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Experimental research on energy losses through friction in order to increase lifetime of hydraulic cylinders

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Abstract. Starting from some theoretical considerations, the article presents some experimental results on the assessment of dry and viscous friction forces that occur in the operation of hydraulic cylinders, the basic elements from the structure of hydraulic drive systems. It also presents some specific aspects regarding the durability of the seals of hydraulic cylinders, in order to increase lifetime of hydraulic cylinders, respectively lifetime of hydraulic drive systems.

1. Introduction

As it is known, improving energy efficiency of industrial machinery and equipment is a constant direction of activity for researchers and manufacturers of such products. On this line, a couple of theoretical and experimental research activities have been developed in order to find new technical solutions for driving, and also to assess/quantify their effects in terms of energy, with a goal to improve efficiency of various drive systems. Such research activities have also been conducted for hydraulic and pneumatic drive systems (Fluid Power systems), and the results obtained were very good, especially in cases when electronic control and adjustment systems have been comprised in the hydraulic actuators, this meaning also applying information technology in drive processes and developing intelligent hydraulic drive systems. To improve energy efficiency of hydraulic drive systems, an important direction of action was to increase energy efficiency of each individual component, targeting a decrease in fluid flow and pressure losses, in energy losses, generally speaking, and correspondingly targeting increased efficiency rates and prolonged life span of components.

One of the most important components of hydraulic drives is represented by hydraulic drive motors, which convert hydrostatic energy into mechanical energy. There are three types of hydraulic motors, namely: linear, rotary and reciprocating hydraulic motors.

This paper discusses issues concerning the **linear hydraulic motors**, also generically known as "***hydraulic cylinders***" and presents some experimental research activities conducted in the institute INOE 2000-IHP in Bucharest, Romania, aiming to assess the total energy losses in the operation of a hydraulic cylinder and increase the life span of these components.

These total energy losses include viscous friction losses occurring on fluid flow [1], friction losses that occur in the hydraulic cylinder rod seal [2], friction losses that occur in the hydraulic cylinder piston seals [3] and [4], and also dry (or Coulomb) friction energy losses in rod and piston guides.

An important part in increasing the life span of the hydraulic cylinders is played by durability of sealing systems, which are the first causing decommissioning of hydraulic cylinders.

On this line, the famous manufacturers of hydraulic cylinders, figure 1, have designed, tested and adopted new materials and novel constructive and sealing solutions, figure 2, high efficiency [5].

Figure 1. Hydraulic cylinder developed by REXROTH.

Figure 2. Novel constructive solutions.

By using new materials, which have low friction coefficients, companies have abandoned the old sealing systems, based on **U** or **V**-shaped gaskets / sleeves, figure 3, and they have developed novel innovative sealing solutions, which on the one hand decrease friction losses, and on the other hand lead to prolonged life span of seals, and implicitly prolonged life span of hydraulic cylinders, figure 4.

Figure 3. Piston seal with U-shaped gaskets.

Figure 4. Novel sealing and guidance solutions.

This was the reason why Hydraulics and Pneumatics Research Institute in Bucharest has developed a serious activity of theoretical and experimental research, in order to know the quantitative and qualitative evolution of friction forces during the working cycles, and thus to know all the resistance forces from inside of hydraulic cylinders. For experimental determination of all resistance forces occurring inside of hydraulic cylinders, during the working cycles, there has been designed and developed an experimental device and a test bench, equipped with modern "on-line" system for measuring the evolution of the parameters of interest, which will be presented in the next chapter.

2. Presentation of experimental research infrastructure

In order to determine the resistance forces occurring during operation of hydraulic cylinders, there has been designed and developed an experimental device able to simulate in the laboratory the real operating conditions of a hydrostatic drive system.

This device has been installed on a test bench already existing in the laboratory, capable of generating the alternative forces for driving the hydraulic cylinder under tests.

2.1. Principle of the experimental device

The principle at the basis of developing the experimental device has consisted in using a hydraulic cylinder in the current manufacturing, vertically mounted by means of spherical joints, in order to remove side forces of gravity and bending forces. Actuation of the cylinder rod, during the upward and downward stroke, is done by the existing test bench the cylinder is mounted on. Creating the working pressures inside the cylinder, alternatingly on the two piston sides, for the two directions of work, has been performed by means of hydraulic circuits controlled by pressure valves, which allow generation of pressure stages.

