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STIFF ELECTROHYDRAULIC DRIVES USING A HYBRID VALVE

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ABSTRACT

One of the main problems of electrohydraulic drives is relatively low dynamic load stiffness due to compressibility of oil. Sudden load variations can cause significant deviations of the position of the drive and, consequently, a reduced precision of the controlled process. This has led to a partial substitution of electrohydraulic drives by electromechanical drives in a low power range recently.
One of the approaches to increase dynamic stiffness of a cylinder is to raise valve dynamics. Thus, the system can react to a control deviation and provide the cylinder with a compensating flow faster.
The objective of this paper is to show the development of a stiff cylinder drive using a new high-response servovalve - the hybrid valve. In contrast to a conventional servovalve with an unmovable sleeve, the idea of the hybrid valve is to actuate both the spool and the sleeve simultaneously in opposite directions. Using a piezo-actuator as sleeve drive provides the hybrid valve with very high dynamics in the range of small valve opening, which should be sufficient to increase the disturbance rejection of the cylinder. The performance of the valve prototype and of the cylinder will be shown, and application fields will be discussed in this work.

KEY WORDS

Cylinder Stiffness, Position Control, Servovalve, Hybrid Valve, Piezo-Actuator

INTRODUCTION

An electrohydraulic linear drive which is operated by a control valve and subjected to an external dynamic load deviates from its reference position until the load is balanced by the increased pressure in the counteractive cylinder chamber. The balancing pressure increases due to a compression of oil in the chamber on the one hand and compensating flow provided by the control valve on the other hand. The ratio of the external dynamic load and the deviation of the drive position due to this load is called dynamic load stiffness. The higher is the stiffness, the more precise control of the drive can be achieved in any manufacturing processes.
The dynamic load stiffness of the electrohydraulic linear drive depends on many factors. Some of them are oil compressibility (oil type, dissolved air in oil), dead volume between the drive and the control valve, drive leakage, friction, availability of accumulators, mechanical backlash between the drive and the driven object, strategy and sampling of the controller, resolution and dynamics of the sensors involved in the control loop as well as static and dynamic characteristics of the control valve [1]. The focus of this paper is the improvement of drive performance by use of a novel control valve – the hybrid valve.

CONCEPT AND DESIGN OF THE HYBRID VALVE

The idea of the hybrid valve is to actuate both the spool and the sleeve, whereas in conventional servovalves the sleeve is fixed. Due to a simultaneous actuation of both parts in opposite directions the control orifices can be opened and closed faster [2]. This enables the hybrid valve to provide the cylinder with a compensating flow faster and therefore to reduce the position deviation during dynamic load variation.

Figure 1 shows the concept of the hybrid valve. Here the spool is driven by a relatively slow conventional valve actuator known as a permanent magnet linear force motor with a large stroke (±0.5 mm), whereas the sleeve is driven by a fast piezo-actuator with a short stroke (approx. 10% of linear force motor stroke).

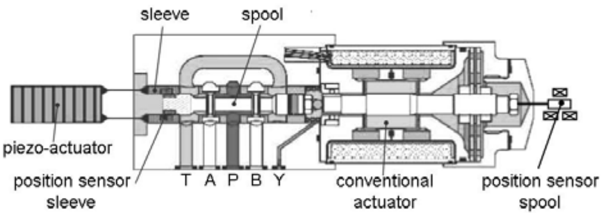

Figure 1 Hybrid valve concept

Spool and sleeve should both be driven in closed position control loops to compensate for the disturbances due to flow and friction forces. Therefore two position sensors should be integrated into the valve measuring spool and sleeve movements.

Besides excellent dynamics, the hybrid valve offers the advantage of high resolution for a small operating signal. Thus, 10% of the valve flow rate can be controlled with a piezo-actuator resolution which is limited by the command signal condition only.

The design of the hybrid valve is based on the modification of a conventional direct drive servovalve D636 by Moog [3] with a nominal flow rate of 37 l/min at a pressure drop of 70 bar over two control orifices.

The piezo-actuator is a low voltage, mechanically prestressed stack actuator (P-843.60) with an integrated position sensor by PI [4]. The position sensor is a Wheatstone bridge of strain gauges bonded to the piezo-ceramics. A membrane sealing has been designed to protect the actuator from oil as this type of piezo is hydrophobic.

