Wang, J. at al. A practical control strategy for servo-pneumatic actuator systems, Control Eng. Pract., Dec. 1999, vol. 7, no. 12, pp. 1483–1488, ISSN 09670661

[Wang 2013] Wang, Y. at al. Experimental Investigation on Thermal Characteristics of Hollow Ball Screw in Different Working Conditions, Adv. Mater. Res., 2013, vol. 690–693, pp. 3266–3270, ISSN 1662-8985

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