Technical Solutions for Digital Hydraulic Cylinders and Test Methods

PhD. Stud. **Ioan PAVEL**[1]**,** PhD.Eng. **Radu Iulian RĂDOI**[1]**,**
Dipl. Eng. **Alexandru-Polifron CHIRIȚĂ**[1], Dipl. Eng. **Mihai-Alexandru HRISTEA**[1]**,**
Dipl. Eng. **Bogdan Alexandru TUDOR**[1]

[1]Hydraulics and Pneumatics Research Institute INOE 2000-IHP; pavel.ihp@fluidas.ro

Abstract: *A cylinder with a continuously variable piston area is considered by many an impossible goal. This paper presents solutions for digital hydraulic cylinders with certain discrete values of multiple surfaces, which, selected by well established rules, can control the force and speed output values although they are supplied with constant pressure and flow. Also hereinafter we present test diagrams for digital pumps and digital switching directional control valves, as well as a test stand model for multiple-area cylinders, their testing methodology and mathematical modeling of a three-area digital cylinder.*

Keywords: *Multiple-area cylinders, digital cylinders, digital hydraulics, digital cylinder test stand, multiple-area cylinder testing methodology*

1. Introduction

Digital Hydraulics refers to systems that use components (actuators or control parts) which have certain discrete values and actively control the system output signal. Digital Hydraulics basically covers most hydraulic equipment: pumps, directional control valves, linear or rotary motors, accumulators [1].
There are two branches in the digital hydraulics:

- Systems based on parallel distribution technology
- Systems based on the switching method.

Parallel distribution systems have a multitude of components (on/off valves) connected in parallel, and the output is controlled by changing the state combination of components. The system has a certain number of discrete output values and it is possible to maintain or adjust the values of the output signal according to well-established rules, most often by a binary code.
Technologies based on the switching method use devices with fast and continuous switching.
There are two main methods by which the input voltage is switched [1]:

- The PWM (Pulse Width Modulation) control
- The PFM (Pulse Frequency Modulation) control.

The PWM (Pulse Width Modulation) control is the most commonly used flow control method, including by the specialists at INOE 2000-IHP. In this method, the ratio between closed and open (pulse width on a frequency step), will vary according to the output requirements of the system. Thus, at constant frequency there are obtained flow variations proportional to the opening time setting for one step.
The PFM (Pulse Frequency Modulation) is based on setting a fixed stationary time on either closed or open from a return period of the valve disk and frequency variation. By varying the frequency, there are flow variations proportional to the adjusted frequency due to the number of fixed stationary stops on or off in the time unit.
PFM can be with two types of initial adjustments:

- On time set constant
- Off time set constant.

A hydraulic cylinder can be actuated with a digital PWM switching directional control valve when targeting speed variation and energy efficiency [2].
There are constantly presented new solutions of digital hydraulic devices or digital hydraulic systems based on digital devices already in series production and existing on the market [3], [4].
The basic idea in promoting and implementing digital hydraulics is to replace the expensive and sensitive servo systems with a multi on/off directional valves assembly or with cheap and reliable switching devices. Parallel connection solution enables good flow control without continuous

switching of directional control valves. Results can be obtained even with slower directional control valves, which reduces the purchase and maintenance price of hydro-powered equipment.
There are some challenges to the switching method that should be addressed, the most important of which are the control method and the switching speed of the digital directional control valves.
Digital technology has the potential to make cheaper, more energy-efficient, and more reliable hydraulic systems, but research and technological development in the field will play a crucial part [4]. The trend was from analog to digital in all areas of technology; now it seems that the turn of Hydraulics came to experience this trend.
In Europe, the concern for scientific research in the field of digital hydraulics is recognized through results disseminated in conferences and papers published in prestigious journals; such results belong to research center at Tampere University of Technology in Finland and Johanes Kepler University Linz, Institute of Machine Design and Hydraulic Drives in Austria [4].
In Romania the foundations of a Digital Hydraulics Laboratory have been laid at INOE 2000-IHP; a team of young researchers perform their activity there; on the basis of several patent applications, they have begun designing and testing digital hydraulic devices. There are thought out new solutions for digital pumps, digital pulse width modulation switching directional valves, multiple-area digital hydraulic cylinders, various schematic diagrams and digital assemblies.

