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Hydro-mechanical torque control using hydraulic potentiometer for open circuit axial piston pump

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ABSTRACT: This paper explores the significance of torque control mechanisms in optimizing the performance and efficiency of open circuit axial piston pumps used in hydraulic systems across industrial and mobile applications. The abstract delves into the key aspects of torque control on open circuit axial piston pumps, elucidating its function in limiting torque input to the pump to prevent engine stalling while maximizing engine power utilization. A torque limiter control mechanism is employed to regulate pump displacement, ensuring that the pump operates within the desired maximum torque level available for hydraulic functions. The proposed controller includes a hydraulic potentiometer to provide linear displacement feedback. This control strategy facilitates optimal utilization of input power, dynamically adjusting pump output based on the system's demand for high pressure or high flow.

Furthermore, the integration of torque control with pressure compensator control and load sensing enables the pump to remain within the power envelope of the pressure-flow curve, enhancing system efficiency and stability. The paper also includes the test results of the pump performance with the hydraulic potentiometer

KEYWORDS: Hydro-mechanical torque control, axial piston pump, constant power regulation, horse power control.

I. INTRODUCTION

The Torque Control feature serves to restrict the torque input to the pump, thereby preventing engine stalling while optimizing engine power utilization. Through a torque limiter control, the pump's displacement adjusts dynamically to uphold a predefined maximum torque input to the pump. This specified torque level typically aligns with the maximum torque required for the hydraulic functions of a machine. The primary goal is to regulate the pump's operation to efficiently utilize the available input power. In situations necessitating high force, the pump delivers high pressure, while in scenarios requiring high speed, it supplies high flow. Integration with Pressure Compensator Control and/or Load Sense ensures that the pump operates within the power envelope of the Pressure Flow curve. If the combination of pump flow and outlet pressure exceeds this envelope, the pump automatically reduces its displacement. While referred to interchangeably as Torque Limiter Control and Horsepower Control, the former term is predominant in mobile systems, whereas the latter is common in industrial systems.

II. PROBLEM STATEMENT

As explained, Torque control in open circuit pumps serves to restrict the input torque to prevent engine or prime mover stalling. To ensure effective torque control, displacement feedback is essential. The industry offers four architectural approaches to achieve this function.

The first design involves a feedback spring housed within the servo piston. The opposite end of the servo piston is linked to a spool. As the servo piston moves, the spring collects displacement feedback and transfers it to the spool (refer to figure 1). Typically, nested springs are employed in this design to accommodate high force within limited space. The arrangement of nested springs approximates the required pressure versus flow hyperbolic curve, resulting in a torque curve with a double hump pattern, as depicted in the figure 1.

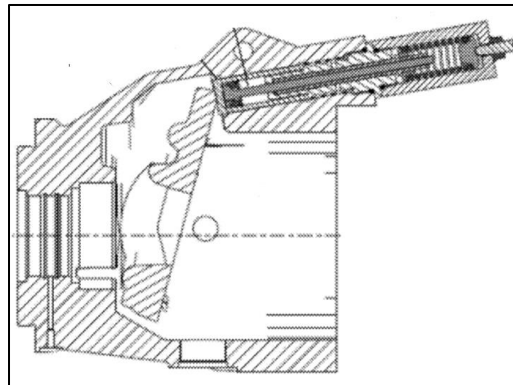


Figure 1 Torque control with feedback spring

The second torque control architecture utilizes external piping, a relief valve, and a cam-slider interface, as illustrated in Figure 2. The cam-slider interface comprises a smooth profile machined on the servo piston, enabling a ball-type poppet to slide along this profile, hence the name cam-slider. Displacement feedback is acquired through this cam-slider interface and directed to the relief valve. As the servo piston moves, the relief valve poppet shifts upward, creating an opening that adjusts the signal pressure received by the modified load sense, consequently de-stroking the pump. In contrast to the first architecture, this design presents limitations. Firstly, it precludes the utilization of load sense functionality, which restricts the system's adaptability and responsiveness. Moreover, the inclusion of external piping introduces challenges related to packaging and transportation, as these components are susceptible to bending and cracking. Additionally, the presence of external piping, at times employed for lifting the pump, poses undesired complexities. Furthermore, the cam-slider interface is prone to surface wear over time, exacerbating issues such as jerks resulting from servo piston stick-slip phenomenon.

