Experimental Researches to Measure the Total Resistance Forces that Appear at the Switching Process of Directional Control Valves

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The paper presents some results obtained in an experimental research, in order to measure the total resistant forces which appear during the switching process of directional control valves. After some theoretical considerations regarding the possibility to calculate the resistant forces, in the second part of the paper there are presented the research infrastructure, the way in which the experimental research was conducted, and also the main results obtained, as well as some conclusions drawn after analyzing the graphical evolution of the total resistant forces, results which have allowed to determine the total resistant forces, needed for dimensioning of the electric coils or the switching mechanism.

Keywords: Tribology, directional control valve, dynamic seals, frictional forces, test bench
Target audience: Tribology & Fluid, Mobile Hydraulics, Industrial Applications

1 Introduction

Increasing energy efficiency of hydrostatic drive systems involves activities of redesign and experimental testing of each core component of the power transmission flow.

While hydrostatic pumps and motors within classic hydrostatic drive systems are the first target in this respect, there are other components, too, that influence energy losses in the system, among which hydraulic directional control valves play an important role. By their functioning mode / scheme that implies sudden changes in the direction of flow and large variations of the flow sections, there results a turbulent flow, with significant energy losses, which requires optimizing the size of the flow paths of the pressurized working fluid.

Changes in the direction of flow at the input of hydraulic directional control valves and sudden variations of section when switching from a working position to another, in addition to classical mechanical forces, give rise to fluidic forces that need to be measured / assessed as accurately as possible, both by theoretical means through classical calculations or hydrodynamic modelling and computer simulations, and especially by experimental means, which allow accurate determination of their value, and the results thus obtained can be used to validate the mathematical models developed.

Assessing as accurately as possible the total resistance forces which occur when switching the hydraulic spool valves from a working position to another is of a great importance to the design activity, when one determines the force required for switching, especially when this force is generated by an electric coil, and it is even more important for large flow dimensions (rated diameters) directional valves, which by design are to be crossed by higher flow rates.

Directional control valves are some of the most important parts in a hydraulic transmission, Figure 1. It is known that in order to carry out the process of directing pressurized fluid or to stop it, there is required a certain method to generate the switching force of the directional spool valve, and this force can be generated in various ways: in a manual, hydraulic, pneumatic, electric etc. way.

Generally speaking, a directional valve, Figure 2, comprises the following main components: body of the directional valve (1), spool (2), compression springs (3) and, depending on the drive type, various subparts are attached, for example two electromagnets (4) or a drive mechanism (5) /1/.

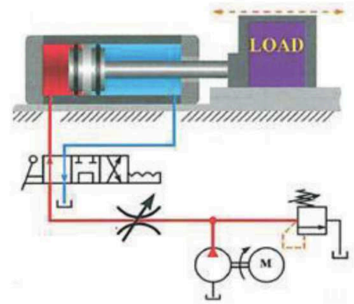

Figure 1: Hydrostatic driving system.

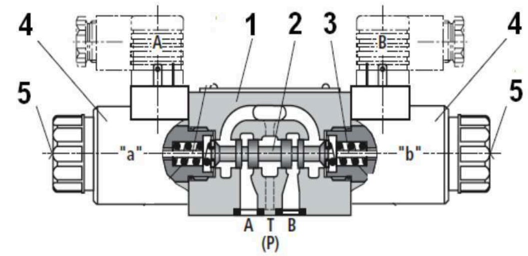

Figure 2: Schematic diagram of a directional control valve /1/.

The spool (or distributor) is the mobile part that connects the inlet port (P) to the outlet ports (A, B); the outlets, and in some versions also the port *P*, are connected to the tank (outlet port T) as well.

There are directional valves with 2, 3 or 4 ports or ways, and 2 or 3 working positions (e.g. 4/2, 4/3).