The position sensor of the spool is a linear variable differential transformer (LVDT). In contrast to the original design of the valve the sensor has been attached to the armature of the linear force motor directly (s. Figure 1) in order to allow the mounting of the piezo-actuator.

The connection of the spool to the linear force motor remained unmodified as a form-locked join in the conventional valve. The connection of the sleeve to the piezo-actuator has been designed as a force-locked join. The sleeve is pushed by the piezo-actuator in one direction only and retracted by stiff plate springs. The force-locked join compensates possible misalignment of the actuator and the sleeve due to manufacturing inaccuracy.

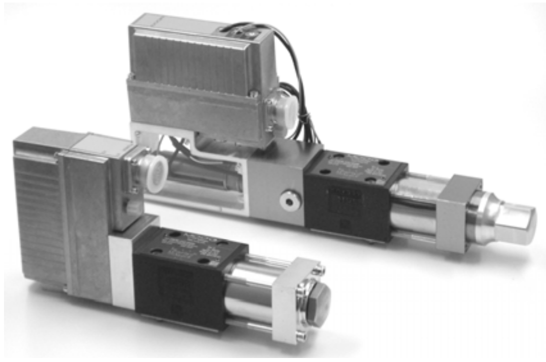
Figure 2 Conventional valve and hybrid valve prototype

Figure 2 shows the conventional valve in front and the hybrid valve prototype in the background. All parts of the prototype except for the original valve parts have been manufactured at IFAS.

PERFORMANCE OF THE HYBRID VALVE

In the following static and dynamic performance of the hybrid valve is shown. All the measurements were been carried out according to ISO 10770-1 [5] with a supply pressure of 140 bar.

Figure 3 presents pressure gain curves of the conventional valve and the hybrid valve. Due to a higher internal leakage of the hybrid valve its pressure gain curve has a slightly smaller slope in the region of hydraulic zero-point.

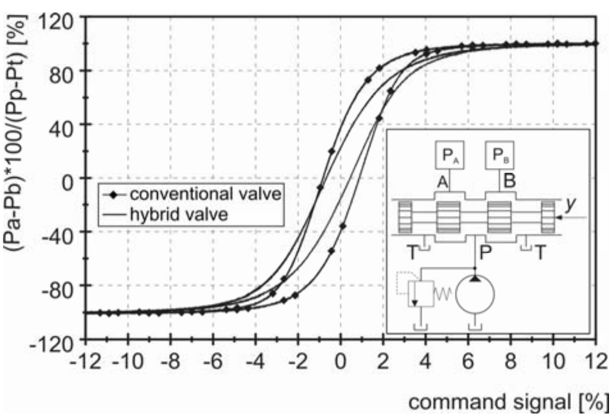

Figure 3 Pressure gain

In order to increase load stiffness of a drive the pressure gain of the valve should be as high as possible. The reduced pressure gain of the hybrid valve will be compensated by its high dynamics.

Figure 4 shows flow gain curves of the conventional valve and the hybrid valve at a constant pressure drop of 70 bar over two control orifices for a command signal of 10%. It can be seen that the slope of the curves is nearly the same in this region of the valve opening. However a smaller hysteresis of the hybrid valve due to an exact control of the piezo-actuator can be clearly recognized in the pressure and flow gain curves. In general the smaller is the hysteresis of a control valve, the higher is the precision of the pressure, velocity and position control of a drive [6].

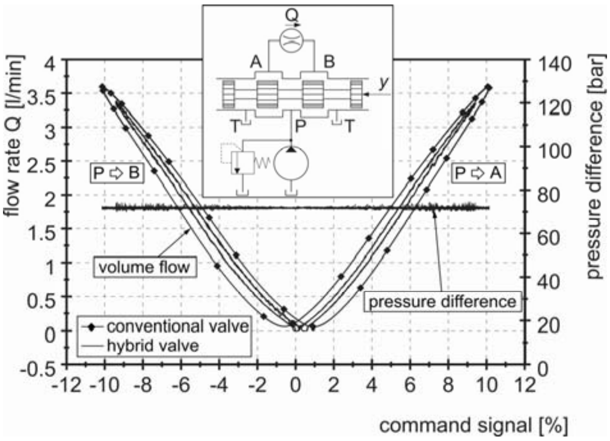

Figure 4 Flow gain

Step responses of both valve actuators are shown in Figure 5. The working ports A and B were blocked during the test. The response time of the piezo-actuator is 10 times faster than that of the linear force motor in the characteristic stroke ranges.

