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DIGITAL LINEAR HYDRAULIC MOTORS

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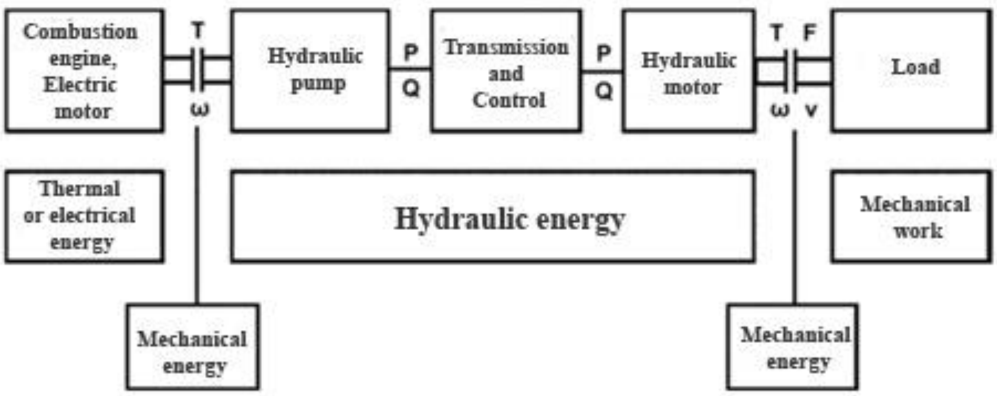
Abstract: *This paper presents a different approach to variation in force and speed of linear hydraulic motors by using multiple-area digital linear hydraulic motors. The article presents multiple-area digital hydraulic cylinder solutions, a stand solution for functional testing, schematic diagram and testing methodology for multiple-area digital hydraulic cylinders.*

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

1. Introduction

Hydrostatic drive is a basic element of complex technologies that are used in the manufacturing, servicing and maintenance industries, but also in many other industries. This technology, according to ISO 5598, refers to the methods and equipment through which signals and energy are conveyed, controlled and distributed by means of a pressurized fluid.
The general structure of a hydraulic drive system, in which energy types can be highlighted, is shown in Figure 1. The thermal or electric energy is converted into hydraulic energy, transmitted to a hydraulic motor, which converts it into mechanical work.



T= Rotative speed, Ω= Torque, P= Pressure, Q= Flow, F= Force, V= Speed

Fig. 1. The general structure of a hydraulic drive system [1]

The final element acting as actuator in a system is the hydraulic motor, which converts hydraulic energy into mechanical energy, type rotative speed and torque (rotary motors) or force and speed (linear motors). The task of performing a translation-rectilinear movement simultaneously with the transmission of force is accomplished by a cylinder with a minimum of structural elements and high power density.
The hydraulic cylinder is the most known equipment in the field of hydraulic drives, as it is also the most widespread execution element of a drive installation and in most cases it is the starting point for the design of the entire hydraulic installation.
The possibilities to vary force and speed along the stroke, as well as the possibilities of using different gripping modes, combined with various levers and joints, make the hydraulic cylinder an indispensable element in most machines and equipment involving hydraulic drives.
In terms of the way in which the drive is performed, namely the way in which the fluid acts on the sides of the piston, power cylinders may be single or double acting.

