DIGITAL HYDRAULICS CIRCUIT BASED ON PWM FUNCTION FOR CONTROLLING HYDRAULIC ACTUATOR POSITION

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Abstract: *Hydraulic systems are used in many different industries, such as multi-source hydrostatic drive systems. In traditional hydraulic systems, a proportional servo valve is used to control the position of hydraulic actuators. The low energy efficiency and high cost of these control valves are two major problems with these systems. Digital hydraulics is one of the most unique ideas on how to solve these problems. Researchers like digital hydraulics because it is inexpensive, it saves energy, it is not sensitive to contamination, and it has low leakage. In this paper, a digital hydraulic circuit is suggested that uses a fast switching on/off valve instead of servo valves to control the position of a hydraulic actuator. Using a proper PWM duty cycle, the flow that passes through the fast-switching valve is controlled in this way. When the control valve is off, excess pump flow flows straight to the tank instead of going through the relief valve. Therefore, the waste of energy caused by the relief valve is greatly reduced. A robust sliding mode controller (SMC) is used to ensure position tracking even when there are uncertainties.*

Keywords: *SMC, Digital Hydraulics, PWM, Hydraulic Actuator Position*

1. Introduction

In this article, a discussion of the literature on the phenomena of DFP (Digital Fluid Power), particularly with respect to multisource hydraulic systems, is presented. In the investigation, the effective application of the phenomenon in multi-source hydraulic drive systems is also addressed. We will discuss a variety of factors related to this phenomenon, including hardware needs, control system design, and specifically whether servo valve technology is preferred as an alternative to proportional valves. The report also discusses the possibilities for further research in this area, as well as its limitations. The fundamental concept of digital fluid power is the design of a control system using hydraulic valves. "Digital fluid power is a new field of fluid power with tremendous scope for innovative solutions," claims Rudolf Scheidl [1]. For a successful implementation, new components, in-depth knowledge of the system, and new control concepts are required. In a book by Mc Cloy titled Control of Fluid Power: Analysis and design [2], Digital Hydraulic Power has been thoroughly described regarding its applicability in both hydraulic and pneumatic systems. Intelligent methods to reduce power consumption and improve energy recovery from hydraulic drives include multi-source hydraulic systems. According to a recent analysis completed in the year 2020 that examined the excavator's truck loading cycle, a thorough Multisource Network Hydraulic System (MSNHS) has also been suggested that significantly reduced the engine input power by about 60% and improved the overall system performance, highlighting the potential for further research in this area. While both proportional valves and servo valves are used to control fluidic flow, they differ from one another in several factors, like spindle overlap, frequency response, actuation mechanism, intended purpose, etc., each of which has advantages and disadvantages. Although proportional valves are continuously variable electrically modulated directional control valves with more than 3% center overlap, servo valves are continuously variable electrically modulated directional control valves with less than 3% center overlap, according to an article by Jack L. Johnson [3]. Keep in mind that this overlap leads to the length of the dead zone, which is essential for optimal control of hydraulic systems. Since the output of a dead zone is zero (the output is "dead" - (no action occurs), a dead zone is a band of input values in the domain of a transfer function in a control system or signal processing system [4]. In terms of intelligent control for hydraulic systems, servo valves are thus gaining greater research potential than proportional valves. A portion of closed-loop applications that were previously only conceivable with servo valves can now be employed with high-performance proportional valves, sometimes known as servosolenoid valves [5]. According to the following findings [6], another study found that a proportional valve performed better when connected to the SMC (Siding Mode Control) than when coupled with a PI (Proportional Integral) controller.

The paper also discusses the digital fluid power as the use of simple hydraulic valves in place of a property valve to build a hydraulic system, control place proportional hydraulic in a multisource hydrostatic drive system to reduce energy consumption, and optimize the energy recovery of the hydraulic system. The main objective is to reduce the cost of building the system and its maintenance, improvements to the ecological perimeter such as energy, noise, emissions of harmful substances and carbon footprint, and so on.

