



## COB-2021-1613 DIGITAL HYDRAULIC PUMP: AN ENERGY EFFICIENCY STUDY

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**Abstract.** *The hydraulic actuation systems have been a popular solution majority employed when robustness, reliability, and a large amount of power allied to a compact size are required. Over the years, this feature has turned the hydraulic systems the most used in the mobile industry as in heavy machinery and aeronautics. However, hydraulic systems are known for their low energy efficiency, depending on the application area and work conditions. The digital hydraulic concept emerges as an alternative to design hydraulic systems avoiding or reducing some issues such as throttling control and energy dissipation. A digital hydraulic pump with variable speed was proposed and compared with a variable displacement pump in a flow rate cycle in different load conditions. The results showed that the digital hydraulic pump has a better global efficiency at low flow rate demand, while at high flow rates, the pump efficiencies were close. The mean global efficiency for the digital hydraulic pump at the cycle was 12% higher than the variable displacement pump. This result demonstrates the potential for energy improvement of the variable speed digital hydraulic pump.*

**Keywords:** *Digital Hydraulics, Digital Hydraulic Pump, Global Efficiency, Variable Speed Digital Hydraulic Pump.*

### 1. INTRODUCTION

In the industry, hydraulic systems have been a popular solution majority employed when a large amount of power allied to a compact size is required. Over the years, this feature has turned the hydraulic actuation systems the most used in the mobile industry as in heavy machinery and aeronautics (CHAKRABORTY *et al.*, 2013; MARÉ, 2016). However, hydraulic systems are known for their low energy efficiency, depending on the application area and work conditions (ACHTEN, 2010). In the last few decades, the claim for more energy-efficient systems has increased the research for new solutions for hydraulic systems, as the digital hydraulics, which aims to reduce the throttling control and improves efficiency and robustness (DONKOV *et al.*, 2020; LINJAMA; SCHEIDL; SCHMIDT, 2011; LINSINGEN; DE NEGRI, 2012).

In this paper, a model to a digital hydraulic pump with rotational speed is proposed and a study case was used to perform an analysis of its global efficiency. In order to compare the results, a model of a conventional solution using a fixed rotational speed variable displacement pump was used and simulated at the same work conditions.

### 2. HYDRAULIC SYSTEMS

Hydraulic systems have a large range of applications, covering the fields of production, manufacturing, and service. They are known for their characteristics of high power density, robustness, and reliability. In general, the systems are composed of four main units, classified as: 1) fluid storage and conditioning unit, which is responsible for storage and conditioning the hydraulic fluid of the system; 2) primary energy conversion unit, generally composed by the pumps, responsible to convert mechanical energy from an external source to hydraulic energy; 3) energy limitation and control unit, which comprises the valves, responsible to control the hydraulic energy able to be used or converted; 4) secondary energy conversion unit used to convert hydraulic energy into mechanical energy that is the desired output from a hydraulic actuation system (LINSINGEN; DE NEGRI, 2012).

#### 2.1 Conventional Hydraulic Systems

The major applications of the conventional hydraulic systems are related to hydrostatic transmissions and control of hydraulic actuators. In these systems, a fluid is used to transport energy, that it is able to be converted in to force or torque at the hydraulic actuators. The hydraulic pumps play an important role at the hydraulic systems, they are the more

commonly device used to transfer energy to the fluid and its energy efficiency is fundamental for a good system work (Suzumori and Faudzi 2018).

With the growing worldwide demand for more efficient systems and the increased cost of energy, the industry is seeking new solutions to replace the traditional resistive control of hydraulic systems performed by throttle valves. One trend has been the adoption of direct conservative control methods at the pump, which are essentially non-dissipative. The flow rate in pump-controlled systems can be regulated by changing the position of internal moving parts in a pump with variable displacement or by changing the rotational frequency of the fixed or variable displacement pump (TEIXEIRA, 2015). Main pump controls strategies can be seen in Fig. 1.

