Testing of Digital Hydraulic Cylinders

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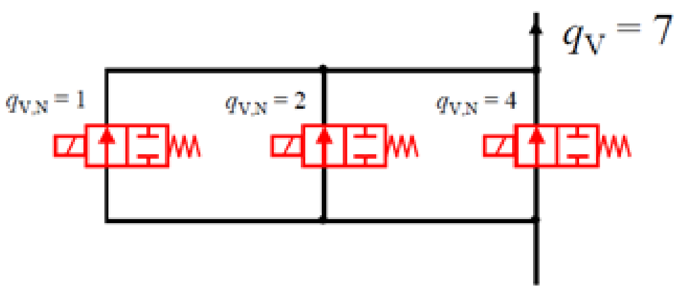
Abstract: *The article presents laboratory testing of an experimental digital hydraulic cylinder model with three surfaces that is powered by constant pressure and flow and achieves steps of force and speed active controlled. The digital hydraulic cylinder has the piston surface divided into three annular, functionally independent areas, and by selecting the combinations of active areas, seven stages of forces or speeds result, that can be controlled by a dedicated distribution block and a dedicated computer system.*

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

1. Introduction

Digital Hydraulics is an alternative, recently developed, to replace drives with servo valves or proportional control valves. Digital Hydraulics means hydraulic systems that contain at least one hydraulic element to ensure discreet, accurate and actively controlled output values. This involves, besides the hydraulic digital elements, an adequate electronic command, so a good computerization of the system.
In classic hydraulic installations, force variation is routinely made by variation of pressure and variation in velocity through flow variation. The basic principle in Digital Hydraulics is section meshing and active control of split sections, and with constant supply pressure and flow rates, variable speeds or forces are obtained at the execution element.
Although the principles of Digital Hydraulics have been applied hundreds of years ago, starting in the year 2000, the foundations of the study of digital hydraulic equipment have been established in renowned universities. For example, version of Digital Hydraulics with parallel distribution developed by Prof. Lindjama of the Tampere University of Technology is based on high-speed on/off simple directional control valves, electrically controlled, that can either take one of two closed or open states by providing in the system steps of actively controlled flow [1].
Figure 1 shows the hydraulic diagram (a) and the table with number of resulted flow rate steps (b) of a 1961 USA patent. The three valves are of different nominal sizes and allow the passage of three different flow values in the situation of constant supply pressure and flow. The combination of the three flow rate values results in seven flow stages that can be actively controlled and delivered to the customers of the hydraulic system according to the system requirements.



V1	V2	V3	Q
0	0	0	0
1	0	0	1
0	1	0	2
1	1	0	3
0	0	1	4
1	0	1	5
0	1	1	6
1	1	1	7

a) b)

Fig. 1. Parallel distribution scheme patented in 1961 in USA. (US2999482) [2]

The purpose of this article is to give an example of a three-dimensional digital hydraulic cylinder that is powered by constant pressure and flow and achieves active steps of force and speeds. In the paper is presented the digital hydraulic cylinder, the test bench and the results of laboratory testing of the experimental model of hydraulic cylinder with three surfaces.

2. Digital hydraulic cylinder with three surfaces

Hydraulic cylinders, also known as linear hydraulic motors or power cylinders, are designed to be executed. They convert energy from hydrostatic energy into mechanical energy, characterized by two parameters, force and speed.
In a conventional hydraulic cylinder, a fluid at a certain working pressure acts on a piston with a particular working area, resulting in a specific linear output force, according to the load to be displaced. If another output force is required, the fluid pressure must be changed because the piston area remains unchanged. From a hypothetical point of view, if the active area of the piston could be changed or only part of the area could be used, the fluid pressure could remain constant and the output force could vary. Unfortunately, there is no means by which the liquid can only act on a portion of a piston, since the pressure fluid acts equally on the entire area containing it [3].
Hydraulic digital technology is a solution to this new approach. By dividing the working area of a piston into solid ringed areas, and by selecting the combinations of active zones, it results in stages of forces and speeds (Fig. 2) which can be controlled by a dedicated computer system in relation to the requirements of the system. The choice of individually or cumulatively selectable combinations of zones / sections leads to a range of 7 steps of forces / speeds outputs with supply at constant flow and pressure in the three-dimensional hydraulic cylinder.