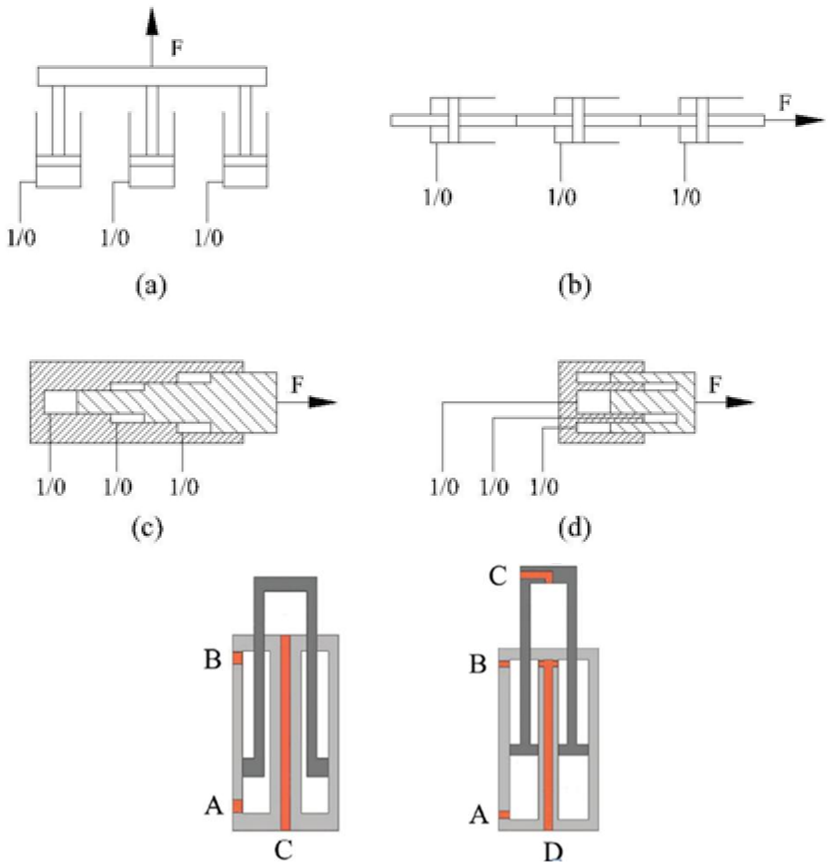
In terms of the ratio of rod diameter and piston diameter, they can be:

- cylinders with the diameter of the piston greater than the diameter of the rod;
- cylinders with piston diameter equal to that of the rod, that is cylinders with plunger pistons.

More recently, a branch of the Hydraulics studies new solutions for multiple-area digital hydraulic cylinders.

2. Multiple-area digital hydraulic cylinders

Digital Hydraulics refers to systems that use binary components connected in parallel or switching control elements which have certain discrete input values and can actively control the system. A system is considered to be digital if it has at least one digitally controlled item.
A digital version for the active control of speed and force in a hydraulic system with constant pressure and flow is the multiple-area digital hydraulic cylinder. The constructive solution is studied in a large number of papers and it involves dividing the active surface of the piston into multiple surfaces with equal areas or with values multiplied following well established rules (Fig. 3 c,d or e), which are powered separately but also cumulatively, to achieve combinations of powered areas with which an active speed or force control on the cylinder stem is obtained. Selecting combinations of supplied areas ensures a relatively linear movement with variable speeds or loads, with possibilities for active control but also secondary control (with energy recovery), thus meeting the energy requirements of a hydraulic system.
The literature offers several examples of theoretical solutions for multiple-area cylinders:



(e)

Fig. 2. Examples of solutions for multiple-area cylinders
serial cylinders; b) inline cylinders; c),d),e) concentric area cylinders [3], [4]

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Driving of multiple-area cylinders can be done by using pairs of on / off devices, Fig. 3, or by means of classic equipment, Fig. 4, depending on the system requirements.