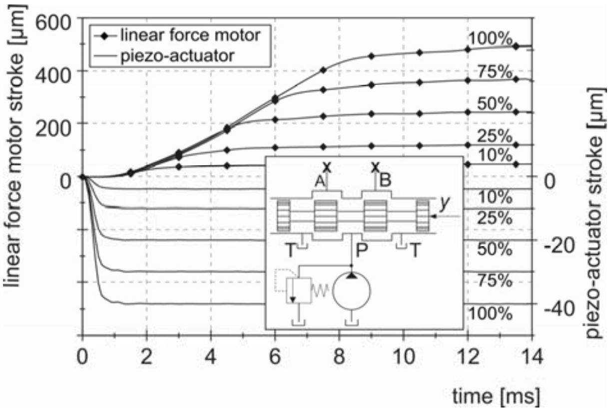

Figure 5 Step responses

Figure 6 and Figure 7 present frequency responses of hybrid valve actuators. Here a continuous sine sweep command signal from 10 Hz to 500 Hz has been applied at different levels. The signal level - 5% and 90% - refers to the nominal stroke amplitude of the actuators (±0.5 mm for linear force motor and ±40 µm for piezo-actuator).

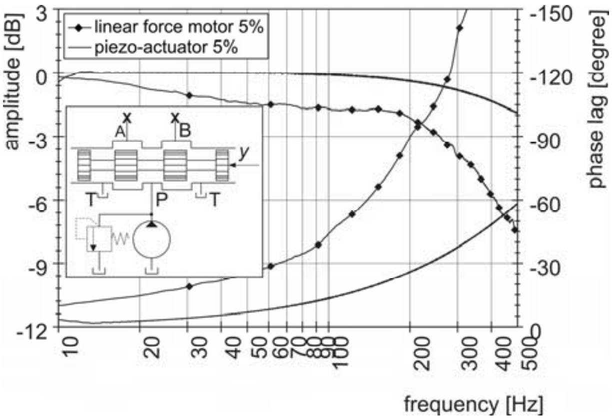

Figure 6 Frequency response of 5%

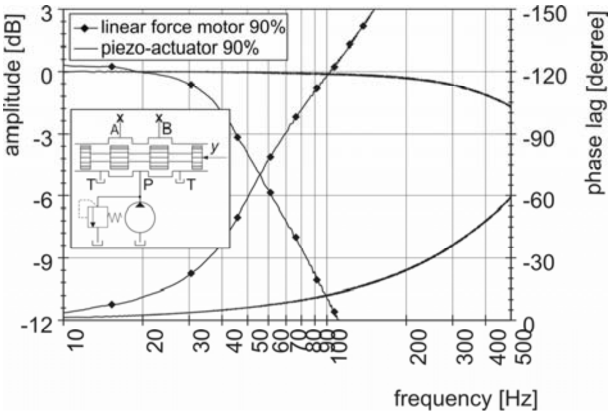

Figure 7 Frequency response of 90%

Whereas the frequency response of the linear force motor decreases with a rising signal level, the piezo-actuator shows nearly the same performance independently of signal level in this frequency range. The high dynamics of the sleeve actuation should raise the response of the valve and increase the load stiffness of the controlled drive.

DRIVE CONTROL STRATEGIES

In this section different position control strategies of an electrohydraulic linear drive are discussed.

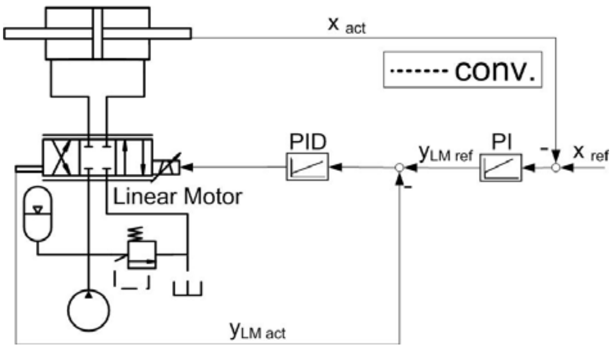

Figure 8 Conventional position control

A simple conventional position control circuit implies a main control loop with a position feedback of the cylinder and a subsidiary position control of a single valve actuator (i.e. linear force motor) (s. Figure 8). The reference signal of the linear force motor $y_{LM\ ref}$ is generated by a PI-controller.