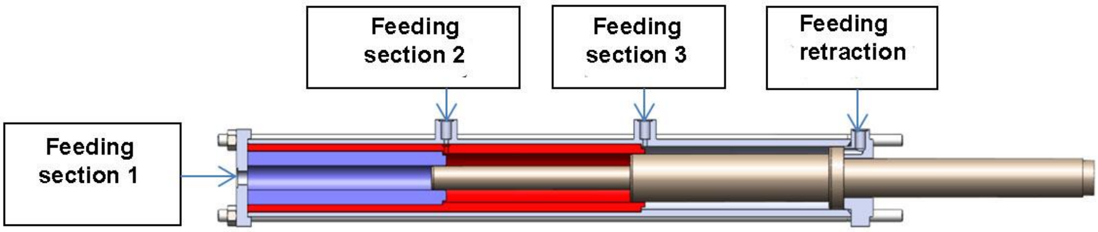


Fig. 2. Feed ports for the digital hydraulic cylinder [4]

The functional model of digital hydraulic cylinder under analysis was designed and manufactured with typical elements of cylinder liners. The construction features are shown in Table 1. The cylinder stroke was 250 mm.

Table 1: Dimensions of surfaces of the experimental digital hydraulic cylinder model

Current number	Cylinder with three surfaces	
	Surface [cm²]	Diameter [mm]
s1	4.906	Ø25
s2	14.712	Ø25;Ø50
s3	13.548	Ø50;Ø65
s retraction	20.606	Ø65;Ø40

3. Test stand for digital hydraulic cylinders

As a technical means of measuring the quality of hydraulic digital cylinders, the hydraulic stand (Fig. 3) is designed to provide the necessary test conditions for the submission of the hydraulic digital cylinders to the defining tests to demonstrate the operating principle V = f (Ai) = f (Ai) at constant pressure and determination of the design characteristics [5].

Fig. 3. Test stand for digital hydraulic cylinders

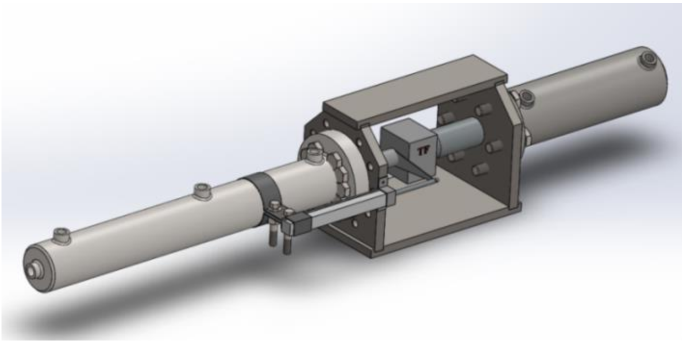


Fig. 4. Multi-surface cylinders testing device [5].

The test device (Fig. 4), together with the pumping station, the distribution block (Fig. 5), the acquisition board, the power supply, the computer and the virtual instrument application, form the test stand of the digital cylinders (Fig. 3).
According to the test stand diagram (Fig. 6), for the alternative pressure / tank supply of the piston surfaces, each of the hydraulic digital cylinder holes is connected to a group of two quick-opening on / off electro-directional control valves. The distribution block (Fig. 5) consists of on / off directional control valves of the same type from ATOS company and has the catalog code: DLEH-2C / CART LEH-2C. Maximum working flow is 12 l / min and maximum pressure is 350 bar.