Figure 3 and Figure 4 below present two flow schemes / sections for the fluid across the body of the hydraulic spool valve, when switching the pressurized fluid flow towards the consumer connected to the port *A*, Figure 3, and Figure 4, when switching the fluid flow towards the port *B*. When performing the switching stroke (-x or +x), the fluid enters the body of the directional valve at an angle of about 69^0, and it develops an **impulse force** upon the spool, and then it goes out through the port *A* or *B*, as appropriate. The initial flow of pressurized oil Q reaches the controlled port, *A* or *B*, with a value of Q_1, decreased slightly because of volume losses q_1 and q_2 occurred through the *metal-to-metal* sealing between the spool valve and the body of the directional valve, and a drive flow Q_{mi}, different from the input one, reaches the input of the hydraulic motor; the difference in flow can be found in the flow leakage at the tank q_{sd}, and partly in the flow Q_{me} discharged by the motor to the tank, which is also decreased because of internal flow losses q_{sm} of the hydraulic motor.

From the above one can note that when the fluid crosses the hydraulic directional valve there occurs a series of oil volume losses, and also pressure losses, and energy efficiency is thus diminished; that is why this aspect requires special attention with the purpose of constructive and energy optimization.

At most hydraulic equipment, **flow forces** occur as a **consequence of the local change of the flow sections**, and thus a consequence of acceleration or deceleration of fluid masses, or a consequence of **changing direction** of flow. The variable flow sections are generated between a cylindrical spool with radial channels and a bush / body of directional control valve with radial channels or slots, most often of circular section /2/. The spool of the directional control valve, by its axial position, controls the flow of fluid Q which enters the directional control valve, and respectively the flow of fluid Q_{mi}, which leaves the directional control valve and goes to the consumer.

The research conducted highlights the fact that **the flow force** actually has two components: a **stationary** component and a **dynamic** one. The **dynamic** component**,** which occurs as a **consequence of the change in flow over time**, acts upon the spool valve in the direction of opening the flow section, in the first case, and in the direction of closing it, in the second case (in the same sense of direction as the stationary flow force), according to equation (2).

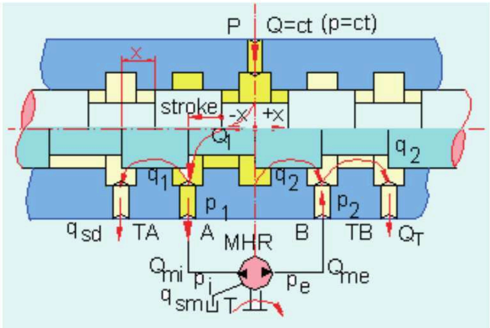

Figure 3: Fluid flow when switching the pressurized flow to the port A.

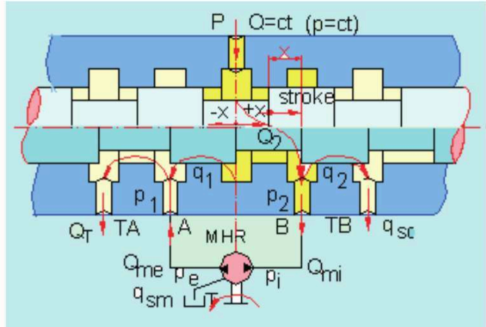

Figure 4: Fluid flow when switching the pressurized flow to the port B.

In paper /3/, the authors aim to analyse the behaviour of the flow force peak values in the initial spool opening of an open center directional control valve and to establish a connection to the behavior of a closed center valve. Finally, a numerical analysis of the flow is performed to confirm and theoretically explain the experimental results. In paper /4/ the authors provided a procedure to analytically estimate the flow force peak value at different pressure drops and flow rates.

The paper /5/ presents an experimental investigation on the significance of the pressure transient flow force acting on hydraulic spool valves. Long time, this flow force effect has been routinely neglected due to its assumed small size. Through analytical and experimental methods, this research shows that flow forces due to pressure transient effects can be comparable in magnitude to the steady flow forces acting on the valve and that the past tradition of neglecting this effect may not always be justified. The paper also shows that the traditional steady flow force model does a fairly good job predicting the steady flow forces on the valve, but more research must be done to develop a good model for pressure transient flow forces.

During the switching operation, which is performed by the movement of spool, the drive mechanism (actuating mechanism) must develop the force required to overcome the **total resistance forces**.