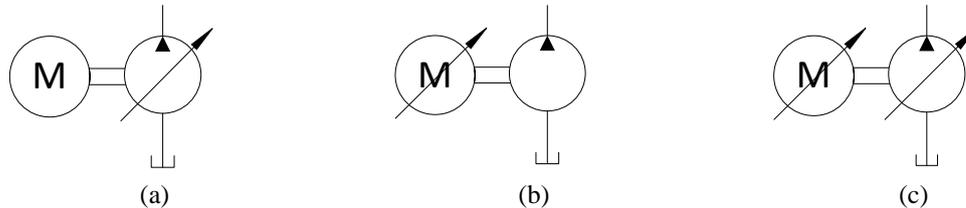


Figure 1. a) Variable displacement control, b) Variable speed motor control, (c) Hybrid control with variable speed and variable displacement pump.

In conventional hydraulic systems, a fixed rotational speed variable displacement pump is a common way to control the pump output flow rate to meet the system demand as pressure and flow rate. This technique is known as Power-on-Demand. Although, this solution are also known for their low energy efficiency when working in low load and volumetric displacement conditions (Achten 2010; Maré 2016).

However, in most machines the concept is implemented using variable displacement control. Only in recent years, the use of variable speed motor with a constant displacement pump concept has become more popular due to the desire for greater robustness and the decrease in the price of electro-hydraulic drives and motor controllers (TAŠNER *et al.*, 2014, apud AGOSTINI 2019). Consequently, variable displacement pump control was used as a benchmark to compare efficiency in the same working conditions with the proposed digital hydraulic pump.

## 2.2 Digital Hydraulics

LINJAMA (2011) defines digital hydraulics as a system composed of discrete components able to control actively the system output. In this aspect, the digital hydraulics can be used in an intelligent way to control hydraulic systems to improve the energy efficiency (BELAN, 2018; NOSTRANI, 2021). The digital hydraulic concept emerged as a promising technology in hydraulic systems where the energy efficiency can be improved by the avoidance of the throttle control and by the use of simple hydraulic components as the on/off valves instead of the servo valves (LINJAMA; LAAMANEN; VILENIUS, 2003; SCHEIDL; LINJAMA; SCHMIDT, 2012).

The digital hydraulic systems are majority controlled by on/off valves in which work fully opened or fully closed. According to the arrangement and the on/off valves control, it can be divided in two main branches, the parallel connection and the fast switching ones (Fig. 2). In the parallel-connected valves, each opened valve contributes to the total output flow rate and the on/off valves are turned on or off only to change the system state. In the fast-switching valve, only one on/off valve is used to control the total output flow rate by a fast commutation between the states on and off. In this case, it can be used techniques as Pulse Width Modulation (PWM) to control the output flow rate by controlling the valve (DONKOV *et al.*, 2020; SCHEIDL; LINJAMA; SCHMIDT, 2012).

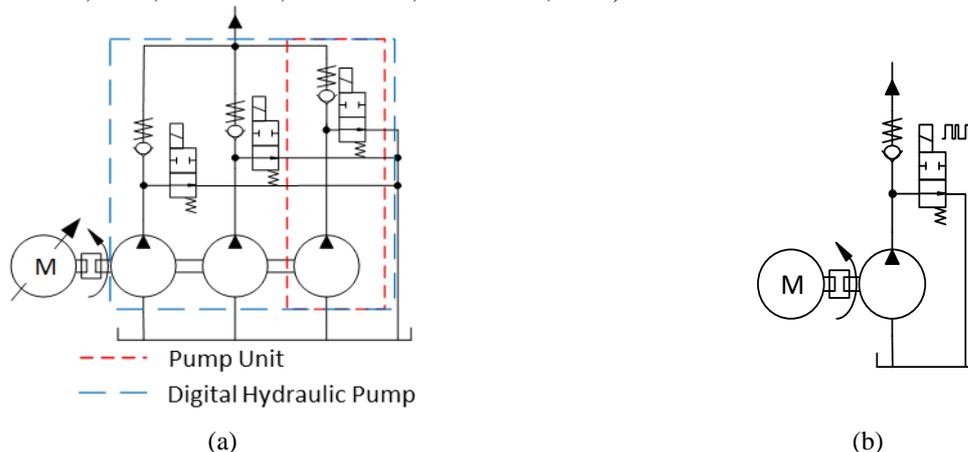


Figure 2. a) Parallel connection, b) Fast switching.