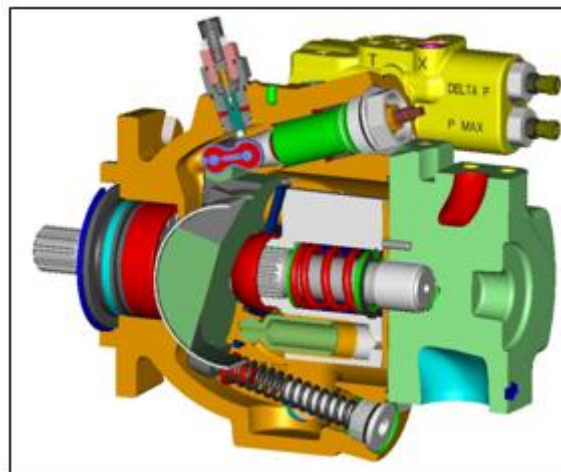


Figure 2 Torque control with cam slider interface & external piping

The third design approach for torque control in axial piston pumps entails mounting the control mechanism directly atop the servo piston, depicted in Figure 3. In this configuration, displacement feedback is obtained through a complex linkage design. While this design represents an improvement over the preceding two, it still yields an approximation of the hyperbolic power curve due to its reliance on springs and mechanical feedback. Additionally, a drawback of this design is the increased height of the pump resulting from the direct placement of the control mechanism atop the servo piston. Furthermore, the assembly process becomes more intricate, adding complexity to the overall system.

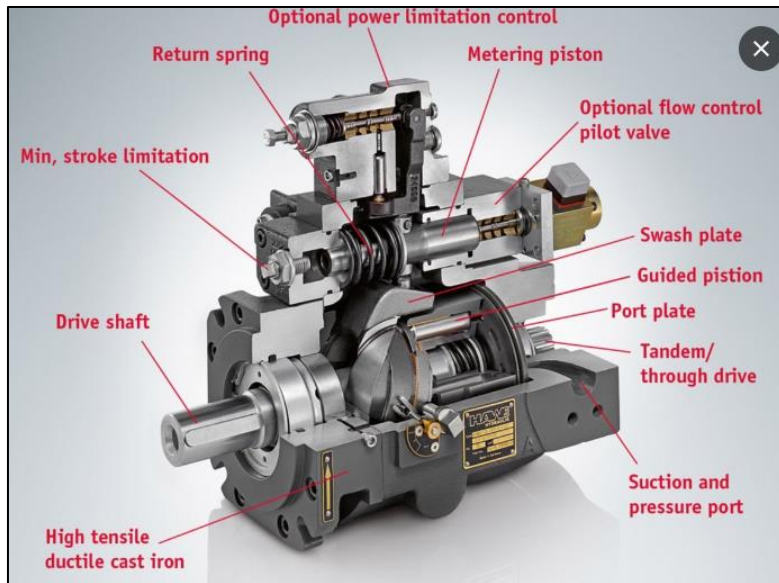


Figure 3 Torque control with linkage feedback

The fourth design variant relies on sensor technology and a solenoid proportional pressure limiting valve, illustrated in Figure 4. Known as Electronic Torque Limiting control, this system integrates a normally closed proportional relief valve (PRV) into a Pressure Compensated/Load Sensing (PC/LS) control configuration. Operating as a PC/LS control, it possesses the added capability of limiting load sense pressure through the integrated PRV by adjusting the solenoid current. When coupled with an angle sensor, this setup enables PC/LS control with electronic torque limiting functionality. This Electronic Torque Limiting control empowers users to electronically restrict pump torque consumption by merging a pressure-limiting PRV and an angle sensor. This torque limitation can be dynamically adjusted with varying engine speeds, facilitating the utilization of full engine torque across all engine speeds and enhancing overall machine productivity. However, it's worth noting that this solution entails a higher cost due to the requisite sensors and microcontroller.

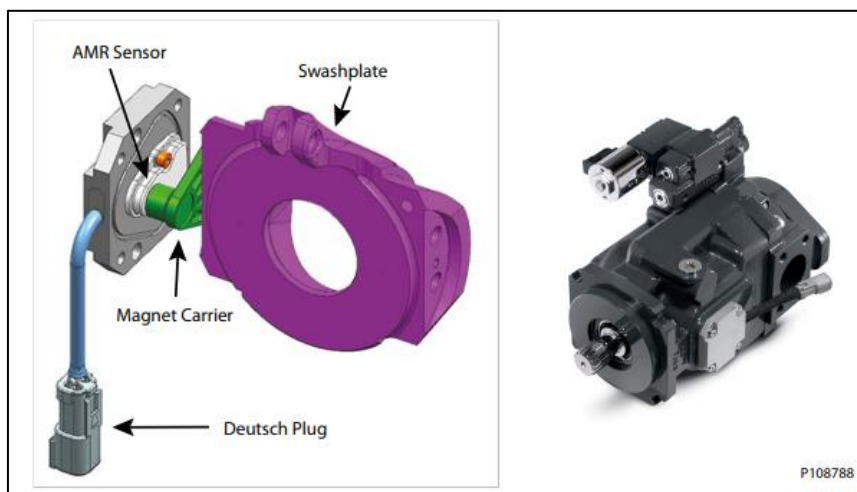


Figure 4 Electronic torque limiting

The graph in figure 5 depicts the flow versus pressure and displacement versus torque characteristics of torque controllers currently available in the market. It is evident from the graph that the majority of pump torque controls exhibit an approximation of the hyperbolic curve, leading to a loss in productivity. Additionally, the prevalent use of

dual spring arrangements in these designs results in torque curves with double humps, as illustrated in Figure 5. Furthermore, conducting end-of-line testing for these torque control systems is intricate and time-consuming.