It is known that single stage directional valves are preferred because they are cheaper and most reliable, but increasing the rated size of coils / solenoids, electric actuators, they no longer cope, no longer develop the force required to switch the spool, so for large sizes, i.e. high flow rates, there are preferred multistage directional valves /6/.

That is why, it is very important to determine the resistance forces in both theoretical and the experimental way, especially when a drive electromagnet must be designed.

2 Some theoretical considerations regarding the switching processes

In switching processes of the hydraulic directional control valve from one position to another, Figure 5, for example to achieve the flowing of the fluid Q under the pressure p transmitted by the pump through the port P to the hydraulic consumer connected to the port A of the directional valve where the flow rate Q_1 reaches, as a low flow rate q_a drains through the metal-to-metal sealing of the spool, as shown in Figure 6, the actuator must develop an axial force F_{ax} at least equal to or greater than the sum of forces opposing the movement of the spool /7/.

There are some theoretical considerations regarding the calculation of forces which are acting on the spool when the fluid flow goes through the directional spool valves, Figure 6.

Figure 5: Hydraulic directional control valve [1].

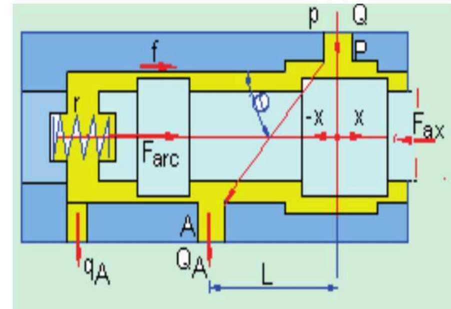

Figure 6: The fluid flow when switching the spool [8].

From Figure 6 one can note that in addition to the **mechanical** forces related to the movement of the spool valve of mass m, there is actuated a quantity of fluid existing along the length L between the ports P and A, which varies over time, and also a **frictional viscous force** that depends on the speed of movement v and the viscous friction coefficient f. In addition to these **dynamic forces** that vary over time, there also occur **static forces** represented by the force in the spring which **varies with spool stroke** x, a spring constant r, and also the **hydrodynamic force** of the **flow of fluid stream** through the hydraulic spool valve, which is calculated on the basis of theorems of impulse and kinetic momentum (Euler's theorems), finally leading us to the equation:

$$F = \rho v Q = \rho v^2 S \tag{1}$$

where: ρ is the fluid density, v is the velocity of flow through the directional valve, S is the section through which flow rate Q of the fluid is flowing. As shown in Figure 2, the flow takes place at an angle θ of about 69° (established by **Von Mises**), so that the projection of the axis of directional valve is given by the following equation, according to /2/:

$$F = \rho v Q \cdot \cos\theta \pm \rho L.\frac{dQ}{dt} \tag{2}$$

By writing the balance equation through projection of the direction of travel, on the X axis, of **all static and dynamic** forces mentioned above, there is obtained the required axial force to be developed by the actuator of the directional valve (solenoid, etc.) according to the equation below:

$$F_{ax} = F_{din} + F_{st} = \left(m\frac{d^2x}{dt^2} + f\,\frac{dx}{dt} + pL\,\frac{dQ}{dt}\right) + \left(p \cdot v \cdot Q \cdot cos\theta\ \pm \rho L.\frac{dQ}{dt}\right) + rx\ + \mu\,(mg) \tag{3}$$

In addition to the forces considered, in spool switching there also occur other forces, of which the bonding force, commonly called stick-slip, is of greater relevance and it is important to the long stay of the spool on a certain position /8/.

Generally, these forces are difficult to be theoretically assessed, so it is **necessary to determine experimentally** the total resistance forces that occur when switching the spool of hydraulic directional valve. Such an experimental determination is presented in the following.

3 Presentation of the experimental research infrastructure

In order to determine the total resistance forces occurring during the functioning of directional valves, there has been designed and developed an experimental device able to simulate, in the laboratory, the real operating conditions of a directional valve, and also a testing methodology. To conduct the experimental research, in the Laboratory of Tribology within INOE 2000-IHP, there was arranged a test bench which includes a data acquisition and IT system, meant to register and process the evolution of parameters, thoroughly presented in /8/.

