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Presenting a Mathematical Model for Determining Oil Leakage in Hydraulic Directional Control Valves with Spool

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Abstract

This article presented a mathematical model for determining oil leakage in directional control valves, based on orifices resulting from spool displacement and clearance. To evaluate the accuracy of the mathematical model presented in different working conditions and to measure the quantities related to oil leakage in the valve including the spool, the design and construction of a hydraulic system was carried out. An acceptable agreement was obtained between the analytical and experimental results in different conditions. Examining the results showed that the use of HL32 and HL68 oils, compared to HL46 oil, in the hydraulic system, respectively, caused a 33.1% increase a 24.4% decrease in the maximum oil leakage, and a 14.2% decrease and a 19.9% increase in the pressure sensitivity of the proportional control valve. On the other hand, increasing the oil pressure in the pump outlet port, from 50 to 100 bar, and 100 to 200 bar, respectively, leads to an increase of 88.6% and 77.8% of the maximum flow gain in the direction control valve. In the same way, by doubling the oil pressure in the pump port, the pressure sensitivity and the flow gain of the directional control valve increased by 33.3% and 41.3%, respectively.

Keywords: Leakage, Pressure Sensitivity, Flow Gain, Mathematical Model.

1. Introduction

In hydrostatic power transmission systems, proportional directional control valves play a critical role in managing the flow of hydraulic fluid. These valves not only facilitate the change in oil flow direction but also enable the adjustment of load speed on the moving components of hydraulic cylinders and motors. This capability is essential for achieving precise control over the operation of hydraulic actuators, allowing for smooth and responsive movement in various applications [1]. The operation of these valves typically involves moving components such as poppets or spools, which alter the communication between different ports and change the direction of the oil flow [2]. Poppet Valves offer better sealing between inlet and outlet ports and are less affected by oil contamination. However, they are less commonly used in hydrostatic systems [3]. Spool Valves, in hydrostatic power transmission due to their dynamic response, lower wear, and more precise control is more prevalent. They require a clearance between the spool and its guide shell, which leads to inevitable oil leakage [1 , 4]. Oil leakage is a significant issue in spool-type directional control valves. This leakage is attributed to manufacturing tolerances, the necessary clearance for spool movement, and pressure differences within the valve ports [3]. Oil leakage in directional control valves, particularly those featuring a spool-shaped moving component, is a common issue that arises from several factors. Firstly, the precision limitations in manufacturing can lead to slight imperfections in the spool and guide shell, which can create gaps. Secondly, a certain clearance is required between the spool's protrusions and the guide shell to allow for smooth movement; however, this clearance can also facilitate oil leakage. Additionally, the varying oil pressures within the valve ports can exacerbate the situation, causing oil to escape through these gaps [5]. In hydraulic power transmission systems, particularly servo-hydraulic systems, oil leakage is often overlooked to simplify design and performance evaluations. However, acknowledging potential leakage is crucial for accurate system analysis and efficiency improvements [6]. Oil leakage in directional control valves can lead to significant issues such as energy loss, environmental pollution, and increased oil consumption. These factors contribute to the creeping motion of external loads, impacting the stability and responsiveness of hydraulic power transmission systems [7].

In recent years, different numerical and analytical models have been presented to predict the volume of oil leakage in directional control valves. Some of the weaknesses of the mathematical and numerical models presented to determine the characteristics related to oil leakage in hydraulic directional control valves include the high complexity of mathematical relations and the inability to use them for designing controllers in servo-hydraulic power transmission systems, the need to conduct numerous experimental tests to determine constant quantities, the inability to use existing mathematical models for different valves, the low accuracy of the results obtained at the moment of valve position change, the lack of proper agreement between the results obtained from solving mathematical and numerical models and experimental results, especially in the valve release state, the lack of continuity in the trend of changes in the volume of leakage oil when changing the valve position, and finally, the inability to predict oil leakage in valves with different overlaps. Accordingly, in this paper, considering the limitations of existing mathematical and numerical models, a novel model is presented that incorporates factors related to valve geometry and the physical properties of oil. This model is grounded in the fundamental relationships that govern oil flow through orifices created by spool displacement and the associated clearances within the valve shell. Then, key performance metrics such as flow gain, pressure sensitivity, and the rate of leakage oil flow are analyzed under different conditions of spool clearance and displacement. Also, To validate our mathematical model, a hydraulic power transmission system is designed and constructed. This system enables us to measure critical parameters associated with oil leakage in directional control valves, particularly focusing on the behavior of spools under various operational scenarios.

