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STUDY ON THE FRICTION FORCES IN A SPOOL – SLEEVE PAIR OF HYDRAULIC DIRECTIONAL CONTROL VALVE

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Abstract: *The article presents test results of static friction forces acting on a spool of a hydraulic directional control valve loaded with axial forces and forces related to the liquid flow. The presented results indicate that it seems reasonable to include frictional forces dependent on the size of axial forces acting on a spool in the mathematical models describing spool movement in directional control valves. This type of dependence does not exist in the commonly used models describing the operational dynamics of the spool-sleeve pair, which may affect the achieved levels of compliance with test results.*

Keywords: hydraulic directional control valve, spool loading forces, friction forces of spool-sleeve pair

1. Introduction

Existing research on the behavior of proportional directional spool valves during operation, especially in terms of the positioning accuracy of boom work systems with hydrostatic drive, has shown that the currently used mathematical models do not meet the expected compliance with test results for some ranges of loads. A proportional valve spool described as a simple dynamic system is in most cases analyzed in steady state. Some recent research focused on the development of directional valves operating in unstable positions, but this solution is not currently used in the industry. The above facts prompted the author to re-analyze the commonly used dynamic model of a spool and were the basis for starting a series of laboratory tests. This article presents selected results of tests performed with the use of a proportional spool directional valve which was specially modified for this purpose. The conducted research allowed a proposal to expand the existing spool dynamic model with an additional friction force, the value of which is related to the size of axial forces acting on the spool.

2. Theoretical analysis – spool as a dynamic system

The research work carried out at the Faculty of Mechanical Engineering, Wrocław University of Science and Technology, included tests of boom work tool systems of industrial machines with hydrostatic drive, and showed that the control accuracy obtained when using proportional electrically controlled hydraulic valves does not meet the expectations of process technology. The main problem is the inability to achieve the required accuracy of the work tool position due to the inertia of the boom work system, i.e. in the mining drilling rig. One of the elements that have a significant impact on the work tool positioning accuracy is the reliable operation of proportional spool directional valves.

In the literature, a spool valve is commonly mathematically described as a mass-spring dynamic system moving in one axis (Palczak, 1999 and Stryczek, 2013). The equation of axial forces, in the case when additional seals are absent in the construction, takes the form of the sum of inertia force (F_i), hydrodynamic force of fluid acting on a spool (F_h), friction forces (F_f) and force of a spring (F_s) balanced by external control force acting on a spool (F_{st}):

$$F_i + F_f + F_h + F_s = F_{st} \tag{1}$$

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These forces can be divided into groups in terms of the variables they depend on. Therefore, the elastic force from a spring (F_s) is a function of spring stiffness parameter (c) and displacement of the spool (x). Friction forces with several dependencies, as described in the literature, are always a function of spool velocity ($\frac{dx}{dt}$). Inertial force is associated with the mass of the spool (m) and instantaneous values of spool acceleration ($\frac{d^2x}{dt^2}$). External control force, in the case of electrically controlled valves is a function of coil parameters and supply current (I).

This research aims at developing more detailed models describing the phenomena which occur during the operation of directional spool valves. The first area of research focuses on the assumption of a fixed position of a spool and the experimental determination of the impact of hydrodynamic force on a spool. The second direction of research investigates the use of numerical flow models (CFD) to determine the nature of dynamic phenomena related to the fluid flow in the centric gap which occurs between a spool and a sleeve (Amirante et al., 2006 and Amirante et al., 2007). The third direction of research focuses on the experimental determination of frictional forces loading a spool. This part of research is aimed at developing a dynamic valve model, which is an indispensable stage in an attempt to develop a new valve design based on the dynamic phenomena occurring inside of the valve (Krishnaswamy and Li, 2002, Yuan and Li, 2005).

In the first stage of the present research work, the focus was on the experimental attempt to determine the actual static friction forces acting on the spool valve. In order to broaden current knowledge, a new type of test was developed to determine the magnitude of static friction forces acting on the spool of an exemplary valve in relation to the variable size of forces which maintain the spool in equilibrium when fluid flow has a non-zero value. For this purpose, a change in a design of the tested hydraulic valve was made.

3. Change of spool valve design for experimental tests

The purpose behind the modification of the valve was to replace the force pair system – i.e. the force generated by the coil and balanced by the force of the spring located on the opposite side of the spool – with the forces of the two coils acting opposite each other. In order to achieve this goal, the original valve assembly was modified (Fig. 1).