2.2. Determination of resistance forces

Determination of total resistance forces is done separately for each of the two strokes, the upward stroke, figure 5, and the downward stroke, figure 6, of the hydraulic cylinder under tests. For each stroke, one shall write the force balance equation, both on the piston and the cylinder liner.

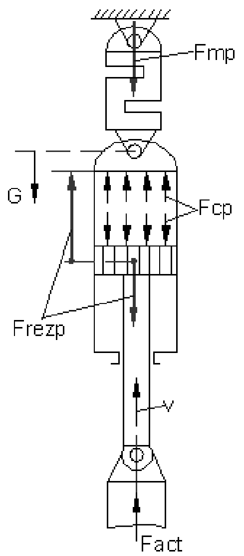

Figure 5. Upward stroke.

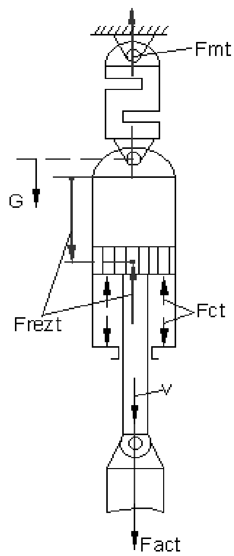

Figure 6. Downward stroke.

In the table 1, are presented the forces balance equations on the upward and downward strokes, both for piston and liner of the cylinder on which the transducer measuring the forces F_{mp}, and respectively F_{mt}, is installed.

Table 1. The forces balance equations on the upward and downward strokes.

Upward stroke, figure 5		Downward stroke, figure 6	
- for piston:		- for piston:	
$F_{act} = F_{cp} + F_{rezp}$	(1)	$F_{act} = F_{cp} + F_{rezt}$	(3)
- for cylinder liner:		- for cylinder liner:	
$F_{mp} + G = F_{cp} + F_{rezp}$	(2)	$F_{mt} + G = F_{ct} + F_{rezt}$	(4)

As one can see in figures 5 and 6, in the above equations, forces F_{cp} and F_{ct} are the hydraulic forces generated by the pressure step (p) at which testing is conducted, applied on the large side of the piston, respectively on its small side. They are calculated automatically by the computing system of the data acquisition and processing system. The forces F_{mp} and F_{mt} are experimentally measured by the force transducer that cylinder liner is suspended to and they are sent to the computing system. The force of gravity G is the total weight of hydraulic parts (cylinder liner, fittings, pressure transducers, gauges and hydraulic hoses) mounted on the cylinder liner. The unknown forces are the resistance forces F_{rezp} and F_{rezt}, which decrease performance of hydraulic cylinders and represent losses in the system.

Experimental research aim is exactly to determine these resistance forces (F_{rezp} and F_{rezt}) and relate them to the calculated nominal forces, produced by the working pressures.

From the above equations (2) and (4), by removing indices p and t, we obtain the calculation relation for resistance forces, in the form:

$$F_{rez} = F_m - F_{cp} \pm G \quad (5)$$

In equation (5), for the upward stroke the force of gravity G enters with minus (-) sign, while for the downward stroke, it enters with plus (+) sign. The computerized system acquires all data, automatically calculates the resistance forces and plots the variation charts for all parameters.

2.3. Presentation of the experimental device

Based on the principle of measuring the forces, shown in figures 5 and 6 and quantified by equation (5), there has been designed the experimental device shown in figure 7, which has been physically developed and installed on the test bench, as one can see in figure 8.

Structure of the experimental device is as follows: hydraulic cylinder under tests HC, spherical joint AS, force transducer FT, bench actuation rod AR, ensuring performing of work strokes, manometer M1 and pressure transducer TP1, on the large piston side, manometer M2 and pressure transducer TP2, on the small piston side, and also hydraulic hoses needed for connecting to the oil tank, by means of two check valves and respectively for connecting to the proportional pressure valves. The pressure steps are controlled directly from the computer keyboard and are kept constant.

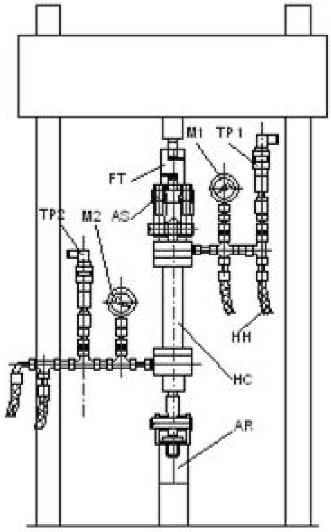

Figure 7. Layout of the experimental device.