## 2.3 Digital Hydraulic Pump

By applying the digital hydraulic concept to the primary conversion unit, it is possible to control the pump output flow rate, changing the direction of the flow rate to the system or reservoir. Each pump unit of a digital hydraulic pump is composed of a fixed displacement pump connected to the hydraulic system by a normally opened on/off valve and a check valve, highlighted in red dashed square in Fig.2a. In the parallel connection, two or more pump units can be used to compose a digital hydraulic pump, and its flow rate output can be controlled independently. One advantage of using a digital hydraulic pump consists on the possibility to direct the flow rate to the reservoir at low pressure which could reduce the energy dissipation at the limitation and control units.

Once that the pumps are connected at the same shaft, they work at the same rotational speed, and the output flow rate is a function of the number of active pumps and their volumetric displacement. It means that increasing the number of pump units will increase the number of available output flow rate values. While the volumetric displacement distribution between the pump units will affect the output flow rate resolution (Fig. 3a).

## 2.4 Variable Rotational Speed Digital Hydraulic Pump

The current study proposes the use of a digital hydraulic pump with variable rotational speed based on two limitations of the digital hydraulic pump with fixed rotational speed. The first limitation concerns the discrete output flow rate where the fixed rotational speed and a limited quantity of pumps give a certain number of combinations (Fig 3a). The second limitation was based on the energy efficiency, where due to the system dynamics of pressure and flow rate demand, it is not possible to keep the best operational point for each pump in each pump combination. It means that in some operational conditions the energy efficiency of the pump combination will be lower, while changing the rotational speed, for the same output flow rate, a better pump energy efficiency could be reached.

Theoretically, by changing the pump rotational speed, the number of output flow rate combinations increases with the available rotational speeds. A given flow rate demanded can be achieved by different pump combinations at different rotational speeds. As an example in Fig. 3b, the system flow rate demanded was  $1 \times 10^4 \text{ m}^3/\text{s}$ , considering a constant pressure, the digital hydraulic pump with variable rotational speed could supply the flow rate using five different combinations of pumps and angular velocity as the combination of the pumps 2 and 3 at 52 rad/s, pumps 1 and 3 at 62 rad/s, pump 3 at 78 rad/s, pumps 1 and 2 at 104 rad/s, and pump 2 at 157 rad/s. In this case, it was possible to note that there is more than one option to use as a combination pump and rotational speed. Therefore, the best global efficiency of the pump was used as a selection criterion.