3.1 Presentation of the experimental device

The principle at the basis of developing the experimental device has consisted in using a manual directional control valve, being in the current manufacturing of the company REXROTH BOSCH GROUP, from its market documents /4/, shown in Figure 7. Since the internal structure of an electrical control directional valve, Figure 8, may be similar or even identical to that of a manual control directional valve, the results of experimental research can be used in calculation and design of electric control coils.

The basic idea used is that, in order to measure the resistance forces in switching of hydraulic directional valves, there should be used the original actuating mechanism for switching, and between the actuating mechanism and the spool of the hydraulic valve there should be interposed a force transducer /8/.

Figure 7: Manual directional control valves /9/.

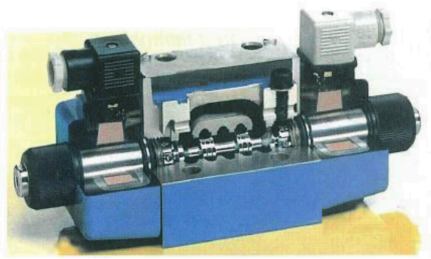

Figure 8: Electric directional control valves.

In order to develop the experimental research aiming at the measurement of total resistance forces that occur in the switching of hydraulic directional control valves, there has been designed a constructive solution shown in Figure 9, based on the use of a manual control hydraulic directional control valve, size 10, /9/, part of the infrastructure of the Laboratory of Tribology within INOE 2000-IHP.

To achieve the experimental device, there has been detached the body of the directional control valve (*1a*) from the mechanism for manual control (*1b*), for placing a force transducer *FT* between the axis of the directional spool valve and the original control mechanism of the directional valve. Physical development of the test device is shown in Figure 10, where one can see the actual technical solutions for developing it.

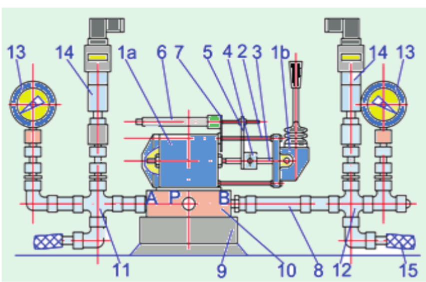

Figure 9: Layout of the experimental device.

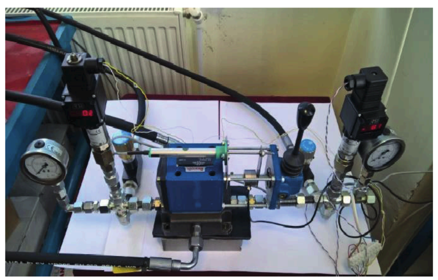

Figure 10: Physical development of the experimental device.

For connecting / coupling the two parts of the main directional control valve, *1a* and *1b*, there were used four threaded rods (2) which have replaced the original screws, thus achieving a space between the two parts of the main directional control valve. In this way, there is created the possibility to insert, by means of threaded sleeves (3), a force transducer (4) between the control rods of the directional spool valve. To measure the stroke achieved by the spool, a rigid blade (5) is attached to the force transducer (4), which drives the rod of a potentiometric stroke transducer (6) that is fixed to the body of the directional valve by a supporting plate (7). The directional control valve is mounted by means of screws on a compatible distribution plate (8) which is placed on another supporting plate (9). From the ports *A* and *B* of the distribution plate (8), pressurized fluid crosses via the two manifolds (11) and (12) to the gauges (13) allowing direct reading of pressure, and also to the pressure transducers (14), by which pressure variations are acquired by the computer system, and through the flexible hoses / piping (15) the fluid reaches the hydraulic motor actuated by the directional control valve /8/.

3.2 Presentation of the experimental test bench

Performing of the experimental research to determine the forces of total hydraulic resistance at switching directional valves has required the design and development of an experimental test bench, inside of the Laboratory of Tribology within INOE 2000-IHP.

The experimental test bench was designed in accordance with the diagram shown in Figure 11 below.