Figure 8. The experimental device installed on the test bench.

When performing the both working strokes, the space generated by piston is filled with oil sucked from the tank by means of check valves, the oil being kept at the set pressure, controlled by proportional pressure valves, so are maintained constant the working forces.

3. Presentation of the experimental stand

To conduct experimental determinations of resistance forces occurring in operation of hydraulic cylinders, there has been necessary to develop a complex experimental stand, comprising both the experimental device and the test bench, and also IT system. Figure 9 presents an overview of the experimental stand, and in figure 10 one can see in detail the data acquisition and IT system.

The existing testing bench, presented in figure 11, by its own hydraulic unit, provides vertical movement in either direction; the movable rod (AR) of the hydraulic cylinder of the existing stand ensures the reciprocating movement to the rod and piston of the experimental device.

In figure 12 one can see the pressure transducer and manometer for the pressure above the piston, and figure 13 shows the pressure transducer and manometer for the pressure below the piston.

Figure 9. Overview of the experimental stand.

Figure 10. View of the IT system.

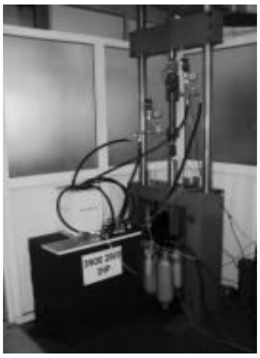

Figure 11. The experimental device on the test bench.

Figure 12. The pressure transducer and manometer above piston.

Figure 13. The pressure transducer and manometer below piston.

Measuring of the piston working stroke inside the cylinder body is done by the stroke transducer presented in figure 14. Figure 15 presents the force transducer used to measure the resistance forces in the piston seals. The oil temperature can be seen on the temperature transducer shown in figure 16.

Figure 14. The special stroke transducer of the existing bench.

Figure 15. The force transducer.

Figure 16. The temperature indicator.

The experimental stand has other transducers as well, such as a digital thermometer for the ambient temperature and also a flow transducer which can measure the oil flow in the main pump of the stand.

By means of special electric cables all signals provided by transducers reach the acquisition board installed on the computer, and this one, based on specialized software, allows capturing, storage and processing of the measured data.

4. Some experimental results

In order to measure and record variation of resistance forces which occur within hydraulic cylinders there has been conducted experimental research which led to obtaining a lot of graphical experimental results; some of them are presented bellow.To this end, there has been necessary to set the parameters of interest and define a testing methodology. The object subjected to an experimental research was a hydraulic cylinder manufactured by Rexroth, having the piston diameter of 40 mm, rod diameter of 25 mm and stroke of 160 mm.

The dimensions of the tested hydraulic cylinder are identical with the dimensions of the main elements of the research devices used to determine the friction forces in rod seal [2] and piston seal, [3] and [4], precisely in order to create the possibility for a comparison of the obtained results.

The methodology for testing the hydraulic cylinder in order to determine total resistance forces occurring during its operation consists in making a series of strokes (1-3 strokes), with certain pressure on the large piston side, during the upward stroke, respectively on the small piston side (on the rod), during the downward stroke. Pressure steps have been created by means of proportional pressure valves (SPP1 and SPP2), with values: 25 bar, 50 bar, 100 bar, 150 bar and 200 bar - the maximum working range of valves. For each pressure step there have been carried out, as a rule, three determinations with three consecutive cycles.

Following the experimental research conducted, there has been obtained a complete set of experimental results, for 5 steps of pressure, with 3 determinations for each step, each measurement having 3 consecutive working cycles. There have been carried out 45 experimental determinations.

For each measurement, there were obtained the complex variation diagrams for the following parameters: the measured forces (F_{mp} and F_{mt}); the working pressure on the large piston side (p_1) and also on the small piston side (p_2); the working stroke (s) and working speed (v). Automatically, by means of the computerized system, there are obtained the values for pressure forces calculated, F_{cp} and F_{ct}, resistance forces F_{rezp} and F_{rezt}, and reports of resistance forces and calculated forces.

The obtained complex graphical variations create a complete picture over the variation of resistance forces during pressure increase.