2. Literature Review

Generation, monitoring, and control of power, as well as transmission of power, can be achieved using pressurized fluids, which is one of the many facets of the expansive field of engineering technology known as fluid power [1]. Because it has a low freezing point, a high boiling point, a significantly larger bulk modulus, and self-lubricating quality, hydraulic oil is often used [2]. Fluid power has a well-defined research domain and academic activities that benefit a wide variety of sectors, including agriculture, infrastructure, transportation, aerospace, marine and industrial, as well as many others that demand high power-to-weight ratios [3]. Fluid power is characterized by its transmission flexibility, user friendliness, simplicity of operation, comparatively low cost, controllability, and management [4], in addition to its ability to generate large power densities. Due to these advantages, fluid power technology is a viable solution for completing crucial activities that require a high power density and a high degree of reliability. Heavy-duty uses include construction trucks, material handling equipment, and military activities, as examples [5]. As a power-generating component, the hydraulic hybrid propulsion system may have one or two hydraulic pump/motor (P/M) units. Moreover, the components of the HHV that are responsible for the storage of energy are called hydropneumatics accumulators. There are three distinct configurations that can be applied to hydraulic hybrid vehicles: serial, parallel, and power-split. In a configuration known as a serial hydraulic hybrid, an internal combustion engine (ICE) serves the function of an accumulator charger, while a hydraulic power unit (P/M) supplies the vehicle with the necessary amount of power. However, in a parallel hydraulic hybrid architecture, the load is mechanistically connected to both the hydraulic P/M and the internal combustion engine (ICE). When compared to the series structure, the parallel HHV configuration is easier to implement and has lower costs because there are fewer modifications made to the conventional vehicle's mechanical components. A power-split hydraulic hybrid can switch between a parallel driveline and a serial driveline for power transmission. A power-split architecture is significantly more complicated than a parallel architecture. As a direct consequence of this, parallel HHV is a better option for businesses that manufacture vehicles. Because the speed of the internal combustion engine (ICE) depends on the speed of the wheels in the parallel configuration, the parallel configuration of the HHV has the disadvantage of having a higher fuel consumption than the series HHV. Previous demonstrations of parallel hydraulic hybrid powertrains for buses were conducted in Japan in the 1980s and early 1990s. These powertrains are currently being developed by Eaton Permo Drive and Bosch Rexroth and are described in [2]. Additionally, over the past ten years, several studies have been conducted on the modeling and simulation of parallel HHV [3, 4]. Between 2008 and 2010, Guo-Qing Liu and colleagues conducted research on the application of a parallel hydraulic hybrid powertrain for an urban bus [2, 5, and 6]. One of the most important contributors to the economy of the United States is the fluid power industry [6-8]. The National Fluid Power Association (NFPA) states that thousands of companies use hydraulic power systems in the United States. These companies are widely considered the most successful industrial enterprises in the United States [7-10], with more than 845,000 workers and a combined annual payroll of more than $60 billion.

3. System Model

The cutting-edge field of digital hydraulics [5-9] optimizes the performance of the hydraulic system, supports new kinds of fluid power application, and reduces energy consumption. This innovation allows efficient replacement of traditional fluid power components such as directional control valves with series of valves that operate in parallel [1]. Poppet-style actuation, as seen in the spool valves in Figure 1, prevents leakage across the valve, making such valve configurations ideal for this application. As a result, this configuration reduces system losses, grants more commands, increases performance and efficiency, and reduces the burden on maintenance budgets [2]. This technology has also been used to replace conventional check valves in fixed displacement pumps, among other configurations, with the aim of increasing the efficiency of traditional systems. It also allows conventional fixed displacement pumps to have variable displacements, which opens up the possibility of restriction and diversion [4]. Mechanical check valves in the inlet and outlet ports of the pump are used by some traditional piston pump/motor designs, such as reciprocating piston pumps, to isolate the high- and low-pressure halves of the system.