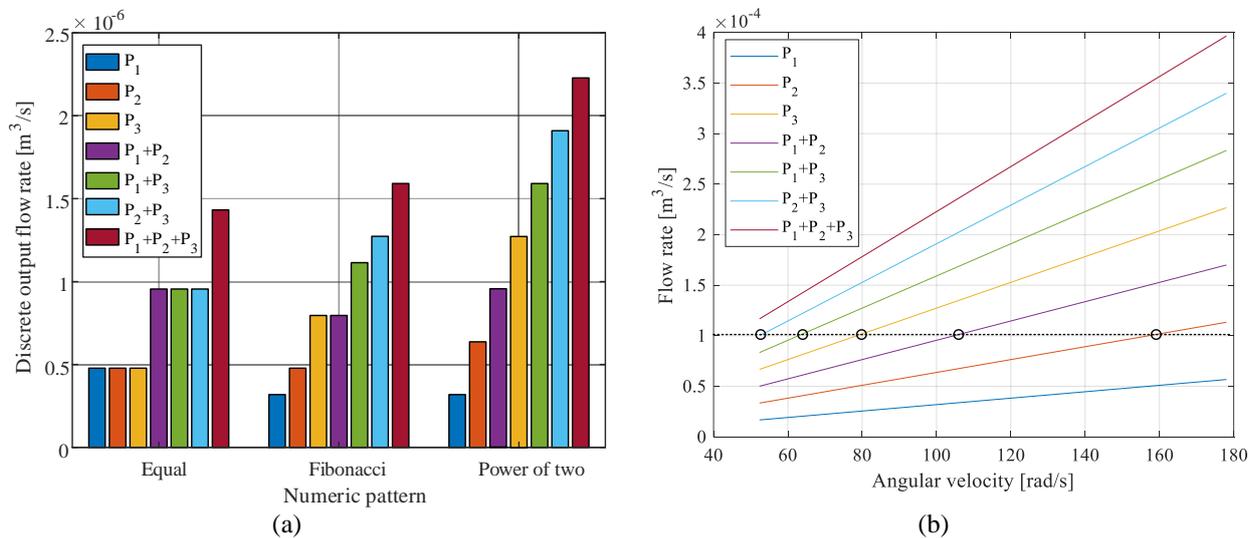


Figure 3. Theoretical flow rate for pump combinations. a) Constant angular velocity, b) Variable angular velocity.

## 3. MODELS AND PARAMETERS

Nowadays, the improvement of energy efficiency is one of the trend topics in the hydraulic industry. Developing more efficient solutions impact the energy save and consumption reduction (ZARDIN; NATALI; BORGHI, 2019). The pump global efficiency is affected by its constructive characteristics and by its working conditions. Borghi *et al.* (2009) and Zardin *et al.* (2019) have proposed models to evaluate the volumetric and mechanical efficiency of an external gear pump, respectively.

### 3.1 Digital Hydraulic Pump Model

In this paper, the focus is not to design a new pump solution from its specific constructive characteristics. Instead of that, the focus is to apply the digital hydraulic concept at already done pump solutions using the manufacturer's data. Therefore, the charts of the pump flow rate and torque, obtained from the manufacturer's data, were used to calculate the volumetric ( $\eta_{vc}$ ), mechanical ( $\eta_{mc}$ ), and global ( $\eta_{gc}$ ) efficiencies by the following equations,

$$\eta_{vc} = \frac{q_{vrc}}{q_{vthc}}, q_{vthc} = \omega D_c, q_{vrc} = q_{vthc} - q_{loss}, \quad (1)$$

$$\eta_{mc} = \frac{T_{thc}}{T_{rc}}, T_{thc} = \Delta p_c D_c, T_{rc} = T_{thc} + T_{loss}, \quad (2)$$

$$\eta_{gc} = \eta_{vc} \eta_{mc}, \quad (3)$$

where  $q_{vrc}$  and  $q_{vthc}$  are the real and the theoretical flow rate of each pump combination, and  $T_{thc}$  and  $T_{rc}$  are the theoretical and real mechanical torque, respectively;  $\omega$  is the rotational speed;  $D_c$  is the sum of the volumetric displacement for each pump combination;  $\Delta p_c$  is the pressure differential for each pump combination;  $q_{loss}$  is the lost flow rate due to the pump leakages;  $T_{loss}$  is the pump mechanical losses. In this case, the manufacturer's data was considered as the real value to the flow rate and torque.

To model the digital hydraulic pump were created three ideal pumps with theoretical output flow rates. A laminar orifice (Eq. 4), connecting the pump outlet to its inlet, was used to reproduce the pump leakage effect to obtain the real flow rate. A real-time calculation of the leakage coefficient ( $k_{leak}$ ) was implemented using the manufacturer's data as a lookup table to obtain the lost flow rate of the pumps,

$$q_{loss} = k_{leak} \Delta p. \quad (4)$$

It is important to note that each pump in a digital hydraulic pump can be in a different pressure condition. For example, in Fig. 4, the pump 1 can be active, connected to the system, while pumps 2 and 3 are inactive, connected to the reservoir. In this case, to calculate the volumetric efficiency only the active pump has to be considered. On the other hand, to the mechanical efficiency, if only the pump 1 is active it is necessary to consider the torque to move the inactive pumps once that they are connected at the same shaft.

The digital hydraulic pump proposed was simulated using the software Hopsan, version 2.14.2, in co-simulation with the MatLab/Simulink®. Hopsan is a free open-source software developed by the Linköping University. It has a hydraulic components library able to create and simulate a large variety of hydraulic systems and their dynamics. Using it in co-simulation it is possible to use the MatLab/Simulink® toolboxes to implement control techniques and mathematical user expressions. Figure 4 presents the model created in Hopsan.