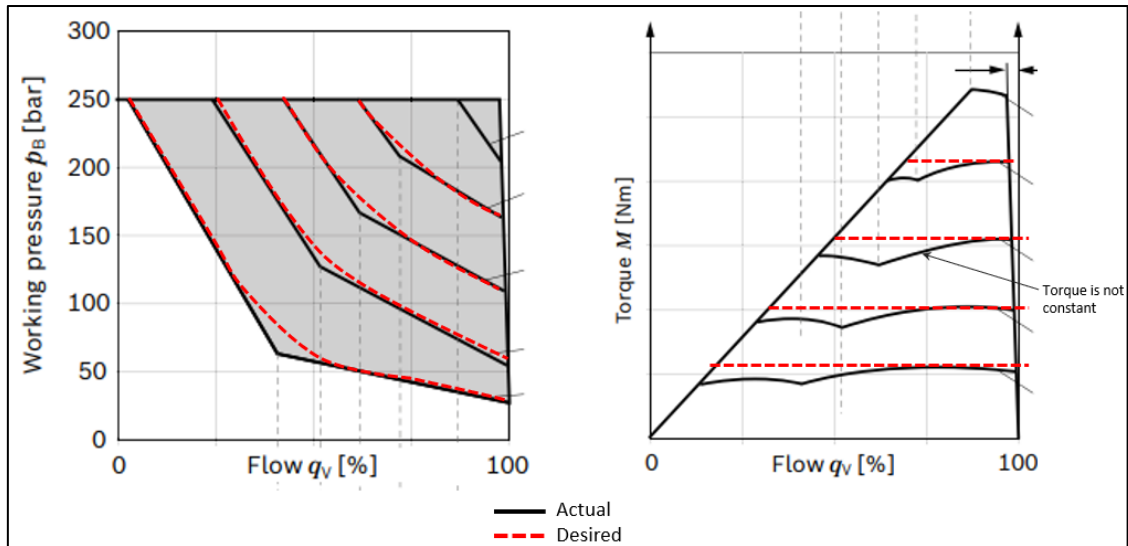


Figure 5 Torque control characteristics

III. DESIGN

Proposed concept design

The schematic of the open circuit axial piston pump with the proposed hydro-mechanical torque control is shown in figure 6.

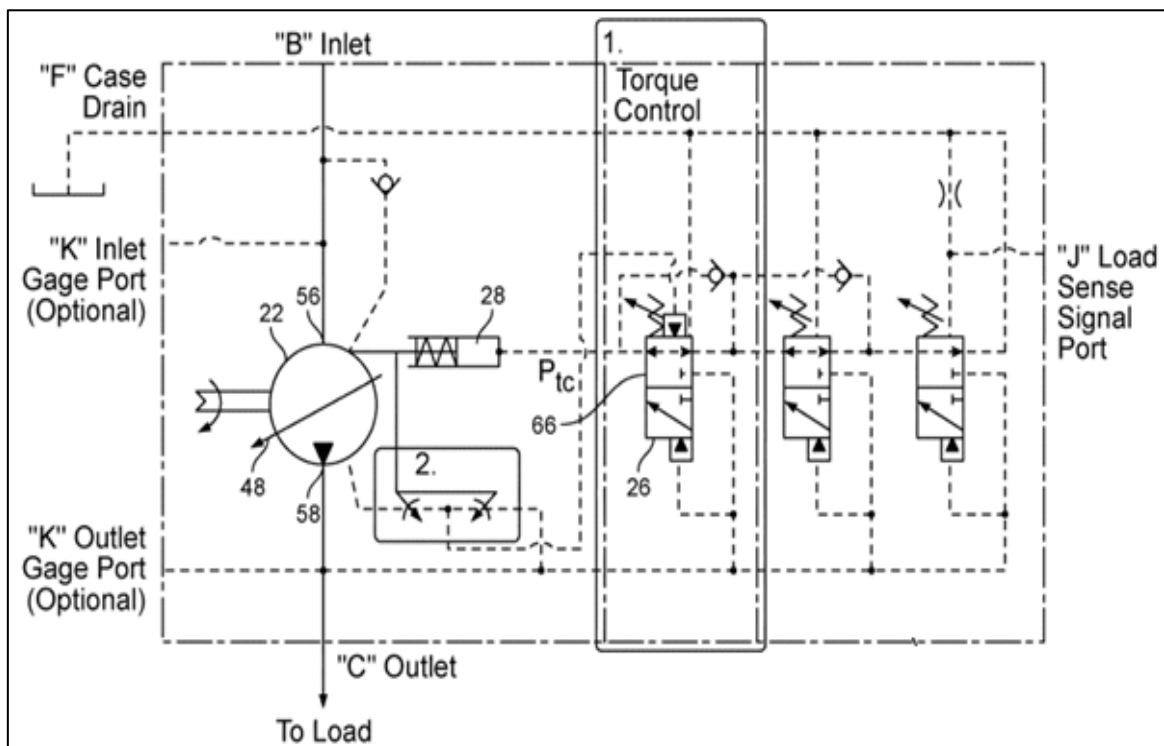


Figure 6 Schematic of Open circuit pump with torque control

The Hydro-mechanical torque control has two primary elements that provide the torque limiting function of the pump. A control valve, which his constructed like and functions like a standard load sense or pressure compensator valve. A ‘hydraulic potentiometer’ that generates a torque limiting signal pressure, P_{TC} which is directed to the control valve spring chamber. See figure 7