2. Digital hydraulic equipment testing diagrams

A system is considered digital if it has a digital mounting schematic diagram or a digital device that controls the output values of that system [5]. In this regard, at INOE 2000-IHP a specialized laboratory has been established, which is equipped with a 300 l oil tank, two 15 KW and 22 KW electro-pumps and three specialized testing devices for which test diagrams were designed and also auxiliary equipment required for testing digital pumps with various-area piston, digital pulse width modulation switching directional valves and multiple-area digital cylinders.

2.1 Testing diagram for digital pumps (Fig. 1.)

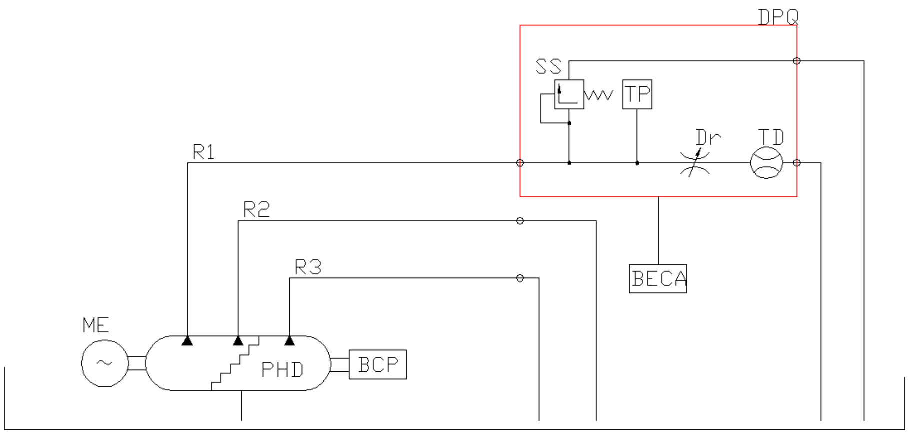


Fig. 1. Testing diagram for a digital pump

Testing the experimental model of the digital pump is done by means of the pressure and flow measurement device which can be mounted on each flow branch - *R1, R2, R3* - of the digital pump and also on combinations of them. The device provides protection against overpressure by means of the *SS* safety valve, pressure monitoring by means of the *TP* transducer, load simulation by means of the *Dr* throttle and flow monitoring by means of the *TD* transducer. Information on pressure and flow values is sent to the *BECA* control and data acquisition unit.
The main objective of these tests is to check the flow at nominal working pressure on each branch of the pump and its ability to provide variable flow by selecting different combinations of branches with different flow rates. There are also monitored the evolution of the flow with the variation of the working pressure, the accuracy of flow control and its pulses.

2.2 Testing diagram for pulse modulation directional control valves (Fig. 2.)

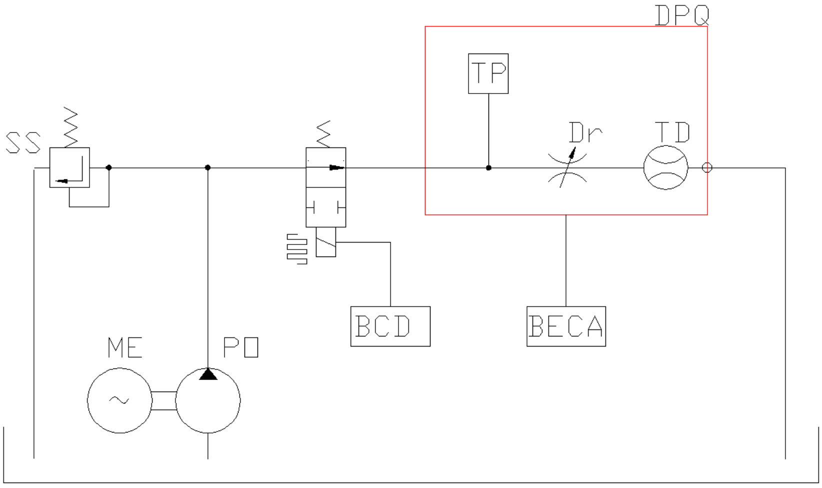


Fig. 2. Testing diagram for pulse modulation directional control valves

For testing digital switching on / off (PWM) directional valves a device (*DPQ*) for measuring the test pressure and flow rate was designed; it consists of a pressure transducer - *TP*, a throttle - *Dr* and a special flow transducer - *TD*. During tests there is also used a control unit for the digital switching hydraulic directional valve - *BCD*. A regular pumping system – *PO* and a safety valve – *SS* are used to supply the directional valve. The parameters to be monitored are pressure and flow depending on the variation of the switching signal.