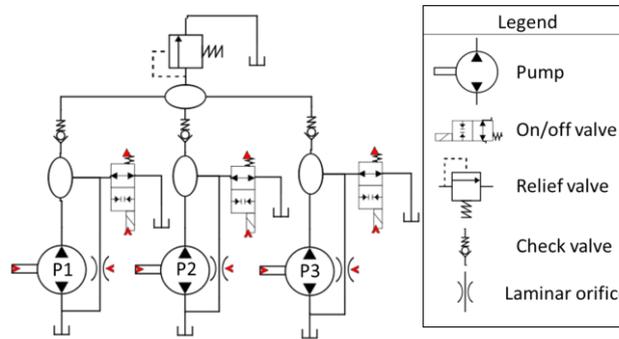


Figure 4. Hopsan system model.

A relief valve was used to control the output pressure of the digital hydraulic pump to emulate a system load. The valve dynamics modeled using the continuity equation and Newton's second law through the Hopsan components as

$$\frac{dp_{sys}}{dt} = \frac{\beta}{V} \left( q_{vrc} - c_d \pi d f x \sqrt{\frac{2|p_{sys} - p_{tank}|}{\rho}} \right), \quad (5)$$

$$\frac{d^2x}{dt^2} = \frac{\left(p_{sys}A_c - B\frac{dx}{dt} - k_s(x_0+x)\right)}{M}, \quad (6)$$

where  $p_{sys}$  and  $p_{tank}$  are the system and reservoir pressure;  $\beta$  is the Bulk modulus;  $V$  is the control volume;  $\rho$  is the fluid density;  $c_d$  is the discharge coefficient;  $d$  is the valve spool diameter;  $f$  is the fraction of spool opening;  $x$  is spool displacement;  $x_0$  is the valve pre load;  $A_c$  is the valve plug pressure actuation area;  $B$  is the viscous friction coefficient;  $k_s$  is the spring elastic coefficient;  $M$  is the valve spool mass.

The check valves were used to do not allow a reverse flow rate at inactive pumps. They were modeled as

$$q_{vcheckvalve} = k_v\sqrt{\Delta p}, \quad (7)$$

where,  $k_v$  is the valve flow coefficient and  $\Delta p$  is the valve pressure differential. The check valve dynamics can be obtained by the Eq. 6, with the parameters adjusted to the check valve.

The on/off valves were used to control the output flow rate given by

$$q_{v_{on-off}} = c_d\pi d f x \sqrt{\frac{2|p_{pump} - p_{tank}|}{\rho}}, \quad (8)$$

where  $p_{pump}$  is the pressure at the pump outlet.

The on/off valve dynamics was proposed by Belan (2018), where it was used two transfer functions with different parameters to modeling the opening and closing time delay of the valve, given by

$$X_v(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} U_c(s), \quad (9)$$

where,  $X_v(s)$  is the valve spool displacement;  $\omega_n$  is the valve natural frequency for the opening or closing movement ;  $\xi$  is the valve damping factor and  $U_c(s)$  is the valve command signal. The time delay corresponds to the time to charge or discharge the valve solenoid before initiating the mechanical valve movement given by Eq. 6.

The pressure and flow rate at each pump outlet and in the digital hydraulic pump outlet are monitored during the simulation, these values are used in the lookup tables that were implemented in the Simulink to calculate in real-time the volumetric, mechanical and global efficiency for each pump combination.

With the information of the desired flow rate, the volumetric efficiency, and the pump parameters, the algorithm calculates the angular velocity necessary to each pump combination supply the flow rate (Eq.1). In the next step, the rotational speed is filtered to a feasible angular velocity range and the resultant pump combination with the best global efficiency is selected.

### 3.2 Variable Displacement Hydraulic Pump Model

For the analysis of the energy performance of the constant speed variable displacement pump, a hydraulic system corresponding to the test circuit was modeled for an open circuit pump unit according to ISO 4409 and ISO 8426. The circuit is composed of a pressure relief valve to emulate the load, and an ideal motor (Fig. 5).