As the hybrid valve has two actuators both of them should be integrated into the drive control loop. The first approach (s. Figure 9) is based on the compensation of a cylinder position error by the piezo-actuator directly. For this reason the reference signal of the piezo-actuator $y_{P\ ref}$ equals the reference signal of the linear force motor $y_{LM\ ref}$ with an opposite sign. There are also subsidiary position control loops of the both valve actuators. The position controller of the piezo-actuator has been implemented as a PI-controller and has been discussed in [7]. This approach is called here “HV cylind.”.

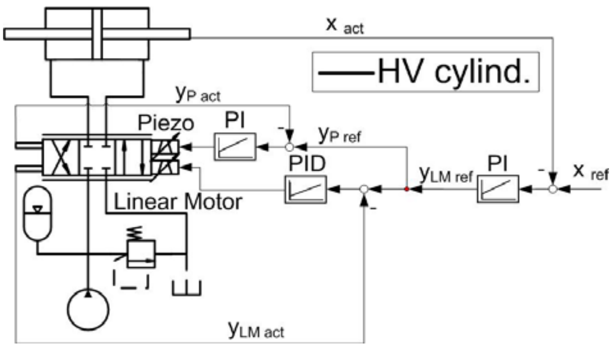

Figure 9 Position control with strategy “HV cylind.”

The second approach (s. Figure 10) relies on the compensation of a linear motor position error by the piezo-actuator. Thus the piezo-actuator contributes to the position control of the drive indirectly. Here the reference signal of the piezo-actuator $y_{P\ ref}$ equals the position error of the linear motor ($y_{LM\ ref}$ - $y_{LM\ act}$). The name of this control strategy is “HV linmot.”.

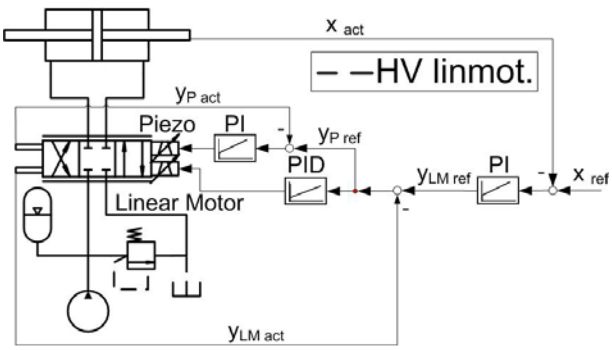

Figure 10 Position control with strategy “HV linmot.”

The advantage of the approach “HV cylind.” is the fact, that the piezo-actuator keeps the valve open until the cylinder position error is reduced to zero. This provides the cylinder with a maximum velocity during the whole response time. In contrast to this the approach “HV linmot.” brings the piezo-actuator to its zero-point very quickly after the position error of the linear force motor has been compensated. So the time of maximal valve opening in this case is shorter and the drive reaches the desired position later (s. Figure 12).

DRIVE PERFORMANCE

For the investigation of drive performance in terms of reference response and disturbance rejection a test rig (s. Figure 11) was built at IFAS. The cylinder at the bottom is a test cylinder which is investigated and can be controlled by the conventional valve or the hybrid valve. It is a low friction state-of-the-art cylinder with an annular gap sealing by Haenchen [8] for challenging control applications. The test cylinder has a stroke of ±25 mm and possesses an integrated position measurement system (LVDT). The control valve is mounted on the test cylinder directly. There are accumulators on the pressure supply line and tank line to reduce pressure variations in these lines near the drive.