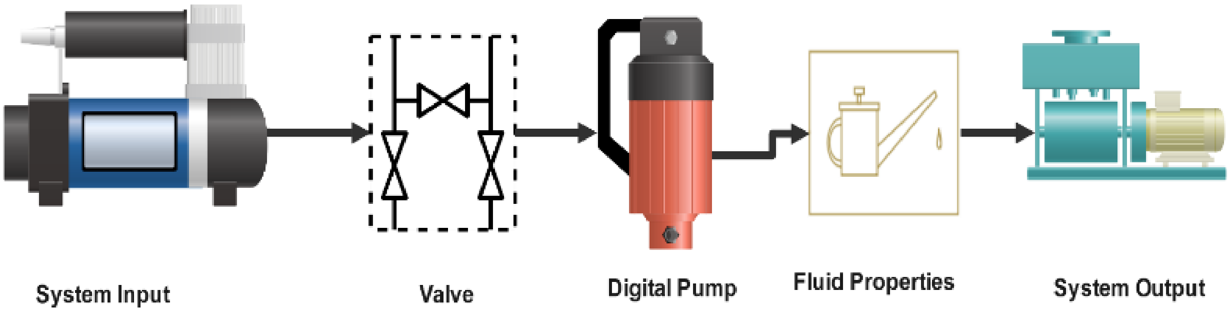

Fig. 1. Schematic of the series hydraulic system for multi-source hydro system configuration

The operation comprises three stages, start-up, cruising, and braking, similar to the parallel design. When the automobile is accelerated rapidly, the clutch (2) separates the engine shaft from the pump shaft. Therefore, it is possible that the hybrid hydraulic pump/motor (6) will do its job. When the accumulator is full, the hydraulic pump/motor will receive the pressurized fluid (5). (6). The acquired hydraulic energy is transformed into mechanical power and sent to the driveshaft (8). After the first burst of speed, the accumulator is allowed to return to its normal fluid level, and the cruising speed is then chosen. Since its pressure is now less than the nitrogen precharge pressure, the engine (1) is forced to run and the clutch (2) is engaged.

Therefore, the axles are driven by a hydraulic pump/motor (6), which is powered by the engine and pumps the fluid from a reduced pressure reservoir (3). The accumulator is where the overflow of high-pressure fluid from the hydraulic pump is temporarily maintained. Pressing the brake pedal causes the engine to break down, the clutch to disengage and the hydraulic pump/motor (6) to switch to pump mode, drawing fluid from low pressure storage and storing it in the accumulator. It is time to slow down now. The kinetic energy of the wheels is transferred into hydraulic energy and is kept in the accumulator in this fashion. Energy reserves will be used to accelerate the vehicle when it is time. When the pump is in the intake stroke, the low-pressure check valve allows the fluid to enter the system through the valve. When the pump cylinder is depleted, the fluid will be shifted to the high-pressure side of the system. This will cause the intake check valve to close, while the exhaust check valve will open due to pressure. In this arrangement, the pump can only produce fixed displacements because the activation of the intake and exhaust valves is exclusively dependent on the pressure difference in the chamber. Therefore, the authors of [6] suggest a digital inline 3-piston pump that is electronically activated and employs digital on/off valves in lieu of conventional valves. This pump would be inline and it would have three pistons. A digital pump/motor with a displacement of 28cc / rev, three displacement chambers, and two quick on / off valves is what the proposal calls for. Figure 4 shows that the pump and motor have been configured to be used with a single displacement chamber. This configuration can be seen in the figure. Valve 1 is responsible for controlling the flow from the low-pressure side, while Valve 2 is responsible for controlling the flow coming from the high-pressure side. Using the suggested configuration, the operation of the valve may be regulated at any time throughout the pumping or driving cycle. Due to the improved controllability and flexibility of the system that this configuration makes feasible, a wide variety of digital pumping and driving approaches are now conceivable [7]. These techniques include flow-diverting and limiting operating strategies. In addition, our team came up with and implemented a mechanically actuated digital pump that, much like its electrically actuated version, can reach high efficiencies over a wide range of displacements. In the following sections, you will get an overview of the mechanical architecture of the digital pump that is actuated mechanically, you will learn about the most efficient operating strategy for the digital pump, that is, actuated electrically, and you will see the results of the experimental testing and validation of the digital pump. The following equations are given:

$$f_v = \frac{s_v * 1000}{v_g * n} \tag{1}$$

$$f_t = \frac{s_v * \partial p}{p_{max} * 600} \tag{2}$$

$$f_{mh} = \frac{f_t}{f_v} \tag{3}$$

$$A_{pump} = \frac{v_g * \partial p}{20 * \pi * f_{mh}} \tag{4}$$

$$A_{motor} = \frac{v_g * \partial p * f_{mh}}{20 * \pi} \tag{5}$$

The size of the accumulator is determined using the following formulae, which are based on the application for which it will be used.