2.3 Testing diagram for multiple-area digital hydraulic cylinders (Fig. 3.)

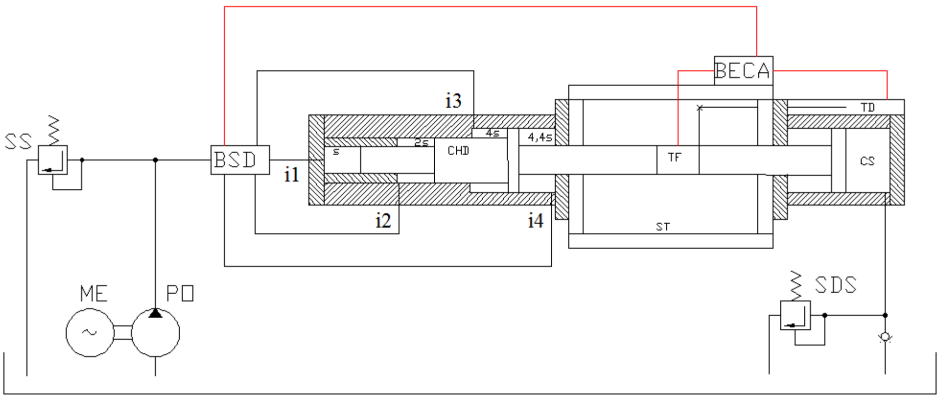


Fig. 3. Testing diagram for multiple-area digital hydraulic cylinders

For testing multiple-area digital hydraulic cylinders a specialized stand is used; it consists of a frame - *ST* which allows to mount the cylinder to be tested - *CHD*, the force transducer - *TF*, the displacement transducer - *TD* and the load cylinder - *CS*. The electronic control and data acquisition unit - *BECA* has the role of acquiring data from the force and displacement transducer and controlling the distribution selection unit - *BSD*. Constant flow and pressure supply is made by using a regular pump - *PO* and a safety valve - *SS*. The load adjustment is done by means of the load valve - *SDS*. Testing of multiple-area digital hydraulic cylinders is done according to the test methodology presented below.

3. Digital hydraulic cylinder test methodology

As a technical means of measuring the quality of the digital hydraulic cylinders we have used the hydraulic stand presented; it is able to provide the test conditions required for subjecting the digital hydraulic cylinders to the defining tests to demonstrate the principle of operation V=f(Ai) at constant flow, F=f(Ai) at constant pressure and to determine the technical characteristics designed. Functional models of the digital hydraulic cylinders under this study cannot be found in the test standards in force, that is why a set of tests inspired by them is required, through which to verify the technical characteristics of the design and demonstrate the basic idea that at constant pressure and flow supply there are achieved (by selecting combinations of areas) at the digital hydraulic cylinder rod variable force and speed values, repeating as determined by specified graphs.

Testing of multiple-area digital cylinders

Testing of functional models will be done on a specialized stand (Fig. 4), with controlled hydraulic load, equipped with force transducer for active control of the force adjusted on the cylinder under test and for data acquisition, and equipped also with displacement transducer for active control of the speed adjusted on the cylinder under test and for data acquisition.