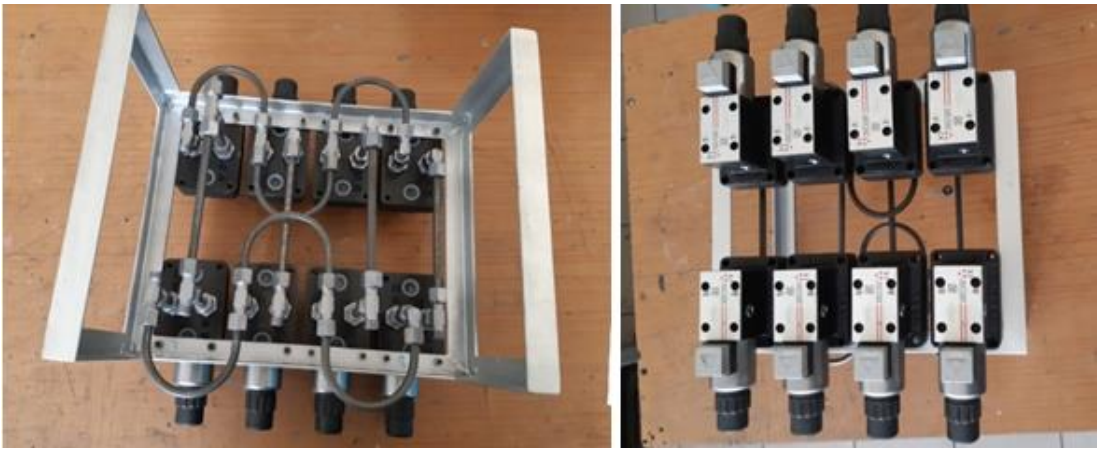


Fig. 5. Parallel distribution block.

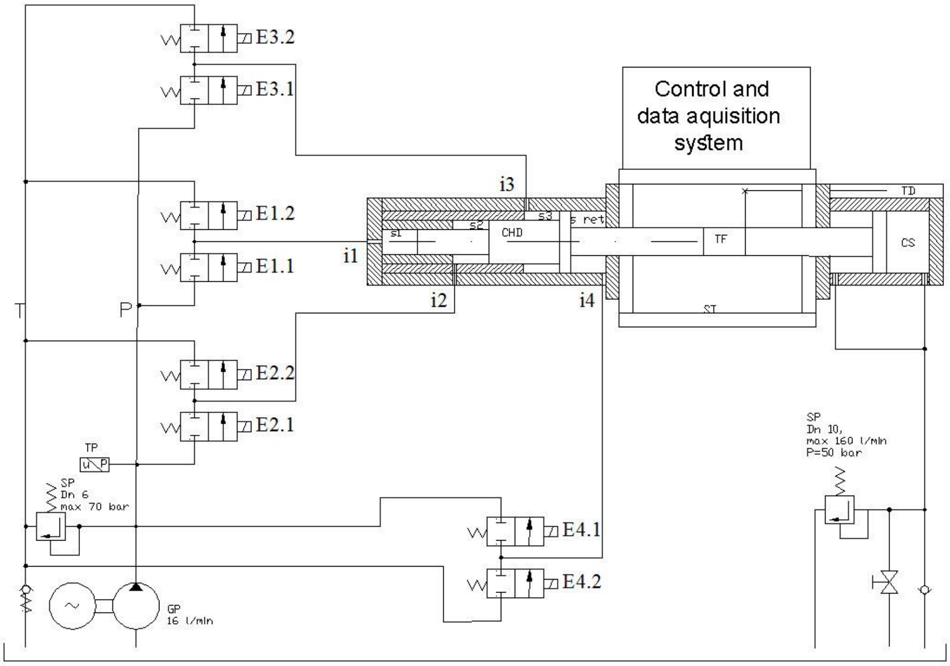


Fig. 6. Hydraulic diagram of the three-surface digital hydraulic cylinder testing bench

By the combination of active electromagnets, selected according to the cyclogram from the Table 2, the three feed surfaces and the retraction surface are properly connected to achieve a step of force and speed in the working range of the digital hydraulic cylinder.

Table 2: Control cyclogram for achieving the speed / force stages in the working range of the three-dimensional digital hydraulic cylinder

Command code Surfaces combination	Electromagnets commands (0=close circuit, 1= open circuit)								Active surface [cm^2]	Calculated values at flow rate of 1.5 l/min and pressure of 65 bar	
	S_1		S_2		S_3		Retraction			Force [daN]	Speed [mm/sec]
	E1.1 (P)	E1.2 (T)	E2.1 (P)	E2.2 (T)	E3.1 (P)	E3.2 (T)	E4.1 (P)	E4.2 (T)			
0	0	0	0	0	0	0	0	0	0	0	0
1(S1)	1	0	0	1	0	1	0	1	4.906	318	51.02
2(S3)	0	1	0	1	1	0	0	1	13.548	880	18.52
3(S2)	0	1	1	0	0	1	0	1	14.712	956	17.00
4(S1+S3)	1	0	0	1	1	0	0	1	18.454	1199	13.87
5(S1+S2)	1	0	1	0	0	1	0	1	19.618	1275	12.75
6(S2+S3)	0	1	1	0	1	0	0	1	28.26	1836	8.85
7(S1+S2+S3)	1	0	1	0	1	0	0	1	33.166	2155	7.54
Retraction	0	1	0	1	0	1	1	0	20.606	1030	9.62

A virtual instrument application implements the command logic for feeding the digital hydraulic cylinder chambers and the data acquisition system for the measured signals.
The electric control block diagram consists of 8 transistors that control the relays coils that supply the solenoids of the hydraulic directional control valves. The commands for the different operating modes of the hydraulic cylinder are given by the virtual instrument application via the electric control block (Fig. 7) which interfaces the digital outputs of the acquisition plate with the parallel distribution block electromagnets.