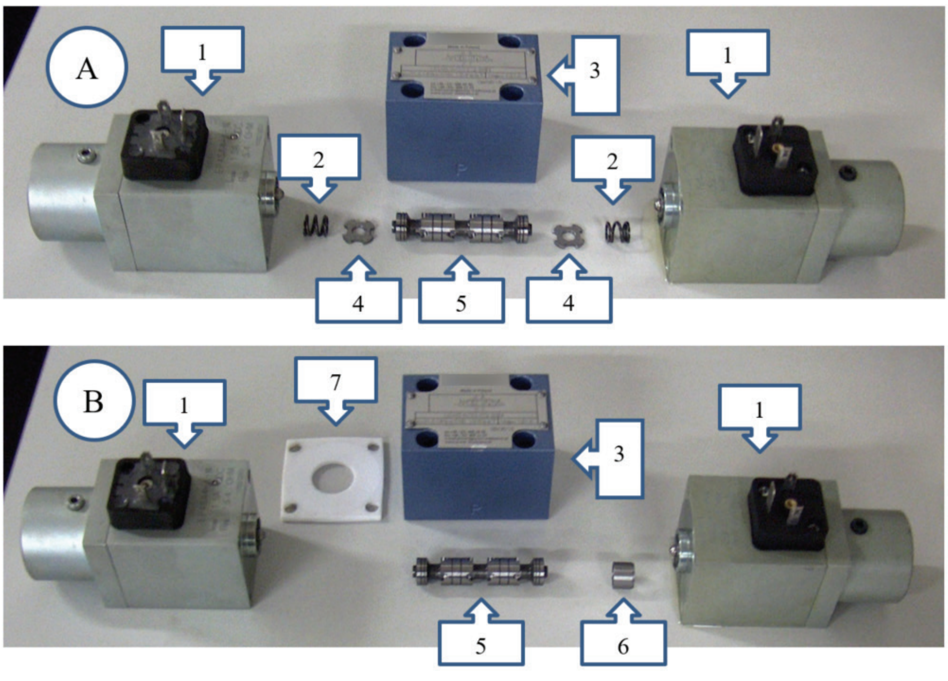

Fig. 1: Standard (A) and modified (B) assembly of proportional valve with a nominal flow of 20 dm^3/min measured for a pressure difference of 1 MPa; 1 – control coil, 2 – spring cooperating with the coil located on the opposite side of the valve, 3 – valve sleeve, 4 – thrust washers limiting the operating range of each spring, 5 – valve spool, 6 – movement limiting sleeve, 7 – washer assembled between the coil and the valve body enabling the operation of both coils in the same displacement range of the spool.

The new assembly of the valve enabled to obtain only two positions, in which the range of movement of the spool corresponded to the range of operation of both coils opposite to each other (Fig. 2). The control coils were supplied from two independent sources. The first coil (S2), which acted with a force preventing the spool from moving (F2) from the initial position (I) to the closed position (II), was supplied with a constant current (I2) equivalent to the constant force acting on the spool, in accordance with coil characteristics specified by the manufacturer. The second coil (S1), whose operation enabled the generation of a force (F1) enabling the spool to move to the closed position (II), was supplied from the system generating a constant increase in the value of current (I1) over time. In the obtained system, the constant force loading the spool (F2) was opposed to the rising force (F1), which enabled determining the difference of the forces moving the spool to the closed position of the valve. The tests were performed on a test rig which allowed different liquid flow rates to be achieved in the directional valve.

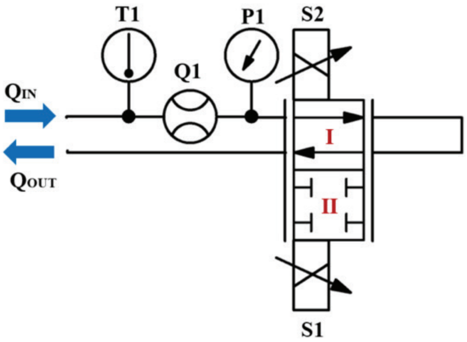

Fig. 2: Scheme of the test system with the modified directional valve, S1 - coil generating force F1 which actuates the valve to the closed position (II), S2 - coil generating force F2 which opposes the actuation of the valve to the closed position (II) and acts to maintain the initial position (I), P1 - pressure gauge on the supply line (P1), Q1 - flow meter measuring the flow rate in the supply line (Q), T1 - temperature transmitter.

4. Test results

During the tests, the following values were recorded as a function of time:

- The intensity of current I1 [A] which supplied the coil actuating the spool to the working position (I) served to determine coil force F1 [N] acting on the spool,
- Voltage U2 of the rising signal controlling the I2 current signal which supplied the coil actuating the spool to the closed position (II) – which served to determine coil force F2 [N] acting on the spool,
- Flow rate in the supply line Q_{IN} [dm^3/min],
- Pressure in the supply line P_{IN} [MPa],
- Fluid temperature in the supply line T_{IN} [°C] – during the tests the medium temperature was maintained in the range of 45÷55 °C.

Fig. 3 shows an example course of external coil forces loading the spool during tests at a constant flow rate.