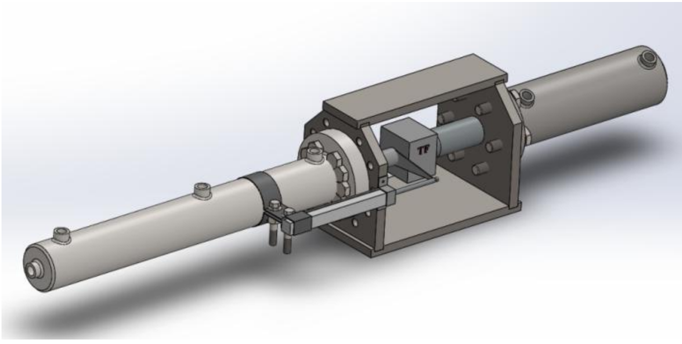
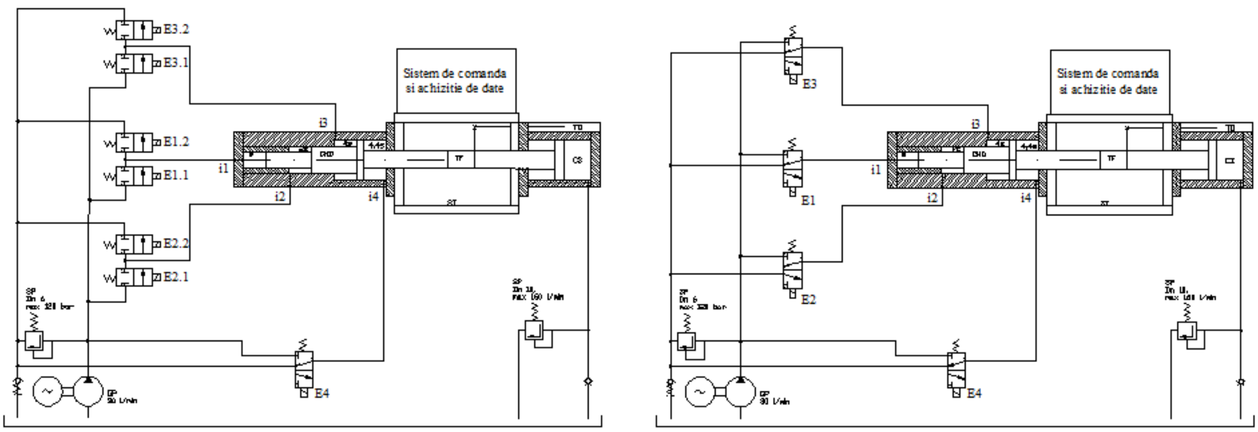


Fig. 4. Multiple-area cylinder test stand

Running tests do not always require tight or fast closing devices. The test schematic diagram can include a standard pumping system and equipment, as shown in Figure 5.b), in which case the number of electromagnets actuated is reduced.



a) b)

Fig. 5. Connection diagram for a three-area CHD test stand
a) on/off directional control valve variant; b) classic directional control valve variant

Caption:
CHD- Digital Hydraulic Cylinder
CS- Load Cylinder
TF- Force Transducer
TD- Displacement Transducer
SP- Pressure Valves
GP- Pumping Unit
ST- Test Stand
E1-4 – Electromagnets

The successive sequences of the tests are as follows:

- re-check that the stand and the equipment mounted on it corresponds to the mounting diagram;
- check exterior tightness;
- check interior tightness;
- check starting pressure and minimum idling pressure;
- force tests are carried out - F=f(Ai) - at constant pressure;
- speed tests are carried out - V=f(Ai) - at constant flow.

The tests on the experimental digital hydraulic cylinder model are performed as follows:
Checking of the exterior tightness is performed to the test pressure of:

- p_{min}
- 0.5 $p_{n,}$ but no more than 50 bar
- 1.25-1.5 $p_{n,}$ but no more than 1.1 p_{max}.