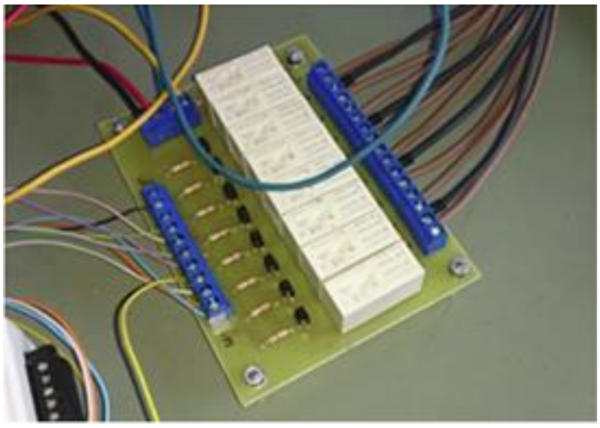


Fig. 7. Electrical command block

The graphical command interface of the application is shown in Fig. 8. The force/ speed step is selectable from the left table (V, F) and the active command of the electromagnets is symbolized by the ignition of a led in the connection diagram confirming the observance of the command algorithm for the three-dimensional hydraulic digital cylinder.

Fig. 8. The graphical interface of the application

LabVIEW offers a graphical programming approach that helps visualize every aspect of the application, including hardware configuration, measurement data, and debugging. This visualization simplifies the integration of measurement hardware, represents a complex logic of the chart, develops data analysis algorithms, and designs customized user interface for engineering.

4. Digital hydraulic cylinder testing with three areas

For the testing of the three-dimensional hydraulic digital cylinder, the test stand was assembled according to the test scheme, the hydraulic and electrical connections for the power and control were made, and the LabVIEW graphical interface was given commands for each combination of surfaces.

Saving experimental data is done automatically by saving the graphs (force, stroke, speed, pressure, flow rate) and the database purchased in real-time testing.

4.1 Test results for variable forces

The result of the variable force test, obtained under the established conditions, is shown in Fig. 9.

Because it is difficult to achieve variable resistive forces during a stroke and at the same time to synchronize with the rod advance steps commands for all the command codes we have opted to perform the variable forces test, at the end of the stroke, with the rod off, at the pressure power supply of 65 bar.

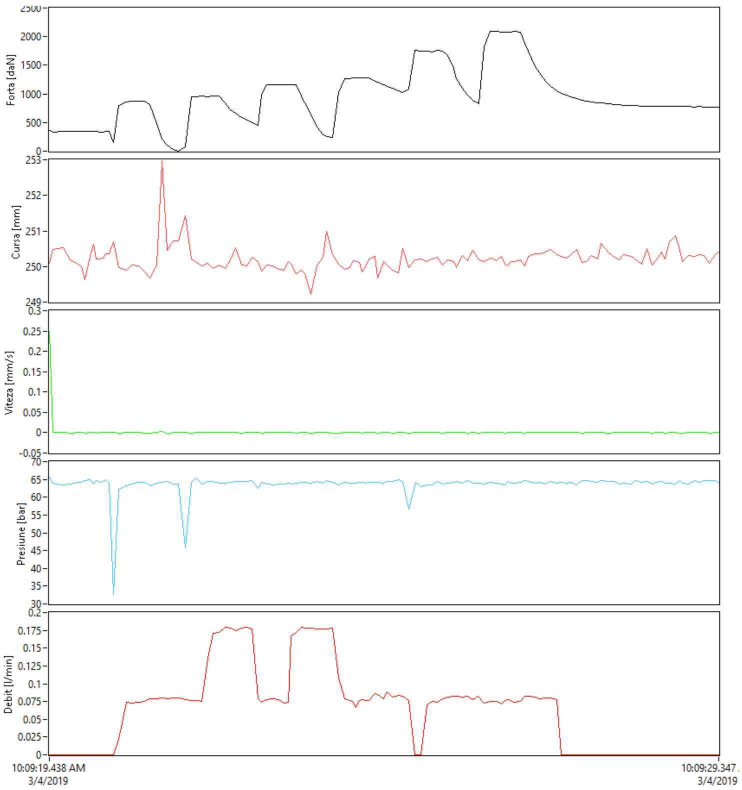


Fig. 9. The result of the data acquisition for the variable forces test at constant feed pressure.