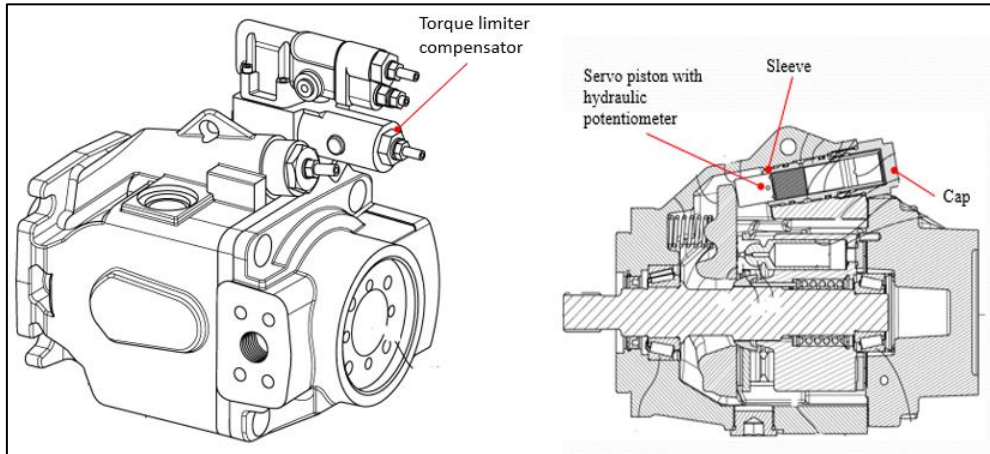


Figure 7 Torque control concept

Torque limiting compensator

The control valve is designed and operates similarly to a conventional load sense or pressure compensator valve. However, in this configuration, a signal pressure, denoted as P_{TC} , is directed to the spring chamber instead of being based on case pressure or load sense pressure. When the force exerted by the pump outlet pressure, P_{out} , on the right area of the spool exceeds the combined force of the signal pressure, P_{TC} , acting on the left area of the spool along with the preload force of the spring, F_s , the control valve redirects pressure/flow to the control piston, causing the pump to de-stroke.

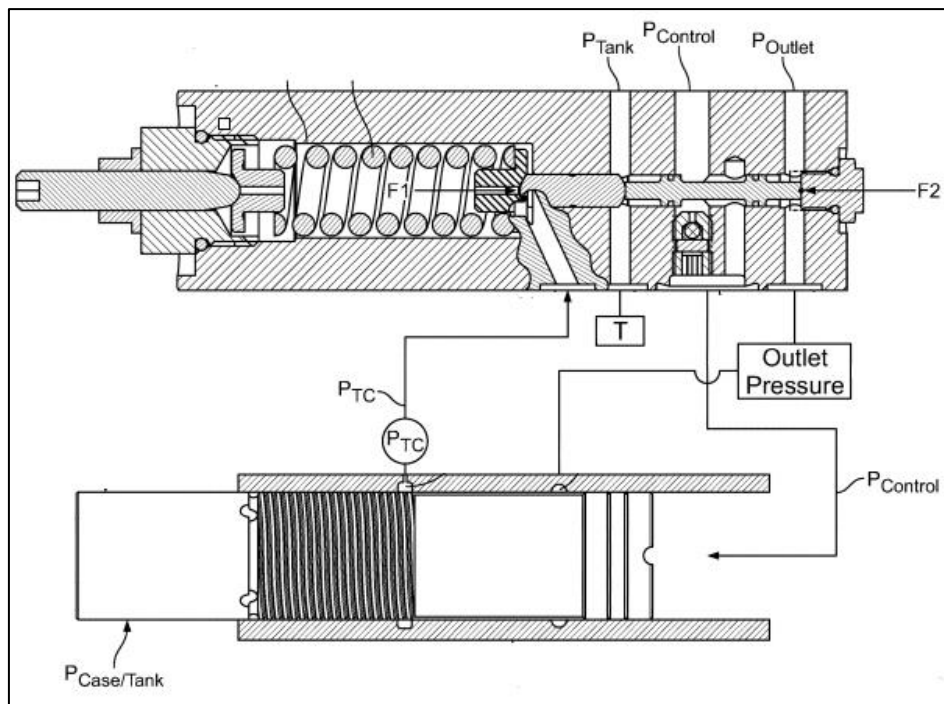


Figure 8 Torque limiting compensator and hydraulic potentiometer

Hydraulic potentiometer

The hydraulic potentiometer, depicted in Figure 9, operates on a principle akin to fluid mechanics. It capitalizes on the known behavior that a fluid moving through a narrow capillary tube experiences a linear drop in pressure from high to low. By measuring this pressure, one can ascertain the fluid's position along the tube. This fundamental concept forms the basis of the torque control mechanism. Rather than employing a straight capillary tube, a spiral groove, resembling the thread of a screw and machined onto the outer surface of the servo piston, is utilized.