after performing five double strokes at the minimum speed (all areas are active).
During the tests, to the outside of the cylinder behind the sealing and scraping system no visible oil traces shall occur which increase over time. It is admissible an oil film under the condition of not agglomerating in the form of drops on the piston rod. The result of the measurements is listed on the test data sheet.
Checking of the interior tightness is usually done in the extreme positions of the piston and in three to five intermediate points located equidistant along the entire stroke of the piston at the test pressure p_i= 1.25-1.5 p_n but no more than 1.1 p_{max},, for 1 minute for each area of the multiple-area cylinder. For the model being tested, commands corresponding to the control code 1,2 and 4 in the command cyclogram are executed.
For each position the internal losses are estimated by using the indications of the stroke transducer (or comparator) for 1 min. Displacement of the rod is not admissible. The result of the measurement is listed on the test sheet.
Checking of the minimum pressure for uniform and shock-free movement of the piston and checking of the starting pressure are done in idling. The working chambers are filled with oil at the ambient temperature at which the test is carried out, kinematic viscosity ν=35 cSt. All surfaces of the multiple-area cylinder are connected to a source of oil under pressure according to the test scheme. There is recorded the lowest pressure at which the piston displacement with minimum speed occurs and also the pressure for which the piston has a smooth motion without shocks for each surface of the multiple-area cylinder but also on all the summed surfaces, over the entire length of the stroke. For the three-area cylinder, commands corresponding to the control code 1,2,4 and 7 in the command cyclogram are executed. Uniformity of the piston displacement speed is checked with a recorder. The result of the measurement is listed on the test sheet.
Checking of the thrust force is made at constant pressure by selecting combinations of sections of the multiple-area digital cylinder, over the entire length of the stroke. Force is measured by means of force transducers with precision class of at least 1 on a stroke sector corresponding to pressure and force stabilization. The resistance-type load is created by means of a hydraulic cylinder powered by a separate hydraulic installation, low pressure, and it can be continuously varied through the adjustable pressure valve. Measurement is made to determine the force variation depending on the combination of selected areas, F=f(Ai) at constant pressure. Check commands are made according to the command cyclogram, successively for all combinations along the advance rod stroke. The result of the measurement is listed on the test sheet.
Checking of the piston speed is made at constant flow; the displacement must be carried out under load, smoothly and without shocks over the entire length of the stroke. Verification is done for each combination of surfaces of the multiple-area cylinder but also on all the summed surfaces, along the advance rod stroke. Measurement is made to determine the speed variation depending on the combination of selected areas, V=f(Ai) at constant flow. Check commands are made according to the command cyclogram. The result of the measurement is listed on the test sheet.
The command cyclogram to make the graphs of F=f(Ai), at p=ct and V=f(Ai), at q=ct for a three-area CHD - F corresponds to the force obtained with the smallest area at constant pressure, and V corresponds to the speed achieved with constant flow for the smallest section.

The command cyclogram for the three-area cylinder

Control code	Input commands							Output values	
	s		3 s		3.76 s		4.2 s	Force	Speed
	E1.1	E1.2	E2.1	E2.2	E3.1	E3.2	E4		
0	0	0	0	0	0	0	0	0	0
1	1	0	0	1	0	1	0	1F	1V
2	1	0	1	0	0	1	0	3F	0.33V
3	1	0	1	0	0	1	0	4F	0.25V
4	1	0	0	1	1	0	0	4.76F	0.2V
5	0	1	1	0	1	0	0	6.76F	0.16V
6	1	0	1	0	1	0	0	7.76F	0.14V
Retraction	0	1	0	1	0	1	1	4.4F	0.227V
Energy recovery (retraction with external load; secondary control)									
-1	1	0	1	0	0	1	1	0.2F	0.227V
-2	0	1	0	1	1	0	1	0.44F	0.227V
-3	0	1	1	0	0	1	1	1.2F	0.227V
-4	1	0	0	1	0	1	1	3.4F	0.227V

The tests will be performed according to the present testing methodology for multiple-area digital cylinders, using the stand, test schemes, and control system codes. The data will be acquired and a test report for the tests performed will be elaborated. The goal will be to demonstrate the idea that the digital hydraulic cylinder is supplied with constant pressure and flow and there are achieved variable forces and speeds, controllable by selecting surface combinations according to the command cyclogram to plot the graphs of F=f(Ai), at p=ct and V=f(Ai), at q=ct.