Because it is difficult to achieve variable resistive forces during a stroke and at the same time to synchronize with the rod advance steps commands for all the command codes we have opted to perform the variable forces test, at the end of the stroke, with the rod off, at the pressure power supply of 65 bar.
To compare test results with calculated theoretical values of the strengths steps made by the digital cylinder at a constant pressure supply of 65 bar, these are shown in Table 3.

Table 3: Calculated values of the strengths steps made by the digital cylinder at a pressure supply of 65 bar

Surface	**Area [cm]**	**Pressure force of 65 bar [daN]**
1-S1	4.906	318.89
2-S2	13.548	880.62
3-S1+S2	14.712	956.28
4-S3	18.454	1199.51
5-S1+S3	19.618	1275.17
6-S2+S3	28.26	1836.9
7-S1+S2+S3	33.166	2155.79

It can be noticed that at the supply of the digital cylinder with a constant pressure of 65 bar, there were obtained levels of forces corresponding to the control codes with values very close to the theoretically calculated values.
The graphical command interface of the application allows for sequential control in automatic mode of the control codes according to the cycle with pauses between commands and for this reason,

after achieving a force, its value tends to drop to 0. The small variations of the flow and the supply pressure are due the switching times of the units in the control unit when the cylinder chambers are connected to the pressure or tank depending on the phase of the control cycle.

4.2 Test results for variable speeds

The result of the variable speeds test obtained under the established conditions is shown in Fig. 10.

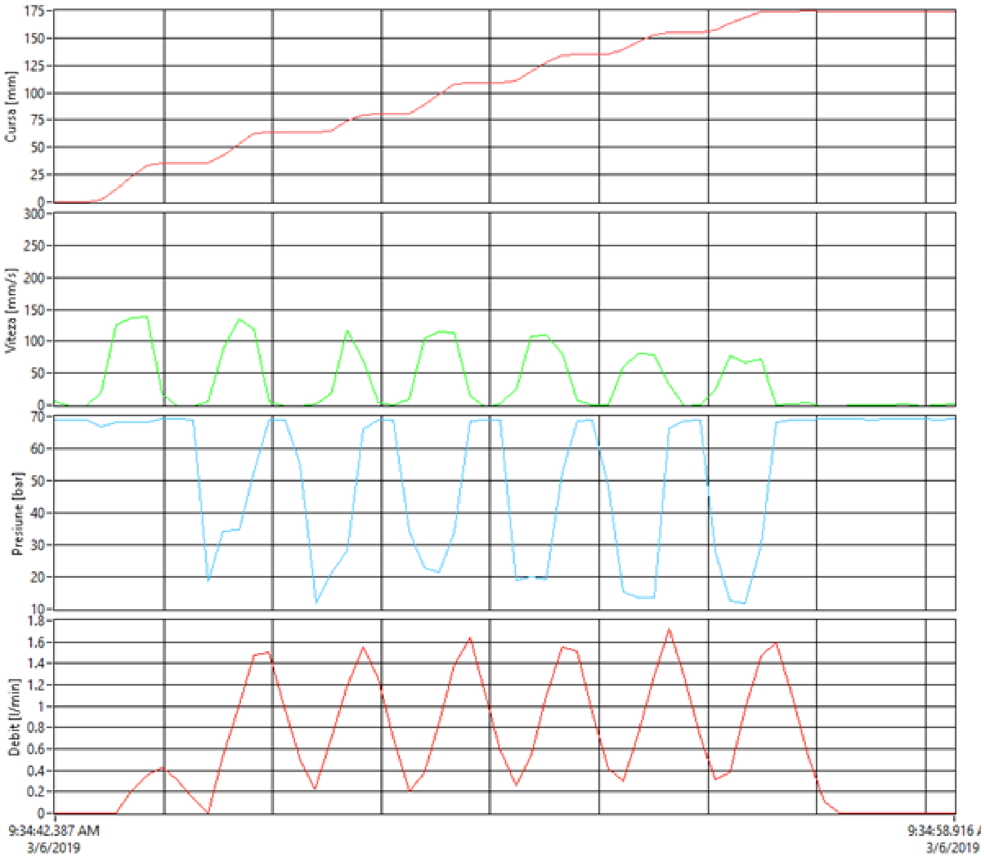


Fig. 10. Result of data acquisition for variable speeds test with constant feed rate.