$$\partial p_1 v_{g1}^k = \partial p_2 v g_2^k \tag{6}$$

$$p_0 * v_0^n = p_1 * v_1^n \tag{7}$$

$$p_2 * v_2^n = \partial p_n * v g_x^n \tag{8}$$

$$v g_1 = \frac{v g_x \left({}^{p_3}/_{p_1}\right)^{1/k}}{1 - \left({}^{p_3}/_{p_2}\right)^{1/k}} \tag{9}$$

The minimum operating pressure of the hydraulic circuit can be specified using these values using the following equation.

$$soc(\%) = \frac{v_x}{v\_max} * 100 \tag{10}$$

The most important output variable of the accumulator block is its State of Charge (SoC). SoC represents the ratio of fluid volume to its maximum by the following equation. The maximum fluid volume in the accumulator corresponds to the maximum gas pressure situation

4. Results and Discussion

In this section, we report the results of a simulation run on a series hydraulic hybrid drivetrain in MATLAB Sims cape, a graphical programming environment created by MathWorks [8]. MATLAB

Sims cape models the series hydraulic hybrid transmission seen in regular terrain hydraulic vehicles. The purpose of the model is to investigate whether a hydraulic hybrid transmission's performance might benefit from replacing its current pump/motor components with digital ones. The digital motor and pump data that was acquired at the tested displacements (25%, 50%, 75% and 100%), pressures (4 MPa, 10MPa and 18 MPa), and shaft speeds (300 RPM, 500 RPM, and 700 RPM) were applied to the physical simulation components to simulate the desired state-of-the-art digital units (pump and motor).
Therefore, the physical pump and motor contained, pressure compensated pump, and adjustable displacement motors are sized according to the maximum and minimum pressures and the needed flow rate of the system, using the imported lookup tables. Accumulator size, along with that of other hydraulic parts like valves, fittings, hoses, etc., is determined by the system's pressure and flow rate, which are measured during acquisition. The digital pumping/motoring data shows that at 300 and 700 RPM, the hydraulic units (5) and (11) are capable of a maximum displacement of 28 cc/rev. There will also be a maximum volumetric efficiency of 94% for hydraulic units, a minimum overall efficacy of 78%, and a pumping efficiency of up to 90%. However, while in the operation unit, (11) can achieve overall efficiency of up to 92.2% and volumetric efficiency of up to 99.99%. To provide additional flow at peak loads, a series hydraulic hybrid transmission uses a gas accumulator that expands and compresses its gas contents under adiabatic conditions (during the acceleration stage). Detailed testing was performed with a variety of duty cycles, one of which is shown in Figure 2.