4. Solutions for multiple-area digital hydraulic cylinders (Fig. 6, 7, 8, 9, 10)

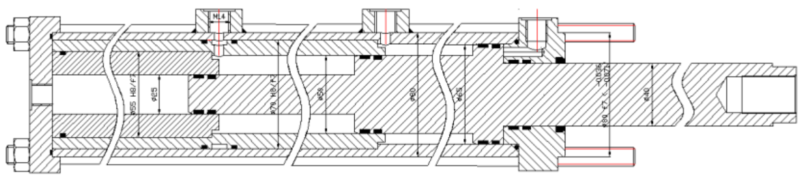


Fig. 6. Solution for a digital hydraulic cylinder with three binary coded areas

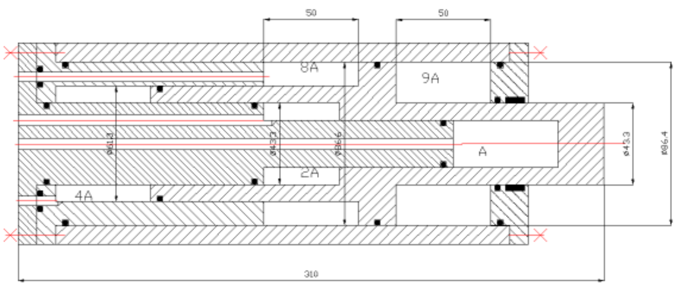


Fig. 7. Solution for a digital hydraulic cylinder with four binary coded areas

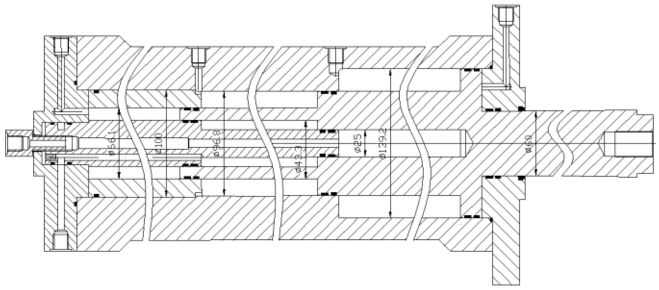


Fig. 8. Own solution for a digital hydraulic cylinder with five binary coded areas

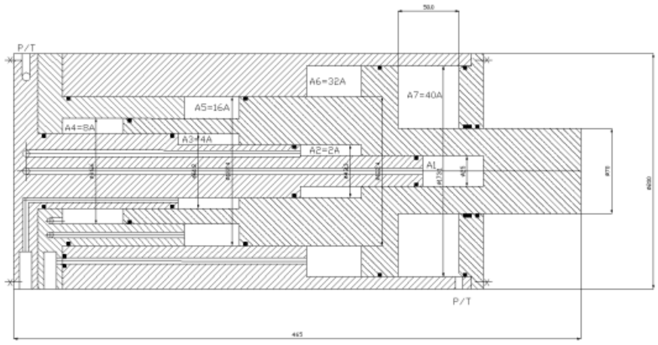


Fig. 9. Own solution for a digital hydraulic cylinder with six binary coded areas

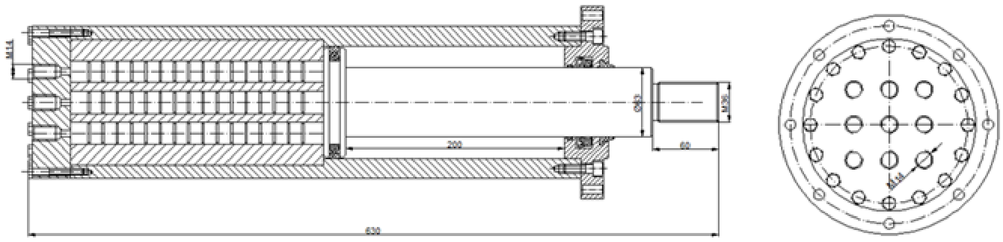


Fig. 10. Solution for a multi-piston digital hydraulic cylinder with nine equal areas (PNM coding)

The result of tests, data acquisition and comparison with mathematical modeling of the three-area CHD will be presented in another paper in a future issue of the magazine.