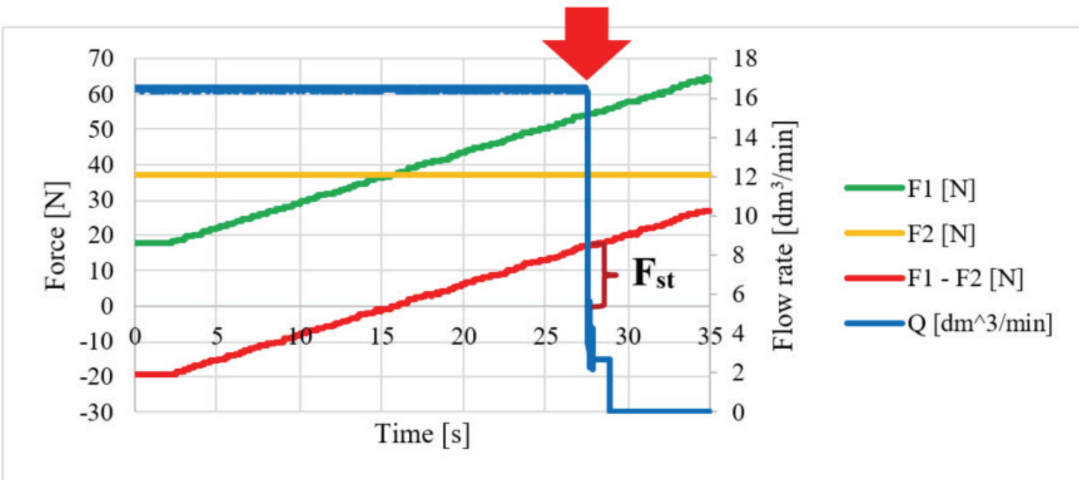

Fig. 3: An example plot of the forces and flow rate during the test of the modified spool valve at the initial flow rate of 16.4 dm^3/min; the arrow indicates the moment of switching the valve from position I to position II.

Full series of test cycles were carried out for different values of force (F2) generated by the S2 coil and for different Q_{IN} flow rates. A strong linear correlation was observed between the magnitude of force F_{st}

(at which the valve spool was moved from working position I to closed position II) and the magnitude of force F2 generated by the coil opposing the displacement. The nature of the observed phenomenon indicates that the static friction force occurring between the spool and the sleeve is related to the size of the axial forces acting on the spool. In other words, the greater the value of external axial forces acting on the spool, the higher the static friction force opposing the movement of the spool. Sample test results are depicted in Fig. 4.

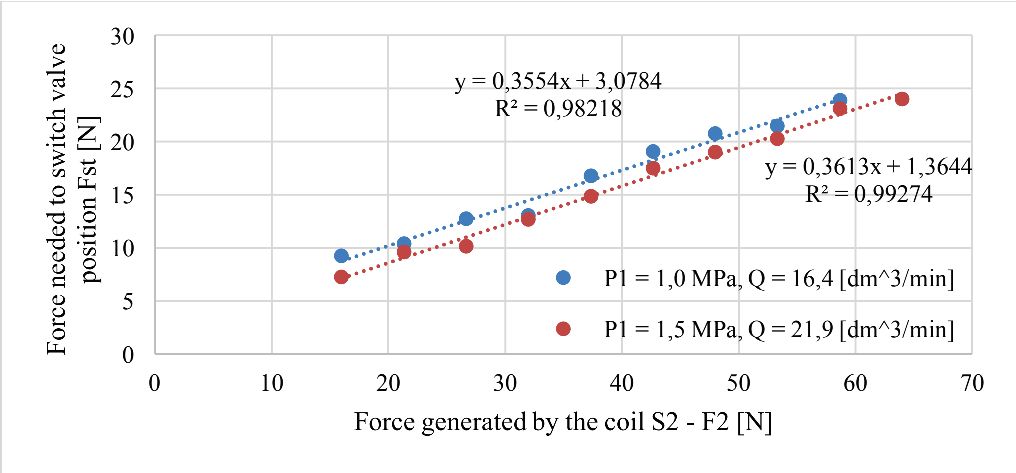

Fig. 4: The plot of F_{st} force values, at which the valve was switched as a function of the force generated by the coil S2 for two flow rates with specified initial conditions of flow and pressure.

The obtained results of experiments allowed to formulate a thesis that it is reasonable to complement the mathematical models of forces acting on a valve spool with a static friction force which is a function of all axial forces acting on the spool. Thus, the new form of the model is:

$$F_T = A \cdot \sum F_{i\,dir} + B \text{ [N]} \qquad (2)$$

where: A – slope of the function determined empirically at the current stage of research, $\sum F_{i\,dir}$ – sum of unidirectional forces acting on a spool [N], B – intercept of the function also determined empirically.

5. Conclusions

The results of the conducted tests clearly indicate that static friction forces occurring between the contact surfaces of the spool and the sleeve not only depend on the values described in the literature, but can also be described as dependent on forces loading the spool. The tests have shown that this relationship is represented with high accuracy by a linear function. The described phenomenon is probably connected with the instability of the spool position in the axis of the sleeve hole, which results in its slight misalignment. Determining the slope of the presented function at this stage can only be done empirically, and its relation to the geometric quantities of the spool and sleeve, viscosity of the hydraulic fluid, temperature and element geometry is a promising field for further research. Importantly, proving the existence of the presented dependence between forces makes it possible to complete mathematical models by describing the dynamics of a spool with an additional factor related to friction forces, and thus to develop models with a greater degree of compliance with test results.

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