The hydraulic potentiometer produces a signal pressure, denoted as P_{TC}, which is determined by the multiplication of the pump outlet pressure, P_{out}, and the pump displacement, D. This pressure is then directed to the spring chamber of the control valve. P_{TC} rises in proportion to P_{out} and diminishes relative to the displacement, D.

$$P_{TC} = \begin{cases} P_{out}, & D = 0 \\ 0, & D = 100\% \end{cases}$$

Expressed in closed form:

$$P_{TC} = P_{out} (1 - D)$$

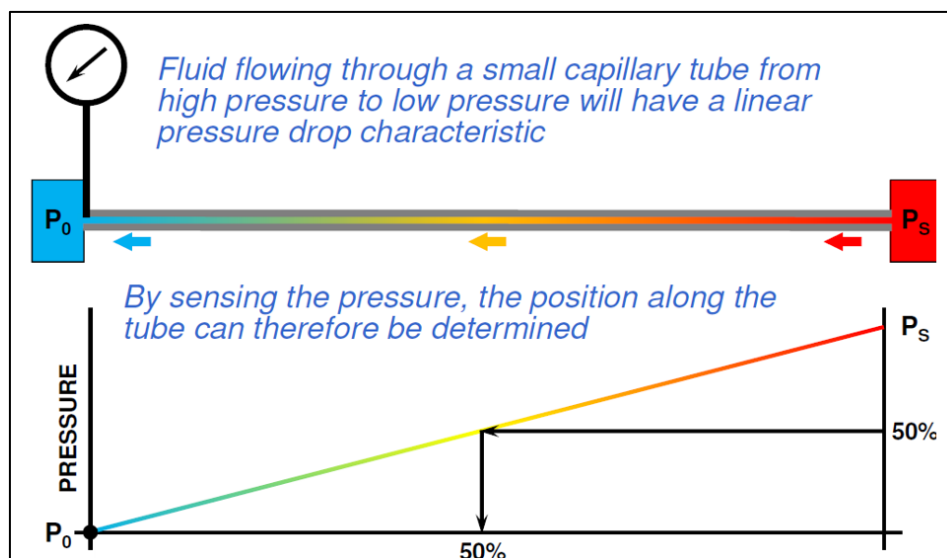


Figure 9 Hydraulic potentiometer principle

When the hydraulic potentiometer generates a signal pressure according to the aforementioned relationship, it ensures a consistent torque limit. This mechanism relies on two primary components: the control piston, which moves alongside the swash plate, and the sleeve, which is attached to the housing and serves as the piston's path. In a pump equipped with torque control, the servo piston remains identical to one without torque control, except for the addition of a spiral groove. This feature forms a lengthy, slender "pipe" connecting P_{out} to P_{tank} (zero gauge pressure). Within this conduit, the pressure decrease from P_{out} to P_{tank} occurs linearly along its length. Utilizing a spiral groove, as depicted in Figure 10, is preferable for creating the "pipe" feature over employing a fixed clearance annular leak or a straight axial groove. This preference arises because the spiral design offers greater robustness in maintaining a linear signal, which is crucial for accuracy in torque limitation, particularly when considering manufacturing tolerances. The spiral feature effectively mitigates variations in annular clearance between the piston and the bore, as well as any eccentricity or tilting of the piston within the bore.

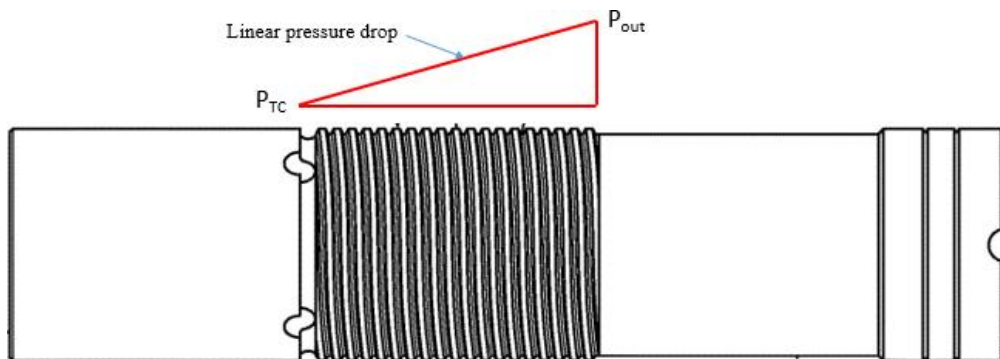


Figure 10 Spiral grooves on servo piston

Considering the servo piston, it's important to note that the annular clearance between the housing bore (the sleeve bore) and the piston's outer diameter is significantly smaller compared to the cross-sectional area of the spiral groove. As a result, the predominant flow occurs along the spiral path. Due to the multiple wraps of the spiral around the piston, the length of the "pipe" is considerable, resulting in a situation of low flow. This characteristic enables a consistent pressure drop, even when accounting for manufacturing tolerances.