5. The mathematical model of the three-area digital hydraulic cylinder

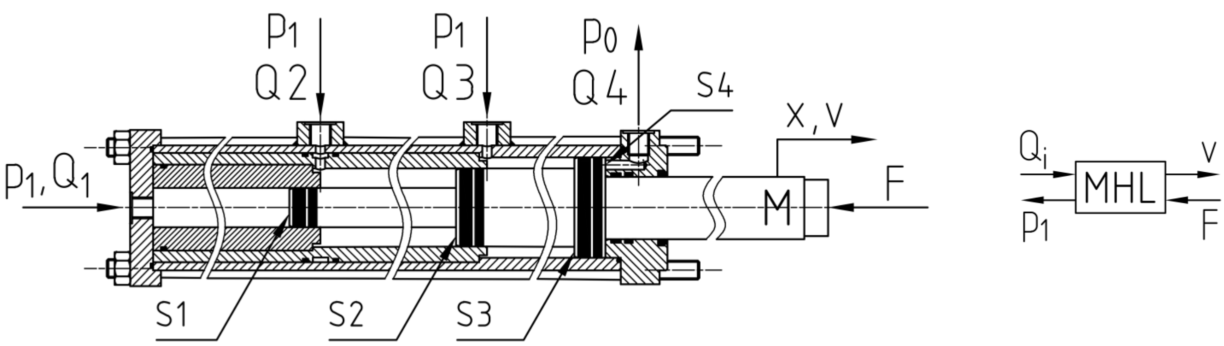


Fig. 11. The physical model

If for the hydraulic cylinder in the figure 11 we consider $p_0 = 0$, the mathematical model is:

$$Q_i = S_i \cdot v + a_M \cdot p_1 + \frac{V_0 + x \cdot S_i}{E} \cdot \frac{dp_1}{dt} \tag{1}$$

$$M\frac{dv}{dt} + b_M \cdot v + c_f \cdot sgn(v) \cdot p_1 \cdot S_i + F = p_1 \cdot S_i \tag{2}$$

In the equations above and in Figure 11 we noted: Q_i – input flow (Q_1, Q_2, Q_3,) [m^3/s], p_1 – motor chamber pressure [N/m^2], v – motor spindle speed [m/s], a_M – linearized coefficient of flow rate losses proportional to pressure [(m^3/s)/(N/m^2)], V_0 – the initial volume of fluid on the left of the cylinder chambers [m^3], x – displacement [m], M – moving mass [kg], b_M – linearized coefficient of force losses proportional to speed [N/(m/s)], c_f – coefficient of friction, F – resistance force [N], E – fluid modulus of elasticity [N/m^2].