2. Methodology

In this paper, at the beginning of the work, a mathematical model was presented to determine the volumetric losses in proportional directional control valves. For this purpose, it is necessary to determine three functional characteristics, including pressure sensitivity, internal leakage flow, and flow gain, in proportional control valves. To estimate the sensitivity of pressure and internal leakage flow in directional control valves, it is necessary to block the channels associated with the hydraulic actuator. In this situation, after calculating the oil flow rate through the orifices resulting from the spool movement and its clearance, it is possible to determine the oil pressure in each of the actuator ports. The pressure sensitivity of the directional control valve is obtained by evaluating the trend of changes in the oil pressure difference in the actuator ports versus the spool displacement. Similarly, in the case of blockage of the actuator ports, the volume of oil passing through the orifices resulting from the spool clearance and its displacement, at the distance between the inlet and outlet ports (P and T ports in the structure directional control valve), will be representative of the internal leakage flow in the directional control valve. Also, the flow gain of the directional control valve is obtained by calculating the oil flow rate passing through the orifices resulting from the spool clearance and its displacement, at the distance between the two actuator ports, under the condition of connecting actuator ports. Finally, to evaluate the accuracy of the presented mathematical model under different working conditions and to measure the quantities related to oil leakage in the directional control valve including the spool, a hydraulic power transmission system is designed and manufactured (Fig. 1).

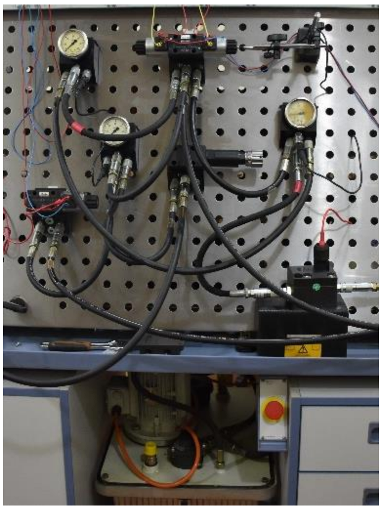
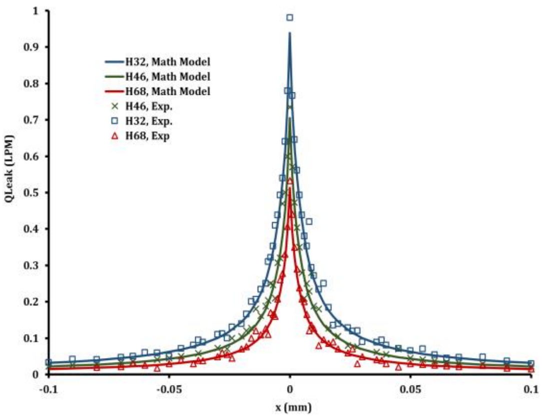


Figure 1. Hydraulic power transmission system for measuring oil leakage in the directional control valve