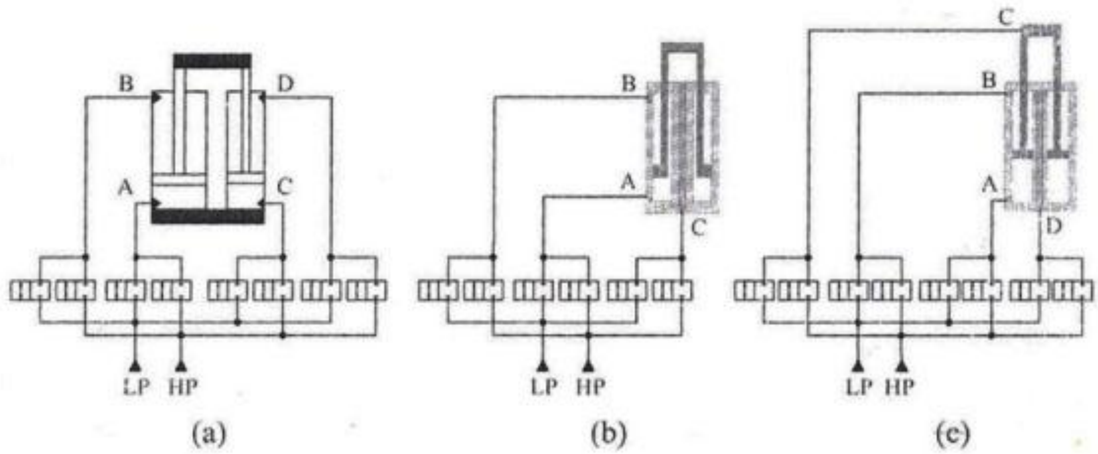

Fig. 3. Driving of multiple-area cylinders by means of on / off devices [2]
LP= low pressure line, HP= high pressure line

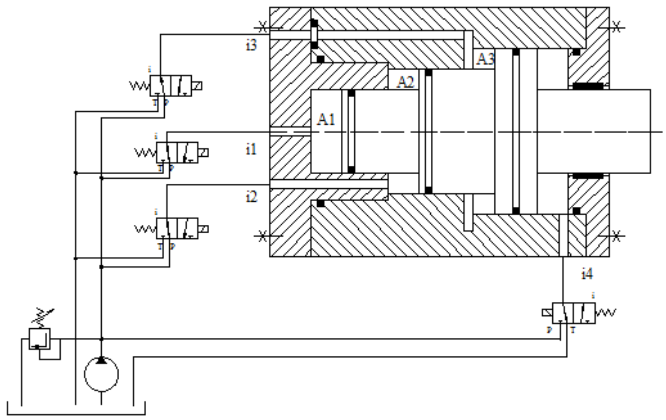

Fig. 4. Driving of multiple-area cylinders by means of classic equipment [2]

A fundamental characteristic of parallel connected digital hydraulic systems is that the output is quantified. The actual number of output values depends on the number of components and coding method. There are several methods for coding the surfaces of a digital cylinder, but the most important are:

- Surface is divided into surfaces of the same value - Modulation Number Pulse (PNM coding)
- The divided areas are in a ratio according to the binary series, 1: 2: 4: 8, etc.
- The divided areas are in a ratio according to the Fibonacci method, 1: 1: 2: 3: 5: 8: 13, etc.

All methods result in a step flow curve (graph), where step size is constant and inversely proportional to the number of items used.
Of the three solutions, the lowest number of output values is obtained by using the method of components of the same size, and the number of output values is N^{+1}. This method is known as Modulation Pulse Number (PNM coding).
Another coding method is following a binary code (divided surfaces with area ratios 1: 2: 4: 8, etc.), where each status combination gives a different output value. If the cylinder has "n" divided surfaces, each having two statuses (to pressure or to the tank), the total number of status combinations is 2^{n-1}. Each of the status combinations can give a different output in the system

and thus the maximum number of output values is equal to the number of status combinations. Fibonacci coding is a method between the PNM and the binary coding.[5]

The team of specialists within INOE 2000-IHP has filed two patent applications for two digital hydraulic cylinder solutions: one solution (Fig. 5) which involves dividing the piston area into three concentric areas multiplied binary [6], technically and technologically feasible, and the other solution (Fig. 9), compact, which involves dividing the piston area into nine equal areas [8], symmetrically arranged around the axis of the main piston. Also, there have been developed within the "Nucleu" project [7] several technical solutions for digital hydraulic cylinders with concentric areas multiplied binary.