The signal pressure, P_{TC} , measures the pressure at a specific point along the piston, which remains fixed relative to the housing/sleeve. It's positioning, along with the axial length and the starting/ending positions of the spiral feature, are meticulously arranged. This arrangement ensures that the signal pressure corresponds to outlet pressure when the displacement is zero and to tank pressure when the displacement is at its maximum. As the control piston moves in a linear manner with the pump displacement, the signal pressure registers pressure in a linear fashion relative to displacement, given a constant P_{TC} value.

Feedback Pin

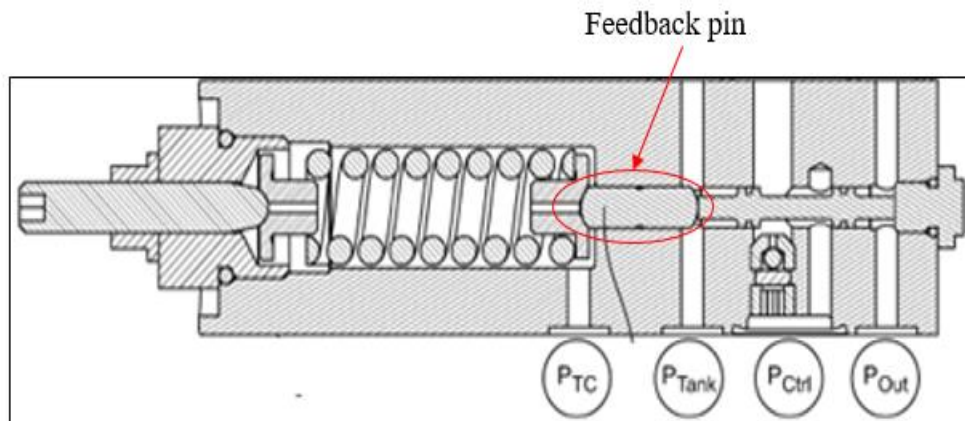


Figure 11 Control valve - Torque limiting compensator

The feedback pin shown in figure 11, characterized by a larger diameter (A) compared to the spool's diameter (B), responds to P_{TC} , while the smaller-diameter spool reacts to P_{out} . There is an initial pressure decline, known as minor losses, during the transition of oil from the wider annulus encircling the servo piston to the narrower pipe, coinciding with an escalation in oil velocity. The discrepancy in diameters plays a vital role in minimizing the impact of both minor losses and pump losses.

IV. EXPERIMENTAL ANALYSIS & RESULTS

Experimental Setup

The hydro-mechanical torque control performance on the pump must be checked to observe its functionality and stability. The experimental setup is similar to actual application of the pump with torque control on the machines with engine as prime mover. Following points need to be verified through the testing.

1. Torque control functionality,
2. System stability
3. Whether the control produces the desired hyperbolic power curve.

Figure 12 displays an open circuit variable displacement pump featuring pressure, flow, and torque control compensators on the test stand. The pump is linked to the electric motor shaft, serving as the prime mover. A manifold connected to the pump outlet port houses a direction control valve and a proportional pressure relief valve. The proportional pressure relief valve is utilized to impose a load on the pump, thereby elevating the system pressure. Notably, the load sense functionality is disabled for the duration of this testing. Various sensors, including those for pressure, speed, flow, and temperature, are employed to accurately measure their respective parameters.