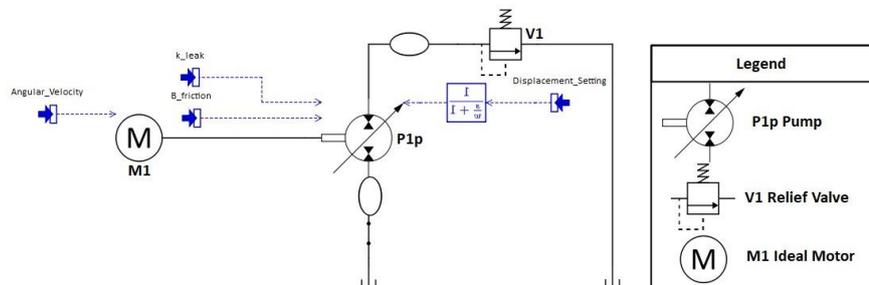


Figure 5. Hopsan system model.

The model used for the variable displacement pump, has as input variables, the angular velocity of the pump, the displacement setting, and has the parameters of viscous friction coefficient and the leakage coefficient, which it can be configured to be an external and/or internal leakage via a ratio coefficient (Kr). The output variables of the pump model are the effective volumetric flow rate at the pump outlet, external leakage and internal leakage. For the calculation of the

energy losses of the variable displacement pump, the total leakage model is also performed using a linear flow orifice. However, the calculation of the mechanical losses of the pump is performed through a simplified viscous friction model.

Therefore, the equations 1, 2 and 3 are adjusted to describe the energy efficiency of the variable displacement pump (Fig. 6). Where  $q_{rp}$  are the real flow rate of the variable displacement pump, and  $T_{rp}$  are the real mechanical torque, respectively;  $\omega$  is the rotational speed;  $D_p$  is the maximum volumetric displacement;  $\varepsilon$  is the displacement setting and  $B_{loss}$  is the viscous friction coefficient as a function of the rotational speed.

The leakage coefficient ( $k_{leak}$ ) and the viscous friction coefficient ( $B_{loss}$ ) are calculated dynamically to represent the volumetric and mechanical efficiency by a lookup table. Using the experimental efficiency map presented by Bravo (2017) it was possible to interpolate the coefficients for each operating point, Fig. 6 shows the calculation process.

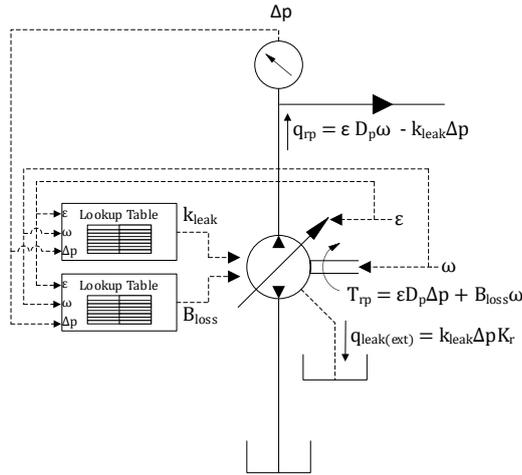


Figure 6. Lookup table calculation process.

The hydraulic pump displacement swash-plate drive model is described in a simplified manner through a first-order dynamics, according

$$\varepsilon_{ref} = \tau_p \frac{d\varepsilon}{dt} + \varepsilon, \quad (10)$$

where  $\varepsilon_{ref}$  is the reference setting sent to the displacement drive and  $\tau_p$  is the pump swash-plate time constant.

### 3.3 Parameters

In this proposal it was considered that the pump angular velocity is supplied by an ideal source and it can vary continuously in the range from 52.36 to 178.02 rad/s (500 to 1700 rpm). The digital hydraulic pump is composed by three pump units with fixed volumetric displacements of  $6.36 \times 10^{-7}$ ,  $8.75 \times 10^{-7}$ , and  $1.27 \times 10^{-6} \text{ m}^3/\text{rad}$  (4, 5.5, and 8  $\text{cm}^3/\text{rev}$ ) model type AZPW external gear pump from Bosch Rexroth (REXROTH BOSCH, 2016). These pumps were called as P1, P2 and P3, respectively. Figure 7 present the global efficiency chart of the pumps and pumps combination at the pressures 10 MPa and 20 MPa.