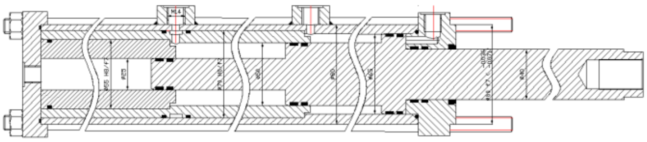

Fig. 5. Patented solution for a digital hydraulic cylinder with three binary coded areas [6]

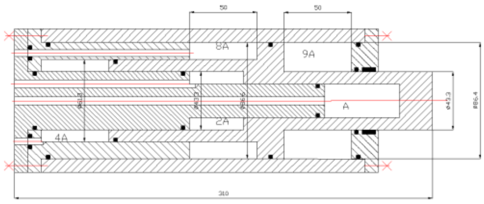

Fig. 6. Solution for a digital hydraulic cylinder with four binary coded areas [7]

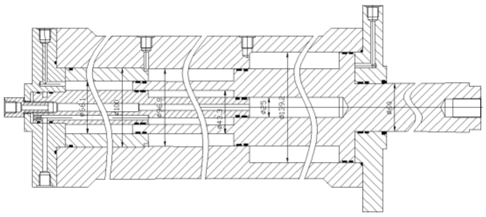

Fig. 7. Solution for a digital hydraulic cylinder with five binary coded areas [7]

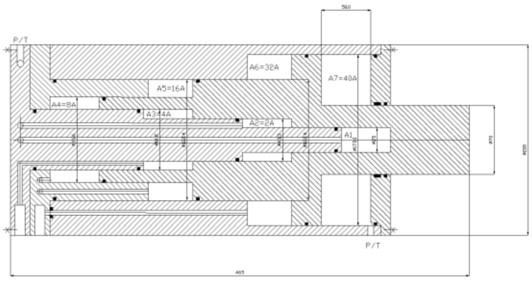

Fig. 8. Solution for a digital hydraulic cylinder with six binary coded areas [7]

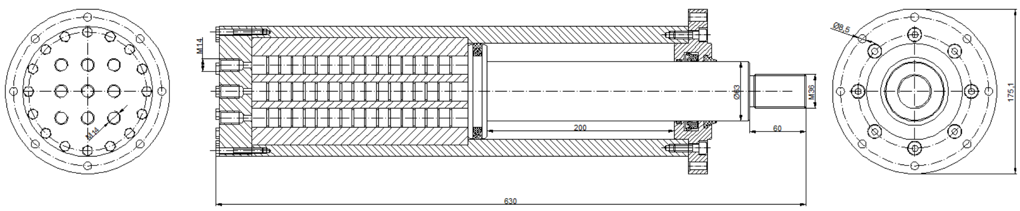

Fig. 9. Patented solution for a digital hydraulic cylinder with nine equal areas, PNM coding [7], [8]

3. Hydraulic digital cylinder test diagram and procedure

As a technical means of measuring the quality of digital hydraulic cylinders there is used the hydraulic stand shown in Fig. 10, which is able to provide the test conditions required for subjecting the digital hydraulic cylinders to functional tests and determination of the technical designed characteristics.