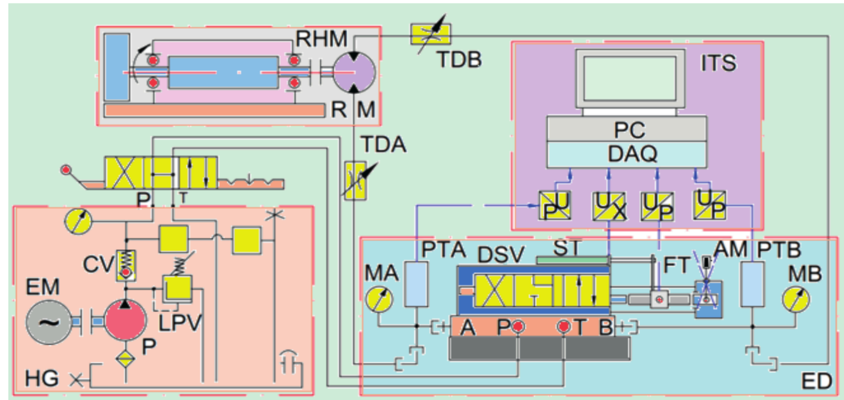

Figure 11: Concept diagram for arranging the experimental test bench.

Besides the experimental device *ED* which contains a force transducer *FT*, a stroke / displacement transducer *ST*, two pressure transducers *PTA* and *PTB*, and two manometers *MA* and *MB*, the test bench also includes a hydraulic mini-station for generating pressurized fluid *HG*, a rotating mechanism *RM* driven by a hydraulic rotary motor *RHM* and a data acquisition and processing system *ITS*, consisting of a data acquisition board *DAQ*, National Instruments type, and a PC type computer. The hydraulic generator *GD* is composed of a gear pump *P* driven by an electric motor *EM*, and assisted by a pressure limiting valve *LPV*, a check valve *CV* and a manual directional valve *MDV* through which pressurized fluid is sent to the ports *A* or *B* of the test device, and from here, through the throttles *TDA* and *TDV*, it reaches the hydraulic rotary motor *RHM*.

Figure 12 presents an overview of the experimental stand, and in Figure 13 one can see in detail the data acquisition and IT system.

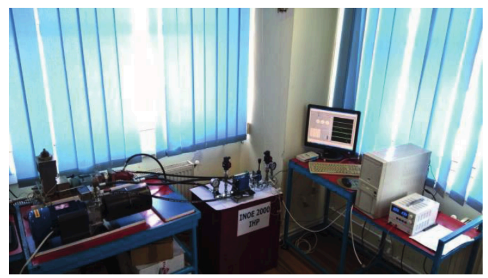

Figure 12: Overview of the experimental test bench.

Figure 13: View of the IT system.

All the signals provided by the transducers reach the data acquisition board *DAQ* installed on the computer, by means of special electric cables, and the *DAQ*, based on specialized software, performs capturing, storage and processing of the measured data.

4 Presentation of some experimental results

The object subjected to this experimental research was a hydraulic directional spool valve, directly operated, with manual actuation, size 10, code 4 WMM 10 J 31/, manufactured by Rexroth Bosch Group, which is a four-way distributor, with three operating positions, the central position providing communication of ports *A* and *B* to the tank *T* and the pump port *P*, closed /10/.

To this end, there has been necessary to set the parameters of interest and define a testing methodology.

With respect to the switching process in hydraulic directional spool valves, the parameters of interest are:

- the spool stroke *x*, measured by the stroke transducer *ST* in Figure 11, item 6 in Figure 9;
- the resistive force *Fax* that opposes the spool movement, which is measured by the force transducer *FT* in Figure 11, item 4 in Figure 9;
- pressure at the port *A*, p_A, which occurs when opening the port *A*, measured by the pressure transducer *PTA* in Figure 11, item 14 in Figure 9;
- pressure at the port *B*, p_B, which occurs when opening the port *B*, measured by the pressure transducer *PTB* in Figure 1, item 14 in Figure 9.

The experimental methodology, thoroughly presented in /8/, consists of performing all the necessary sequences to manually command of the hydraulic directional valve, in order to acquire the signals from all the transducers, and then process them on a computer to obtain variations of interest parameters in numerical and graphical forms.