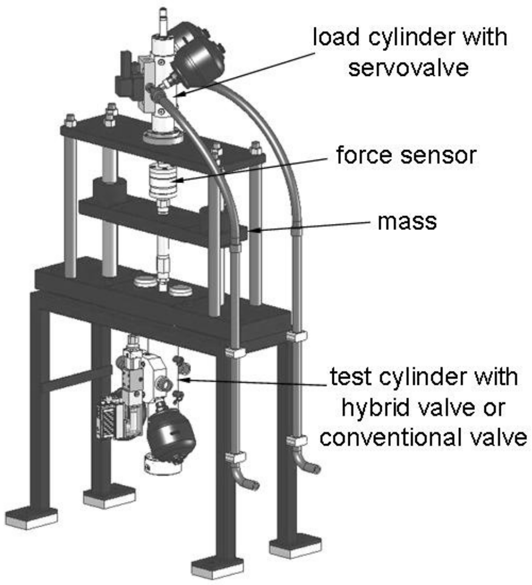

Figure 11 Test rig

The test cylinder is operated in a position control. The disturbance for the test cylinder can by applied by a load cylinder on the top of the test rig. The load cylinder is driven by a high response servovalve D769 by Moog [9] in a force control. The test rig offers a good flexibility in changing the load level and the time constant of the load change. Furthermore it is possible to attach an adjustable mass on the test cylinder and to vary its eigenfrequency. The control circuit has been implemented on a DS1103 PPC controller board by dSPACE [10] and operates at a sampling rate of 10 kHz.

Figure 12 shows the strokes of the valve actuators and the reference response of the test cylinder controlled by the conventional valve and by the hybrid valve with two different control strategies. Here a step reference signal X_{ref} has been applied to the unloaded test cylinder. It can be seen that the cylinder controlled by the hybrid valve with strategy "HV cylind." reaches the reference position faster. The stroke of the linear force motor and the piezo-actuator is approximately in the same range. The improvement of the response compared to the conventional system can be estimated to 30%. Due to the limitation of the piezo-actuator stroke this improvement reduces for higher steps of the reference signal.

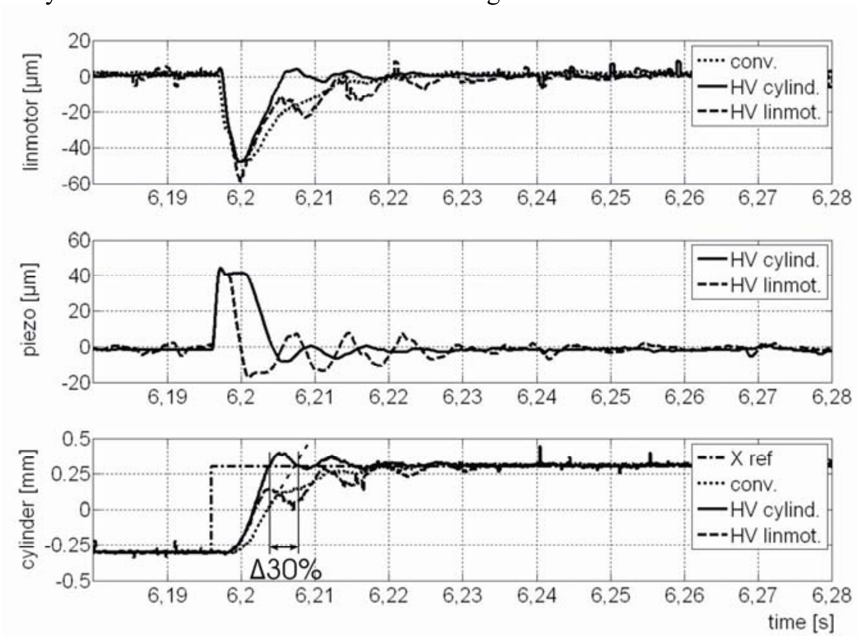

Figure 12 Reference response of the test cylinder

The disturbance rejection of the test cylinder is presented in Figure 13. Here a dynamic disturbance force of 10 kN, which is 90% of the maximum load force at the given supply pressure of 100 bar, has been applied on the test cylinder by the load cylinder. Two curves in the middle of the figure show the strokes of the valve actuators. The position deviation of the test cylinder is presented at the bottom of the figure. The deviation can be reduced by 26% when the test cylinder is controlled by the hybrid valve with a strategy "HV cylind.". Thus the dynamic load stiffness of the drive has been improved by 26%.