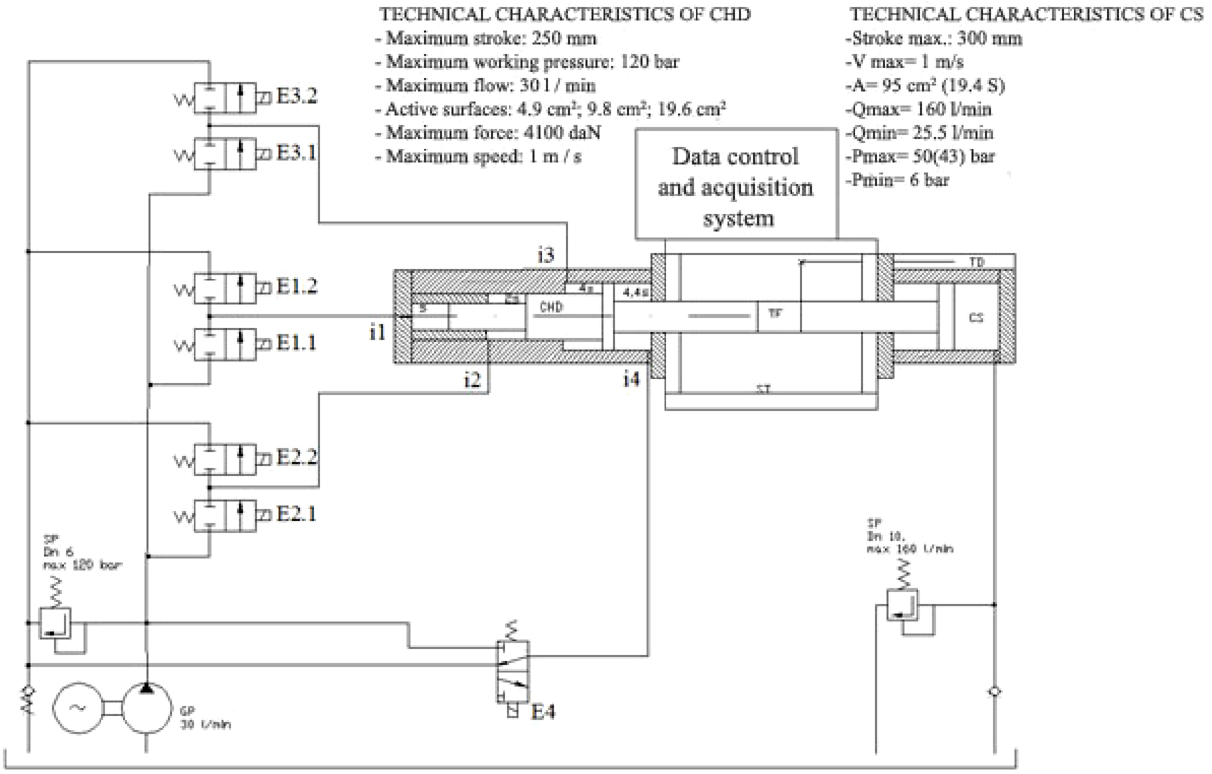

Fig. 10. Diagram of digital hydraulic cylinder test stand

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

Because of dividing of their active area, multiple-area cylinders cannot be tested according to standard methodology; that is why it is necessary to conceive a set of tests inspired from the mentioned methodology, through which to verify the technical characteristics designed 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, actively controlled force and speed values, repeatable according to specified graphs.
Testing is conducted on a specialized device, as depicted in Fig. 11, composed of:
- load cylinder (1) which creates the simulated load;
- force transducer (2), for active control of the force adjusted to the cylinder under testing;
- displacement transducer (3) for active control of the speed adjusted to the cylinder under testing;
- frame (4).
The two transducers also enable data acquisition.

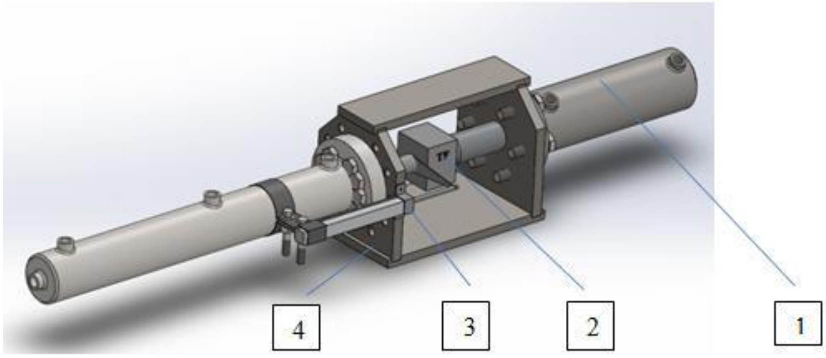

Fig. 11. Multiple-area cylinder test device [7]

The stand consists of a frame (4) which allows direct grip or attachment through an adaptive flange of a wider range of digital hydraulic cylinder.
Between the rods of the two cylinders there is positioned the force transducer (2), and the position transducer (3) is fixed on the side. The data control and acquisition system is located next to it. Configuration of the connection of the control components and configuration of hydraulic connections will vary depending on the type of cylinders under tests and the test to be performed, according to the testing methodology presented below.
Testing of multiple-area digital cylinders at variable forces and speeds with constant pressure and flow is done by selecting combinations of surfaces.
The successive sequences of the tests are as follows [9]:

- re-check that the stand and the equipment mounted on it correspond 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 digital hydraulic cylinders 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 3-area cylinder commands corresponding to the control code 1,2 and 4 are executed, and for the 5-area cylinder commands corresponding to the control code 1,2,4,8 and 16 are executed; the control codes are listed in the command cyclogram of each of the cylinders.
For each position the internal losses are estimated by reading the indications of the stroke transducer (or comparator) for 1 min. Displacement of the rod is not admissible. The measurement result is added to 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 and kinematic viscosity v=35 cSt. All

surfaces of the multiple-area cylinder are connected to a source of oil under pressure according to the test diagram. 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 3-area cylinder commands corresponding to the control code 1,2,4 and 7 are executed, and for the 5-area cylinder commands corresponding to the control code 1,2,4,8,16 and 31 are executed; the control codes are listed in the command cyclogram of each of the two cylinders. Uniformity of the piston displacement speed is checked by means of a recorder. The measurement result is added to 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 measurement result is listed on the test sheet and compared to the expected result.

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 measurement result is listed on the test sheet and compared to the expected result.

The command cyclogram to plot the graph 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.

Control code	Input commands							Output values	
	s		3 s		3.76 s		4.2 s		
	E1.1	E1.2	E2.1	E2.2	E3.1	E3.2	E4	Force	Speed
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

Fig. 12. The command cyclogram [7]

1. Expected results for rod advance:

a) For: F=f(Ai)

F=P x S

Where: F- Force; P-Pressure (constant); S-Surface (variable)
We obtain the proportional force corresponding to the command code.

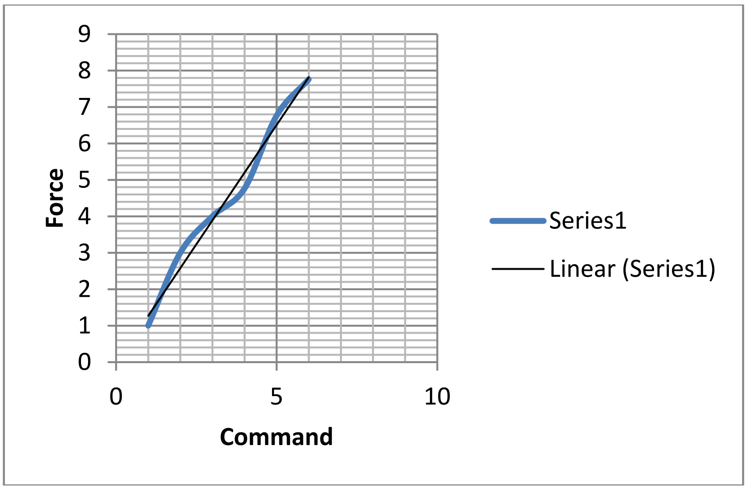

Fig. 13. Expected results for rod advance (1) [7]

b) For: V=f(Ai)

$V=\frac{Q}{S}$

Where: V- Speed; Q- Flow (constant); S-Surface (variable)
We obtain the proportional speed corresponding to the command code.

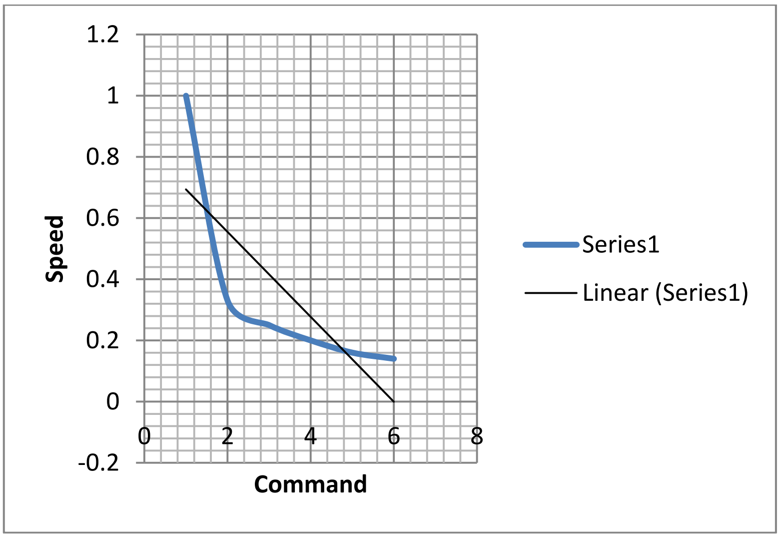

Fig. 14. Expected results for rod advance (2) [7]