An example of numerical values of the parameters of interest, obtained at a set of experimental determinations, can be seen for the upward stroke, with pressure on the large piston side, in table 2, and for the downward stroke, with pressure on the small piston side, in table 3.

Table 2. Parameters on the upward stroke.

P_1 [bar]	F_{mp} [daN]	F_{cp} [daN]	F_{rezp} [daN]	F_{rezp} / F_{cp} [-]	F_{rezp} / F_{cp} [%]
25	507.12	491.72	27.40	0.056	5.6
50	819.44	801.93	29.51	0.037	3.7
100	1407.53	1390.00	33.36	0.021	2.1
150	2012.60	1996.20	43.98	0.017	1.7
200	2654.60	2599.72	66.88	0.026	2.6

Table 3. Parameters on the downward stroke.

P_2 [bar]	F_{mt} [daN]	F_{ct} [daN]	F_{rezt} [daN]	F_{rezt} / F_{ct} [-]	F_{rezt} / F_{ct} [%]
25	233.20	238.10	4.90	0.020	2.0
50	411.92	423.52	21.00	0.027	2.7
100	730.06	784.31	54.25	0.069	5.3
150	1062.16	1151.25	89.08	0.077	7.7
200	1386.81	1537.41	150.62	0.098	9.8

There are obtained a lot of complex graphs resulted for each pressure steps and a certain speed step. One experimental result is given in figure 17, where there are plotted the complex characteristic graphs for pressure step values of 200 bar and high speed (theoretically about 100 mm/s). The graphs shown in figure 17a are taken directly from the PC screen, while the graphs shown in figure 17b are the same, but delivered by the computer. From the above graphs one can notice **the repeatability in value** for the 3 consecutive cycles, which substantiates the accuracy of experimental determinations for all parameters of interest (stroke, speed, pressures, and measured forces).

From tables 2 and 3 presented above one can notice that **the total resistance forces** occurring in the operation are proportional to the working pressure of the hydraulic cylinders.

Based on the experimental data listed in tables 2 and 3, there have been plotted the variation graphs for measured forces F_{mp} and F_{mt}, shown in figure 18, for calculated forces F_{cp} and F_{ct}, in figure 19, and also for resistance forces, as quantities in figure 20 and as a percentage in figure 21.

These graphs obtained have been analyzed in detail and there have been drawn some particularly interesting conclusions.

From the graphs in figures 18 and 19 one can see that the measured forces (F_{mp}) and the calculated forces (F_{cp}) are higher on the large piston side, compared to those on the small piston side (F_{mt} and F_{ct}), which is normal, given the different piston surfaces.

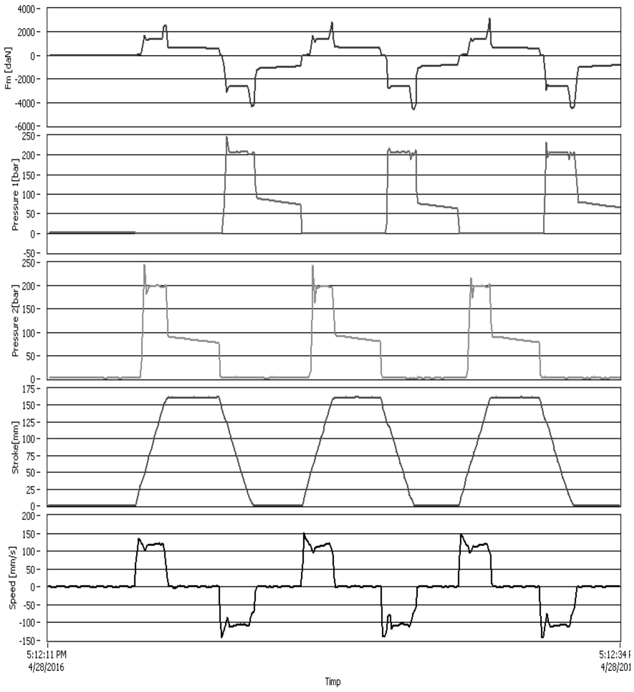

Figure 17. The complex graphs for pressure step of 200 bar.