Following the experimental research, there have been obtained a lot of complete sets of experimental results, for 4 steps of pressure: 25 bar, 50 bar, 75 bar and 100 bar. For each pressure step, each measurement had 3 complete working cycles, for each half of cycle - 3 determinations, which means 6 determinations per cycle, and also for each quarter of cycle - 3 determinations, which means 12 determinations per cycle. In total, there were 21 experimental determinations for each pressure step. For 4 pressure steps there resulted 4x21 = 84 determinations.

After each experimental determination the computer screen displays the complex graphic for all the parameters of interest, as shown in Figure 14. The software especially developed allows one to process and save data in both numerical and graphical forms.

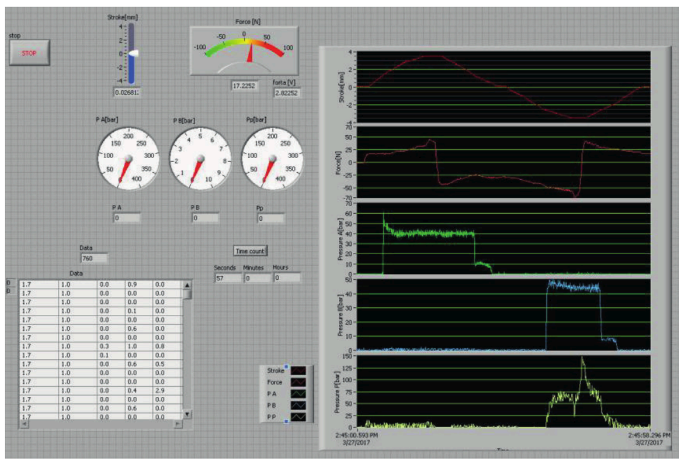

Figure 14: Variation of the interest parameters on the computer screen.

Two examples of complex graphics achieved are presented in Figure 15, for the pressure step of 50 bar, and in Figure 16, for the pressure step of 100 bar.

After analyzing the complex graphs obtained some important conclusions have been drawn, namely:

- the graphs of variation of each parameter of interest have a logical progression, normal and repeatable;
- the pressure values correspond to those directly read on the gauges *MA* and *MB*. They are slightly lower than the pressure values set at the pressure limiting valve (*LPV*) because of pressure losses along the circuits of the hydraulic rotary motor (*RHM*);
- the overall shape of the graph of **spool stroke** corresponds to a full work cycle in the drive / control mechanism with positive or negative values corresponding to the direction of movement of the control handle. Imperfections, small variations on the graph are due solely to the uneven manual drive done by the human operator;

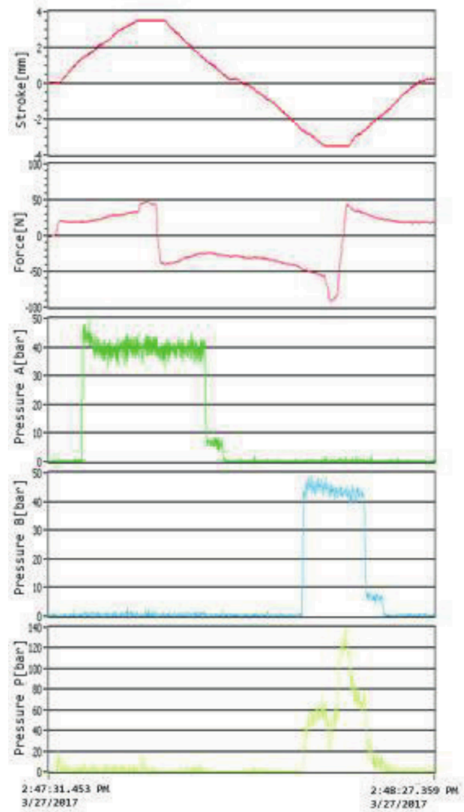

Figure 15: Complex graphs for the pressure step of 50 bar.