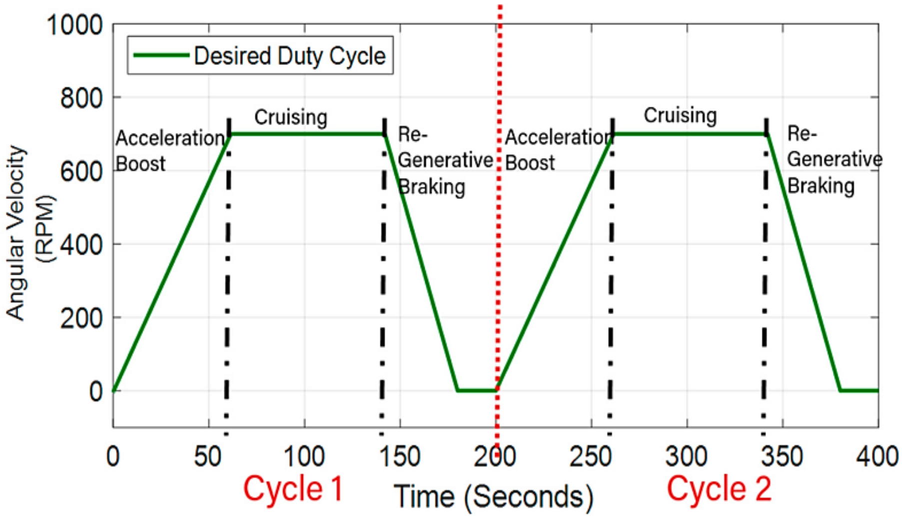

Fig. 2. The desired duty cycle

As a result, each tyre had a calculated moment of inertia of about 0.37 kg2 after being rotated once. Moments of inertia were determined for each tire, and a mild physical torque source was provided at the motor shaft to account for the values. Here, we break down the workings of the simulation model at each phase. The accumulator is shown in Figure 3 after being precharge with fluid to a pressure higher than that at which the system operates. Since the pump is turned off, the accumulator is used as a backup power source. When the vehicle is in motion, the energy stored in the accumulator is transferred to the motor (11). The stored pressure regulates the opening and closing of the valves. Because the accumulator nitrogen pressure is higher than the system pressure currently, the valve does not open (7). The flow is then directed through valve (9) and blocked at valve (8) by maintaining valve (7) in its unactuated position (10).

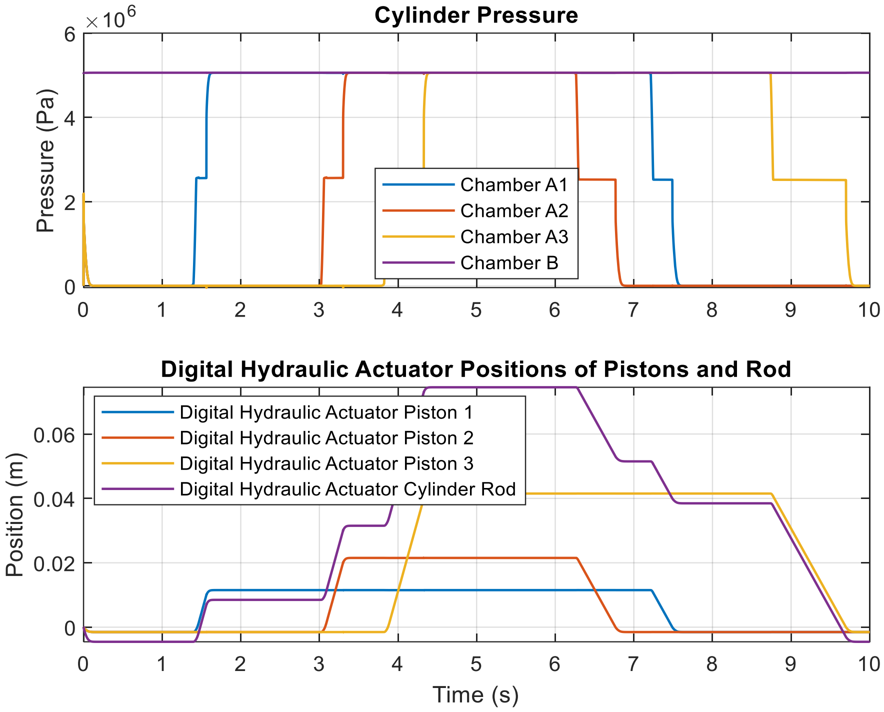

Fig. 3. The resulting pressure and flow simulation results at the pump's discharge and accumulator port throughout the duty cycle

As the acceleration phase ends, the accumulator's fluid level begins to drop, and the pressure of the recharged object falls below the pressure of the system. Since the accumulator has practically little energy left, a second hydraulic power source is required to drive the wheels. At this point (cruising), the clutch is engaged by an electrical signal from the engine after the precharge pressure has dropped. To put the motion into action on the wheels, the pump begins to push the fluid flow from the hydraulic tank (low-pressure reservoir) into the hydraulic motor (11), which still functions as a motor. Since valve (10) is still closed, fluid is supplied to the motor in the same way as it was during the acceleration phase: through valve (9).