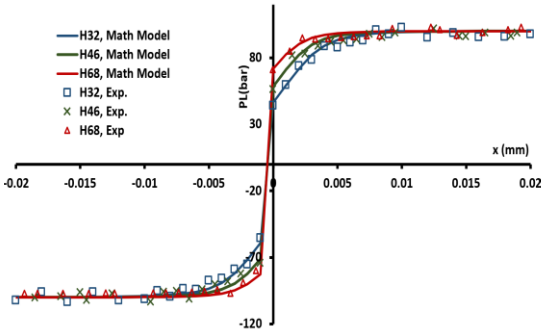
3. Discussion and Results

Figure 2 shows the trend of changes in performance characteristics related to leakage in a four-port, three-position directional control valve, resulting from solving a set of mathematical equations, depending on the spool position, under the influence of three types of hydraulic oils commonly used in the country (HL32, HL46, and HL68 oils). From the findings illustrated in Figure 2a, it is evident that the type of hydraulic oil significantly influences leakage rates in the valve's neutral position. Notably, HL32 oil exhibits a maximum leakage that is approximately 1.33% higher than that of HL46 oil. This suggests that HL32 may have a lower viscosity or different lubricating properties that contribute to increased leakage. Conversely, HL68 oil demonstrates a leakage rate that is about 4.24% lower than that of HL46 oil, indicating that it may provide better sealing characteristics or lower viscosity, which can reduce leakage. Furthermore, when comparing the average leakage flow rates of the three oils in the proportional directional control valve used in the hydrostatic power transmission system (as depicted in Figure 1), it is observed that all three oils-HL32, HL46, and HL68-exhibit higher leakage rates than those predicted by the mathematical model. Specifically, the average leakage flow rates are 4.5%, 4.2%, and 3.8% higher for HL32, HL46, and HL68 oils, respectively. This discrepancy suggests that the mathematical model may not fully account for certain real-world factors affecting leakage, such as temperature variations, oil degradation, or the specific characteristics of the valve components.

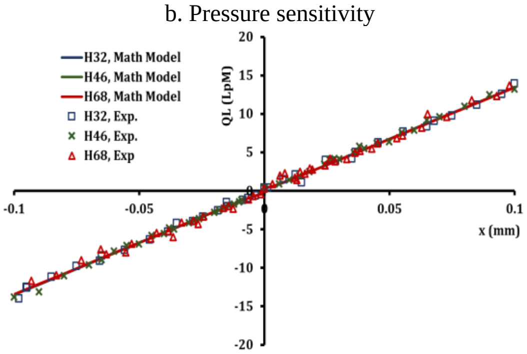
According to Figure 2b, when HL32, HL46, and HL68 oils are used in the hydraulic power transmission system, the pressure sensitivity quantity of the directional control valve is determined to be 3.57, 4.16, and 4.99 $bar/\mu m$, respectively. In other words, when HL32 and HL68 oils are used in the hydrostatic power transmission system, the pressure sensitivity of the four-port, three-position proportional directional control valve decreases by 14.2 percent and increases by 19.9 percent, respectively. Further investigations show that when HL32, HL46, and HL68 oils are used in the hydraulic power transmission system, the results of experimental measurements of the pressure difference due to the directional control valve load are, on average, 1.4, 3.8, and 3.4 percent lower than the results obtained from solving the mathematical model, respectively.



a. Leakage flow rate



b. Pressure sensitivity



c. Flow gain

Figure 2. Performance characteristics related to leakage in directional control valve under the influence of different hydraulic oils

According to Figure 2c, if HL32, HL46, and HL68 oils are used in the hydraulic power transmission system, the gain quantity of the directional control valve is determined to be 1.34×10^{5}lpm/μm. Studies show that if HL32, HL46, and HL68 oils are used in the power transmission system, the results of experimental measurement of the oil flow rate passing through the valve actuator channels are, on average, 4.3, 3.9 and 3.6 percent higher than the results obtained from solving the mathematical model, respectively.

Next, the effect of oil pressure on performance characteristics related to oil leakage in directional control valves is examined. The results indicated that increasing the oil pressure from 50 bar to 100 bar resulted in an impressive 88.6% increase in the maximum oil flow rate of the valve. Similarly, raising the pressure from 100 bar to 200 bar led to a 77.8% increase in flow rate. Moreover, the analysis showed that when the oil pressure in the pump output port is doubled, there is a notable 33.3% increase in pressure sensitivity. This increase in pressure sensitivity is accompanied by a 41.3% rise in the flow gain of the proportional directional control valve. These findings highlight the significant impact of oil pressure on the operational efficiency and performance characteristics of the valve, particularly in terms of flow rate and sensitivity, which are critical for applications requiring precise control of fluid power.

4. Conclusions

The article presents a mathematical model aimed at evaluating oil leakage in directional control valves, particularly focusing on the orifices formed by spool displacement and clearance. To validate this model, a hydraulic system was designed and built to measure oil leakage and other pertinent parameters under various operating conditions. The results demonstrated a strong correlation between the analytical predictions of the model and the experimental data collected across different scenarios. A key finding of the study is that the type of hydraulic oil used has a significant impact on both leakage rates and the sensitivity of the system to pressure changes. Additionally, the research explored the effects of increasing oil pressure at the pump outlet. The results indicated that elevating the pressure resulted in considerable increases in the maximum flow gain through the directional control valve, as well as heightened pressure sensitivity. This suggests that both the choice of hydraulic oil and the operating pressure are critical factors in the performance and efficiency of directional control valves in hydraulic systems.

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