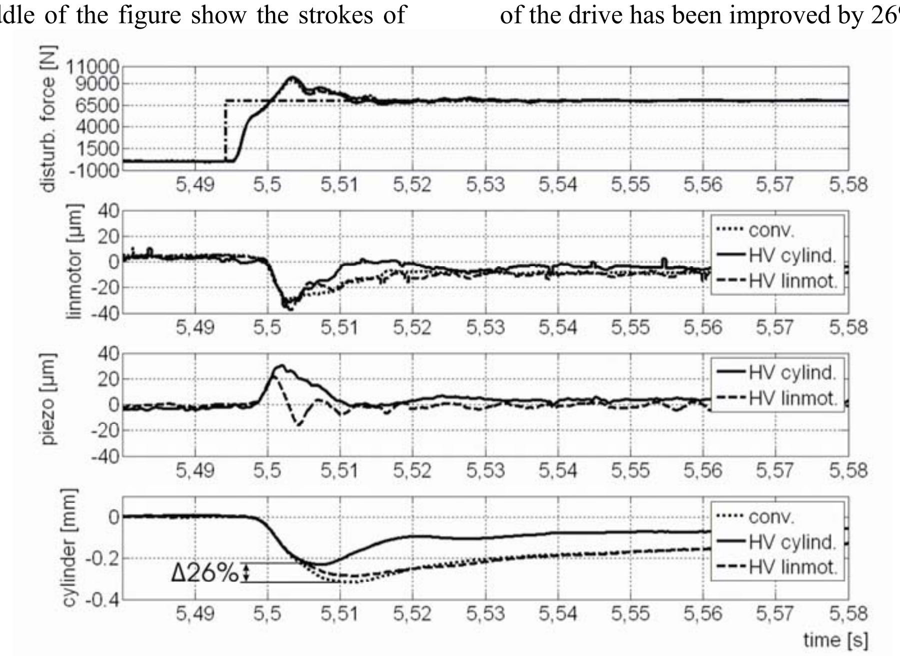

Figure 13 Disturbance rejection of the test cylinder

CONCLUSION AND PERSPECTIVES

Facing the problem of relatively low dynamic load stiffness of electrohydraulic drives the hybrid valve has been developed at IFAS. Its concept combines a conventional electromagnetic actuator and a piezoelectric actuator in an optimal way for direct drive valves. Whereas the relatively slow conventional actuator with a large stroke provides the drive with a good reference response, the fast piezo-actuator with a small stroke results in an outstanding disturbance rejection of the drive. The hybrid valve prototype shown in this paper possesses static characteristics comparable to a conventional valve and dynamic characteristics outmatching that of a state-of-the-art valve.

Even using just relatively simple control strategies with a position feedback of the drive a remarkable improvement in the drive performance has been achieved. The small signal reference response of the drive has been enhanced by 30% using the hybrid valve. However, this effect decreases for large signal reference responses. At the same time the disturbance rejection in terms of dynamic load stiffness of the drive was improved by 26%. This effect has no dependency on the load magnitude as the reaction of the valve to any disturbances of the drive is always in the range of very small valve openings.

The hybrid valve will be able to improve the position, velocity and force control of electrohydraulic drives in machine tools, mills, presses, injection molding machines and testing machines. Further research will focus on implementation of more sophisticated control strategies with a feedback of acceleration or load pressure alteration of the drive.

The development of the hybrid valve has shown that piezo technology can be successfully implemented in industrial hydraulic valves. This technology has already proved itself in the automobile industry, where piezo-actuators, similar to the one presented in this paper, have been used in fuel injectors since 2002. Taking into account falling costs of the piezo-actuators due to mass production for the automobile industry they become a very attractive alternative or supplement for hydraulic valve technology.

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REFERENCES

1. Murrenhoff, H., Servohydraulik - Geregelte hydraulische Antriebe, lecture notes, IFAS, Shaker Verlag, ISBN 978-3-8322-7067-4, Aachen, 2008.
2. Patent US2007079879, Highly Dynamic Valve Servocontrol Device, 04.12.2007.
3. http://www.moog.com/media/1/d636_d38seriesvalves.pdf.
4. http://www.physikinstrumente.com/en/pdf/P842_843_Datasheet.pdf.
5. International Standard ISO 10770-1:1998(E), Hydraulic fluid power – Electrically modulated hydraulic control valves – Part 1: Test methods for four-way directional flow control valves.
6. Götz, W., Haack, S., Mertlik, R., Elektrohydraulische Proportional- und Regelungssysteme, Robert Bosch GmbH, ISBN 3-933698-00-6, 1999.
7. Reichert, M., Murrenhoff, H., Increasing the Dynamic Load Stiffness of Electrohydraulic Linear Drives, 6th International Fluid Power Conference (IFK), Dresden, Germany, 2008, 2, pp. 145-157.
8. http://www.haenchen.de/2html_1/download/Prospekt_Ratio_en.pdf.
9. http://www.moog.com/Media/1/D769seriesvalves.pdf.
10. http://www.dspace.de/ww/en/inc/home/products/hw/singbord/ppcconbo.cfm?nv=bbp.