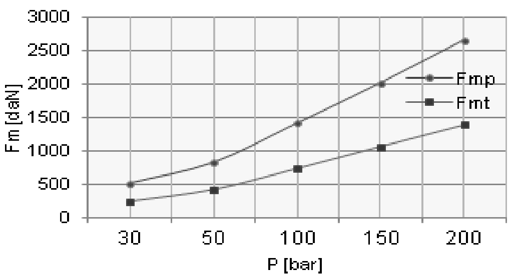

Figure 18. Variation of measured forces.

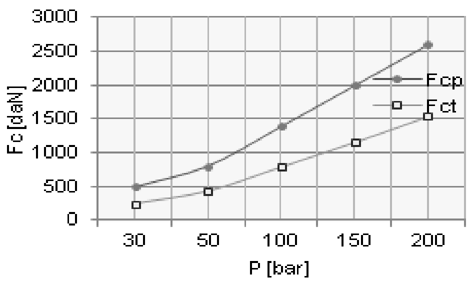

Figure 19. Variation of calculated forces.

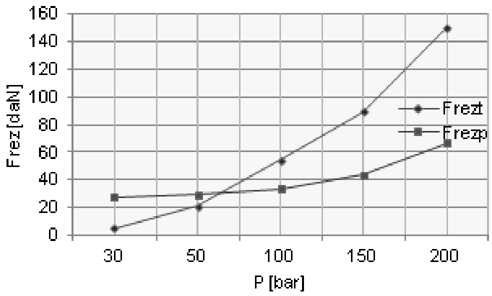

Figure 20. Variation of resistance forces.

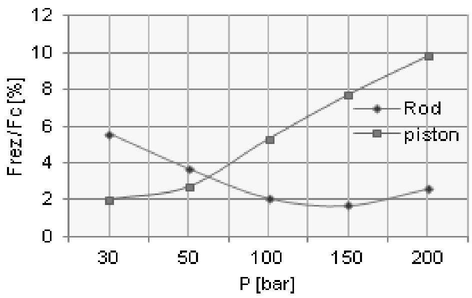

Figure 21. Percent variation of the F_{rez}/F_c ratio.

In figure 20 one can notice that, for the pressures greater than 50-60 bar, the resistance forces measured on the small piston side (F_{rezt}) are higher than the resistance forces on the large piston side (F_{rezp}). This can be explained by the fact that, when pressing ia made on the piston, the resistant forces are generated by friction of the seal and the guidance of the piston, and when the pressing is on the rod, the resistance forces are generated by the friction of the seal and guide on rod and, also, by the friction on the seal and guide of the piston. At pressure under 50-60 bar, the friction forces on seals are most important, compared to the guides forces and, therefore, the forces on the piston are largest.

As a matter of fact, the graphs in figure 21 show that, as a percentage, the ratio of resistance forces (F_{rez}) and theoretically calculated forces (F_c), which is **the expression of energy losses** over the two drive strokes of hydraulic cylinders, is higher on the retraction stroke of the rod than on the extension stroke, and active useful forces are higher on the extension stroke.

In these conditions, energy efficiency is much lower in the retraction stroke of the rod, where losses are (3 – 10) %, and higher in the extension stroke, where losses represent only (3 - 5) %. These values are for innovative materials and novel sealing and guidance solutions, which are much lower than those indicated in the literature, based on traditional solutions, generically estimated at about (10 – 15) %, but no difference is made in terms of losses over each of the two strokes [6].

5. Conclusions

This paper presented the infrastructure and the results obtained following the development of an experimental research, on assessment of total resistance forces occurring in operation of hydraulic cylinders, in order to determine energy losses and efficiency for the two working strokes of cylinders.

Following the design and development of an experimental device and test bench, there have been obtained several complex numerical data and variation graphs for the parameters of interest, which enabled assessment of resistance forces, and respectively assessment of energy losses.

By using a high performance hydraulic cylinder, it has been demonstrated not only that resistance forces are **different as percentage for the two strokes** of the hydraulic cylinder, but also that they are higher on the small side of the piston, where active force developed by the hydraulic cylinder is lower and, therefore, energy efficiency, when performing the retraction stroke, is much lower than the efficiency when performing the extension stroke. On the extension stroke, the losses are much lower, and on the retraction stroke, the losses are higher, but not as high as reported in the literature.

These results and conclusions represent an original contribution of the paper authors.

Decrease of energy losses by adopting novel materials and innovative guiding and sealing solutions results in **increased life span** of the hydraulic cylinders used in hydrostatic drive systems.

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