2. Expected results for energy recovery in the case of retraction with external load (secondary adjustment):

a) For force

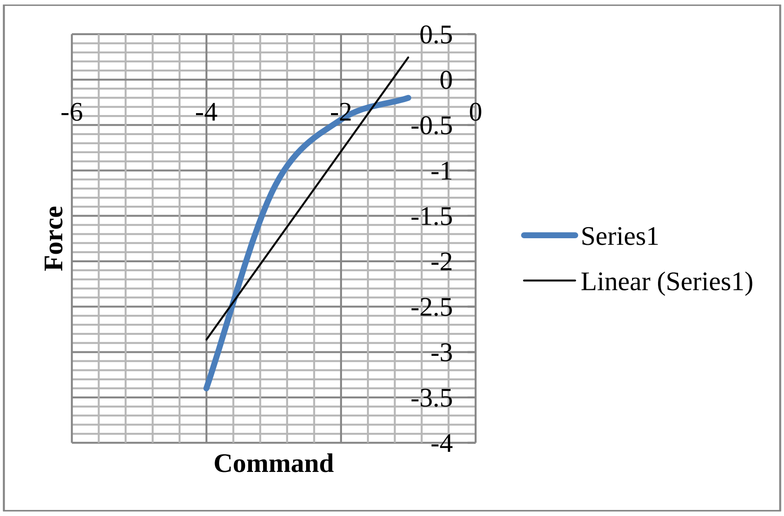

Fig. 15. Expected results for rod retraction (1) [7]

b) For speed

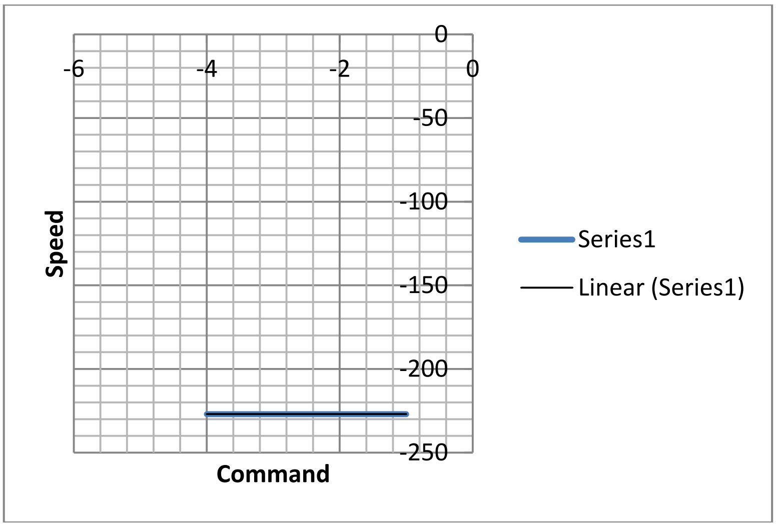

Fig. 16. Expected results for rod retraction (2) [7]

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

4. Conclusions

The basic idea in promoting and implementing digital hydraulic cylinders is to replace the expensive and sensitive servo cylinders by multiple-area cylinders with an assembly of multiple on/off directional control valves, which are cheap and reliable. Digital technology has the potential

to create cheaper, more energy-efficient and more reliable hydraulic systems, but a decisive role will be played by research and technological development in the field. For the digital hydraulic cylinder segment the challenge lies in developing simple, technologically achievable, more compact and cheaper technical solutions. The emergence of experimental models of multiple-area digital hydraulic cylinders required the establishment of a functional testing methodology and their testing diagrams and this paper tries to meet this requirement.
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. 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 [10].

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