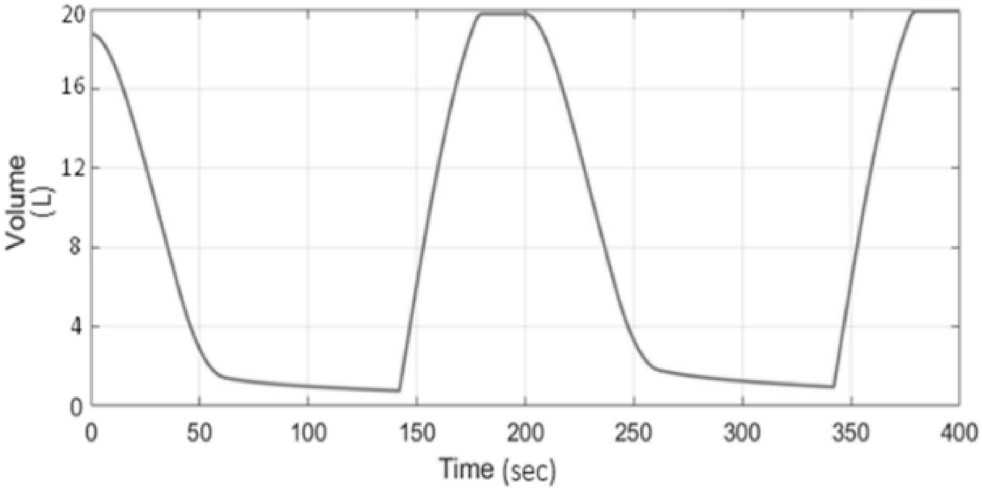

Fig. 4. Simulation outcomes for the fluid volume inside the accumulator

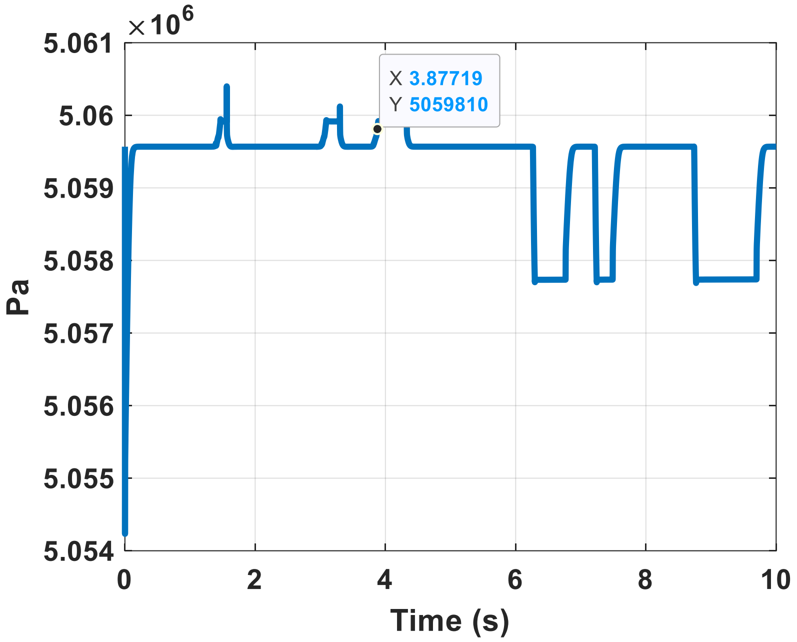

Fig. 5. Simulation of the pressure drop across the motor

Figures 4 and 5 illustrate the shifts that occur in the amount of fluid in the accumulator and, separately, the pressure drop that occurs in the motor throughout the period of the needed duty cycle for the different transmission stages (acceleration, cruising, and braking). Acceleration occurs when the stored energy is released into the intake port of the motor to increase the rotational velocity. Because of this, the motor operates in driving mode. 4.

5. Conclusions

It is apparent that fluid power is a critical part in almost every industry, including transportation, the construction of manufacturing facilities, etc. The development of models that can take the best advantage of the idea of digital fluid power is urgently needed in this era of intelligent technological systems. Due to the significant potential for energy recovery in multisource hydraulic drive systems, such models must be constructed as a first step. To determine system errors, the simulated model and the real system must be contrasted. This may lead to improved energy efficiency, less losses, and improved system performance. Due to the poor operation of conventional variable displacement pumps at partial displacements, the average efficiency of series hydraulic hybrid drivetrains is between 64% and 81%.

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