The variable speeds test was executed in the time of rod advance stroke for each control code. The result of data acquisition for the variable speeds test with constant feed flow rate and the automatic speed steps control of the graphical interface created in the LabVIEW program is shown in Fig. 10.

It can be seen on the data acquisition graph the decreasing trend of the speed values for the seven stages automatic control. The variation of the pressure and flow between the speed steps ordered is due to breaks between commands when the cylinder holes are connected to the tank and the pressure and flow rates tend to drop to 0.

To compare test results with calculated theoretical values of the speed steps made by the digital cylinder at a constant flow rate of 1.5 l / min, these are presented in Table 4.

Table 4: Calculated values of the speed steps achieved at a constant flow rate of 1.5 l / min.

Surface	Area [cm]	Speed at feed flow rate of 1.5 l/min [mm/sec]
1-S1	4.906	51.02
2-S2	13.548	18.52

3-S1+S2	14.712	17.00
4-S3	18.454	13.87
5-S1+S3	19.618	12.75
6-S2+S3	28.26	8.85
7-S1+S2+S3	33.166	7.54

Calculation algorithm for maximum speed:

Calculation of maximum speed:

$$V_{max} = \frac{Q}{S_{min}} = \frac{1.5l/min}{4.9cm^2} = \frac{1.5\cancel{dm^3}}{0.049\cancel{dm^2}X60sec} = \frac{150mm}{2.94sec} = 51.02mm/sec \quad (1)$$

Large speeds of cylinder rod, made at small sections, generate increased flow rates to cylinder chambers with larger sections, which are connected to the tank, leading to large enough pressure drops on the exhaust circuits (basin) and negative influences in the operation of the digital cylinder, because of the created pressure drops, the safety valve of the station reaches to discharge at the basin some of the flow that is no longer constant. The control units in the distribution block must be chosen and dimensioned for the flow rates in each section of the digital cylinder.

5. Conclusions

Adjusting the force and speed of conventional hydraulic cylinders requires expensive and complex pressure and flow regulators, and often in classic control variants with significant energy losses and in demanding fluid filtration conditions.

When using hydraulic digital cylinders in installations that include Hydraulics, the regulation of force or speed can be done with classical instruments with constant flow and pressure supply, without pressure drops in appliances, under normal fluid filtration conditions. The dimensioning of the hydraulic digital cylinders can be done strictly on the desired field by determining the number of surfaces and their size.

Digital technology has the potential to make cheaper, more energy-efficient, more reliable hydraulic systems, but a decisive role will be given to research and technological development in the field. For the digital hydraulic cylinders segment, the challenge is to make simple, technologically feasible, more compact and cheaper technical solutions.

The approach is new and has some challenges. For example, controlling a low speed digital cylinder system is not as good as a proportional hydraulic apparatus, or a variation in the speed of switching of larger diameters digital equipment, or small variations in flow and pressure during switching, or the speed switching still small of the control device. All this is challenging for research in the field, and if solving the application of digital solutions could be a current practice. The first results are very promising, but additional research is always needed.

The hydraulic cylinder digital research stand presented is the first achievement in the field of Digital Hydraulics in the Hydraulics Institute and in the country and allows complete testing, in a dynamic regime, to determine the main functional parameters.

Over the next period, cost reductions and increased energy efficiency will be dominant as success factors for any industry. Hydraulic equipment manufacturers are now due to review their energy consumption solutions. Proper dimensioning and choice of the best technical and economic solutions ever since the design phase could make the hydraulic systems the fastest and most efficient form of power transmission. Energy savings resulting from the implementation of the right solutions can improve the technico-economic performance of the technological lines in which they are used, ultimately reflecting in the execution price of products placed on the market. At the same time, through energy savings and the efficient use of resources, it contributes to the foundations of sustainable development.

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