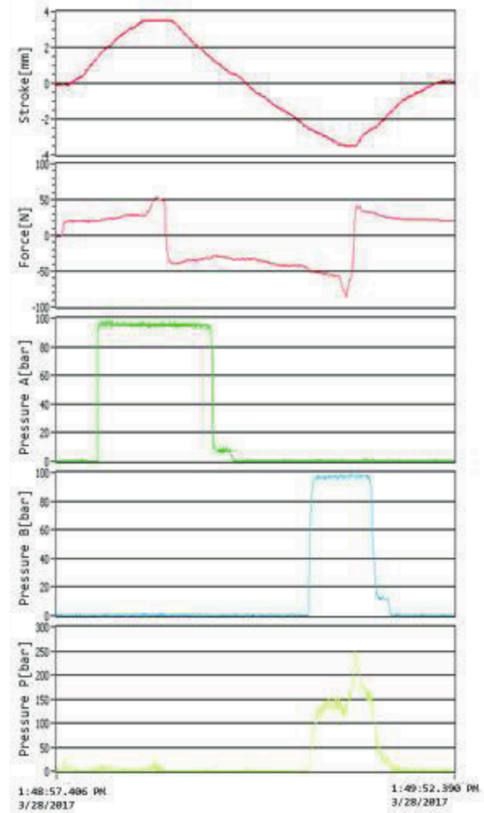

Figure 16: Complex graphs for the pressure step of 100 bar.

- with the exception of the peaks, mean values of the resistance forces over a quarter of a stroke, are within the range (20 - 30) N /10/, when extending the spool, and within the range (30 - 40) N, when retracting the spool, respectively the force transducer, which seems logical and corresponds to the recommendations in the literature /11/;
- comparing the evolution graphs of the resistance forces displayed in Figure 15 and Figure 16, one can notice that, although **the working pressure is doubled**, the resistance forces vary in the same range of minimum and maximum forces (– 50 N, + 50 N), and this is valid for all the pressure steps in the range (25 – 100) bar;

- from a comparative analysis of the graphs of variation of the resistance forces for the **four pressure levels, no significant differences appear** in direct proportion to the increase of pressure value. This may be due to internal pressure balances based on special profiles of surfaces of elements in motion;
- the final conclusion is that the total resistance forces do not depend on the working pressure, and the variation of these forces needs to be investigated in the variation of the fluid flow, research which will further be conducted in the next period.

5 Summary and Conclusion

The paper presents an experimental study developed in INOE 2000-IHP with respect to the assessment of total resistance forces occurring in the switching of a directional control valve, taking into account various pressure levels. There have been presented the research infrastructure and the main results obtained during the progress of this experimental research, and finally some useful and interesting conclusions.

It has been necessary to design and development an experimental device and a test bench, which led to obtaining of several complex variation graphs for the parameters of interest, and this enabled the assessment of resistance forces that occur during the switching process of the directional spool valves.

Following the analysis of the numerical data and complex graphics obtained, it was concluded that the graphs of variation of parameters of interest, especially resistive force, have a normal shape, and their mean values fall in a range of values close to the values mentioned in the technical literature of reference /10/, /11/.

A very important conclusion is that we cannot talk about a significant variation in the resistance forces with increasing pressure, the pressure having a small influence on the switching force of the directional spool valves.

Through the numerical and graphics results, especially through the conclusions reached following the comparative analysis, this paper has special scientific value, and further research on this topic is required.

6 Acknowledgements

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Nomenclature

Variable	*Description*	*Unit*
x	Spool Stroke	[m]
r	Spring Constant	[N/m]
F	Hydrodynamic Force	[N]
ρ	Fluid Density	[kg/m^3]
v	Velocity of the Flow	[m/s]
Q	Flow Rate	[m^3 /s]
S	Area / Section of Flowing	[m^2]
θ	Flowing Angle	[^{0}]
L	Length of Fluid Volume	[m]
t	Time	[s]
F_{ax}	Axial Force	[N]
F_{dyn}	Dynamic Force	[N]
F_{sta}	Static Force	[N]
m	Spool Masse	[kg]
f	Viscous Friction Coefficient	[Ns/m]
μ	Dry Friction Coefficient	[-]

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