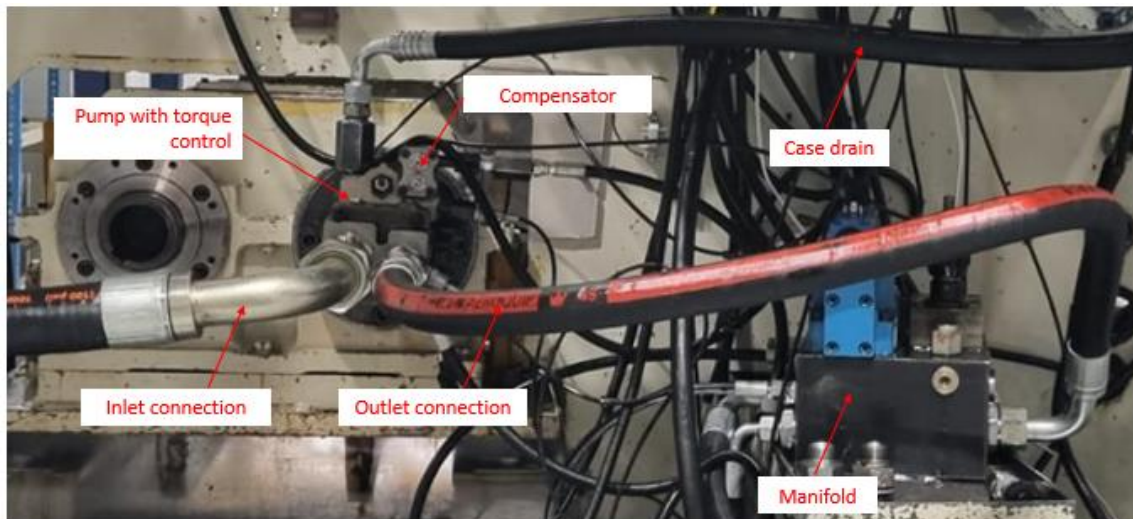


Figure 12 Pump with torque control on test stand.

The proportional relief valve's pressure settings are contingent upon the input current signal, which is regulated by a controller to adjust the valve and elevate the system pressure as required. Testing is conducted across various input speeds, pressures, and temperatures. The torque control compensator is configured to uphold a consistent torque of 47 Nm. Employing an open circuit variable displacement axial piston pump with an 18cc displacement, tests were conducted at 1500, 2000, 2700, and 3000 rpm, with results meticulously recorded. A swash angle sensor is employed to precisely capture the swashplate angle.

To evaluate the torque control functionality, a pressure ramp test is conducted. This test involves gradually increasing the pump outlet pressure from low to high levels and subsequently reducing it. The ramp-up and ramp-down durations are maintained at approximately 45 seconds each, with a 5-second hold period. This precise control is achieved by modulating the input current to the proportional relief valve of the test stand in a linear fashion.

V. RESULTS

During testing, the outlet pressure of the pump was systematically increased from its minimum value to 280 bar before being gradually reduced. Figure 13 illustrates the plot depicting pump input torque, outlet pressure, and displacement over time, with the X-axis representing time and the Y-axis representing torque, pressure, and displacement. Observing Figure 13, it becomes apparent that despite the continuous rise in pressure, the pump input torque remains capped at 47

Nm. This is achieved through the reduction of the pump's displacement, as evident from the figure. Notably, the torque curve maintains a consistent flat profile, exhibiting no variation as the pressure escalates.

Figure 14 illustrates the pressure versus torque curve for the tested pump. The X-axis represents pressure, while the Y-axis represents pump input torque. Remarkably, the plot exhibits minimal hysteresis. This notable characteristic can be attributed to the displacement feedback mechanism facilitated by the pressure PTC received through the potentiometer. As the outlet pressure escalates, the pump adeptly adjusts its displacement, continuously de-stroking to uphold a constant input torque level.

As previously discussed, existing designs lack a hyperbolic power curve primarily due to their reliance on dual spring arrangements. In contrast, this concept, rooted in hydraulic feedback mechanisms, yields a flow versus pressure curve that closely approximates the ideal hyperbolic form, as depicted in Figure 15. Here, the X-axis represents pump outlet flow, while the Y-axis denotes pump outlet pressure