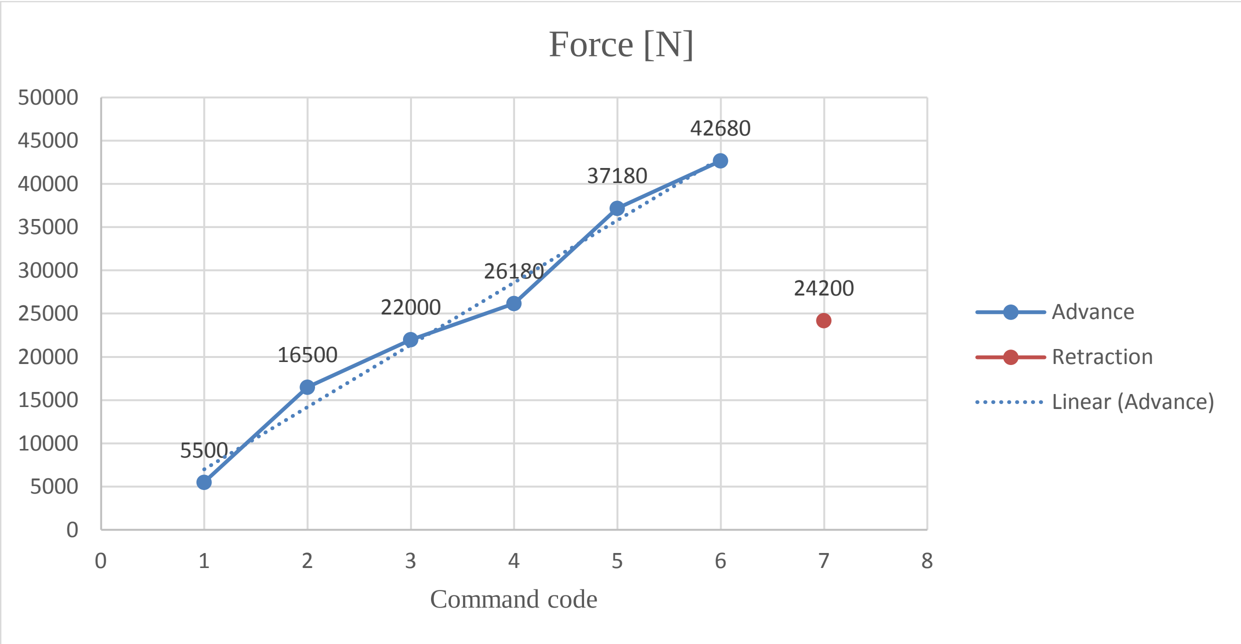


Fig. 12. The forces achieved by the hydraulic cylinder

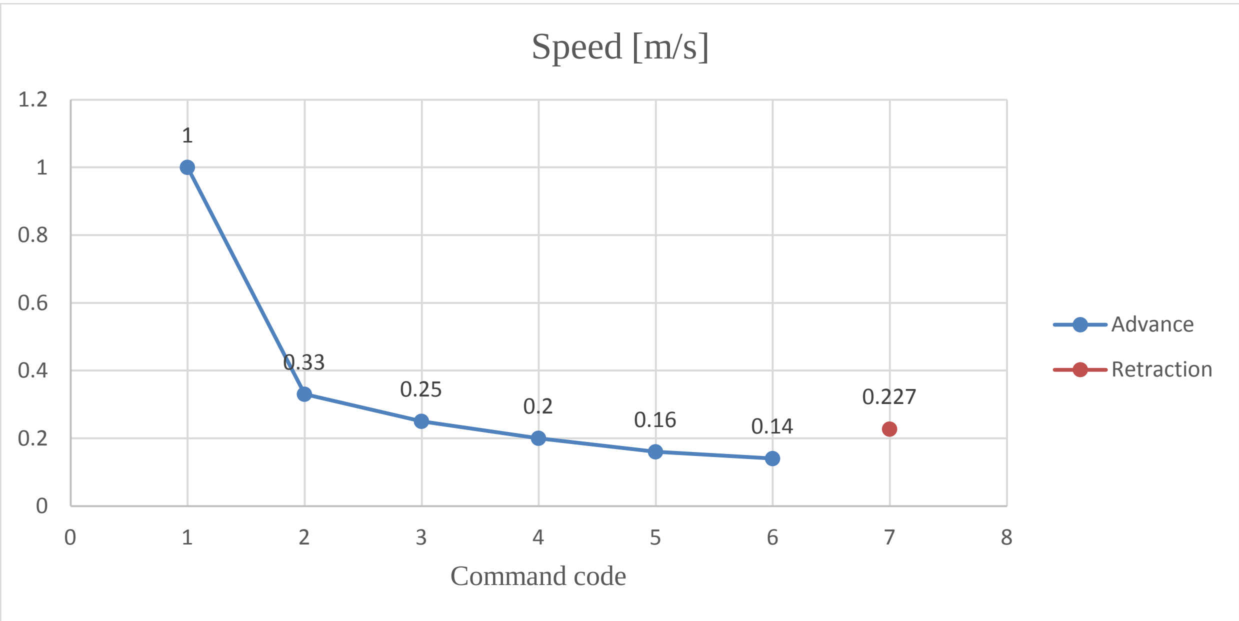


Fig. 13. The speeds achieved by the hydraulic cylinder

In the previous graphs one can see the quasi-linear variation of force and the variation of the hydraulic cylinder speed supplied from a constant flow source.

6. Conclusions

The conclusions arising from this paper are as follows:

- Testing of digital hydraulic equipment can be done on test stands equipped with standard hydraulic devices;
- Electronic control systems are specific to digital hydraulic equipment;
- In our case, test solutions are chosen to determine the correct operation of digital hydraulic equipment, not to determine factors that influence their dynamics;
- The next stage in the research work of the team within INOE 2000-IHP is to improve the functional performance and the manufacturing technology of digital devices, allowing for easy introduction of them into manufacturing on a large scale and reducing their cost price.

Over the next period, cost reductions and increased energy efficiency will be dominant as success factors for any industry. Currently, the hydraulics industry is not fit to meet these requirements: classic hydraulic systems and components are rather expensive and energy-inefficient [6].
Correct dimensioning and choosing the best technical and economic solutions could make the hydraulic systems the fastest and most efficient form of power transmission. Energy savings resulting from the implementation of digital hydraulic solutions can improve the technical and economic performance of the technology lines in which they are used, reflecting ultimately in the execution price of the products put on the market. At the same time, through energy savings and efficient use of resources, they contribute to the foundations of sustainable development.

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