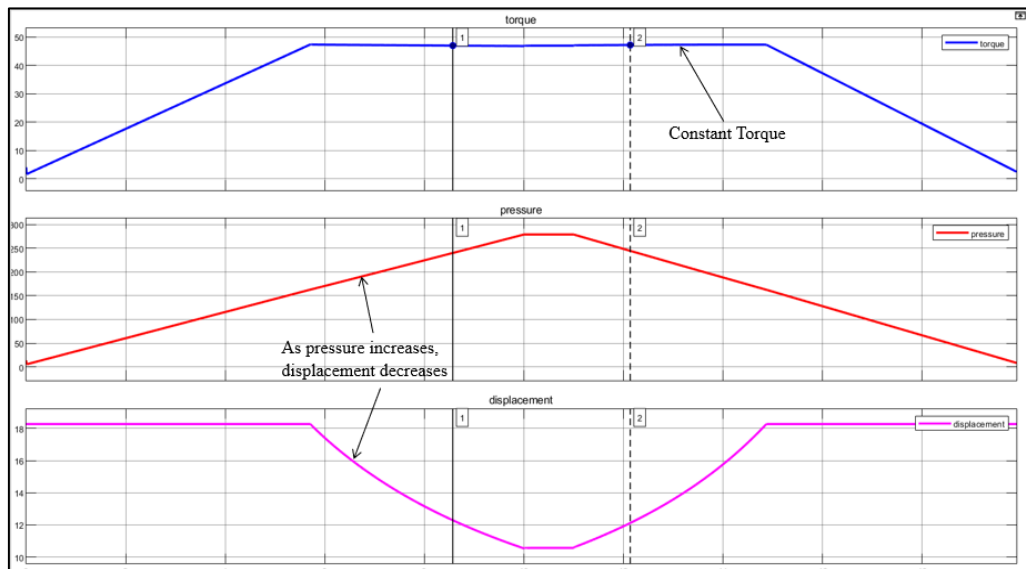


Figure 13 Torque, pressure, displacement vs time

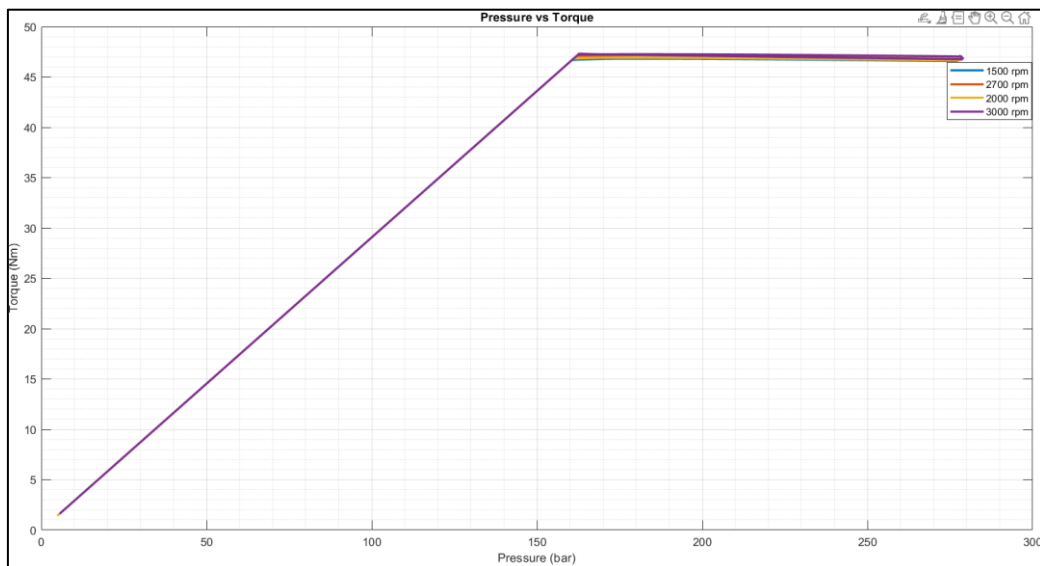


Figure 14 Outlet pressure vs Torque.

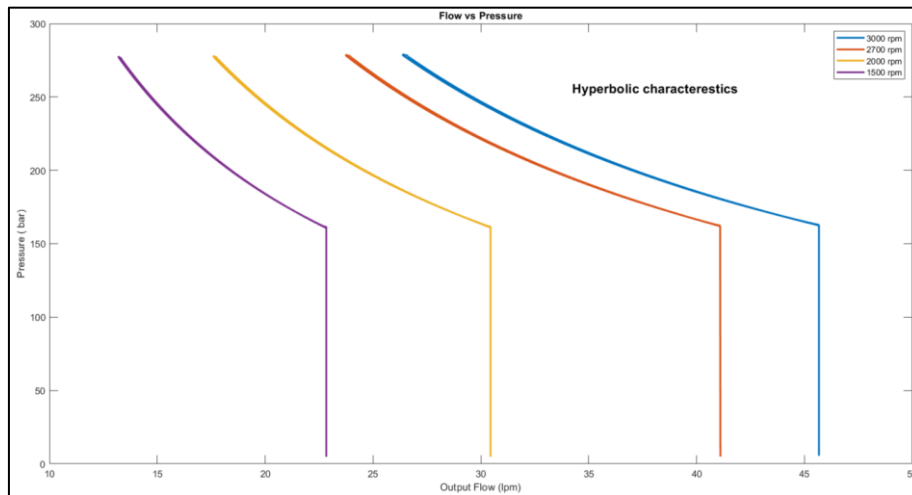


Figure 15 Flow vs pressure at different speeds

VI. CONCLUSION

The primary objective was to devise a hydro-mechanical torque control system capable of maintaining a consistent torque curve, as opposed to the erratic double hump torque curve often encountered. Moreover, the aim was to ensure that this system exhibits hyperbolic characteristics when employed for power control purposes. Upon analyzing the results, it becomes evident that the torque control incorporating a hydraulic potentiometer has successfully achieved these objectives. The hydraulic potentiometer component of this system plays a pivotal role by providing continuously variable feedback, thereby enabling precise tracking of the ideal hyperbolic flow-pressure curve. Unlike some mechanical feedback mechanisms prone to failure, the hydraulic feedback employed here ensures reliability and stability without succumbing to common failure modes.

One of the significant advantages of this torque control system is its seamless integration with existing pressure compensation and load sense functions. There is no compromise or degradation in the performance of these functions, ensuring optimal hydraulic system operation.

Furthermore, the versatility of this system is noteworthy. A single torque limiter control mechanism is capable of accommodating and adjusting to various setting variations, covering a wide range of torque requirements. This simplifies the control process and streamlines operational procedures, contributing to enhanced efficiency and productivity in hydraulic systems.

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