The relief valve parameters are: spool diameter 0.0025 m; fraction of spool opening 1; viscous friction coefficient 1200 N.s/m; maximum spool displacement 0.0015 m; spring elastic coefficient 10000 N/m. The check valve parameters are: valve flow coefficient  $7.5 \times 10^{-7} \text{ m}^3 / (\text{s} \sqrt{\text{Pa}})$ ; natural frequency 200 rad/s; damping factor 0.7; pressure crack valve 0.2 MPa. The normally opened on/off valve parameters are (NOSTRANI, 2021): natural frequency to turn the valve on 206.9; natural frequency to turn the valve off 600 rad/s; spool diameter 0.046 m; maximum spool displacement 0.001 m; time delay on 0.03 s; time delay off 0.067 s; discharge coefficient 0.67. The fluid density was 870  $\text{kg}/\text{m}^3$ .

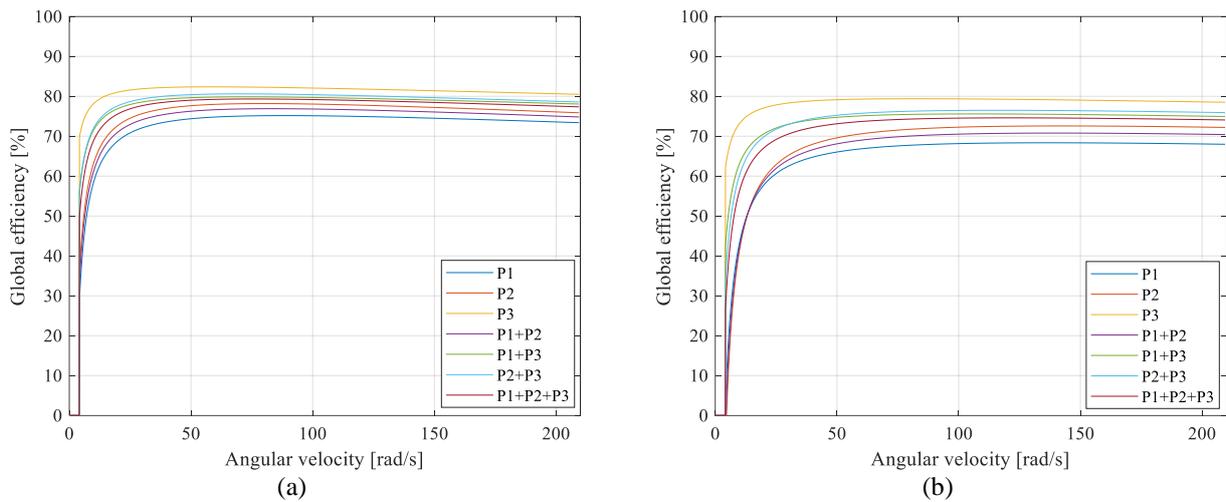


Figure 7. a) The pump global efficiency at 10 MPa, b) The pump global efficiency at 20 MPa.

For the energy analysis of the constant speed variable displacement pump the A10VO pump model from Bosch Rexroth was used, studied by Bravo (2017) the characteristics of the axial piston pump are the volumetric displacement of  $4.45 \times 10^{-6} \text{ m}^3/\text{rad}$  ( $28 \text{ cm}^3/\text{rev}$ ) and the proportional electric control of the pump swash-plate with a time constant of 0.14 s. The volumes used in the model have both  $5 \times 10^{-3} \text{ m}^3$ , the angular velocity is an ideal source and has been adjusted to 109.95 rad/s (1050 rpm).

To create the lookup table, the experimental efficiency maps provided by Bravo (2007) were used. Fig. 8 shows the volumetric and mechanical efficiency maps. It is possible to observe that, due to the nominal operating pressure of 250 bar, the pump has high mechanical efficiency in operating regions close to 170 bar. The tests carried out also show the variation in efficiencies as a function of the angle of the swash-plate.

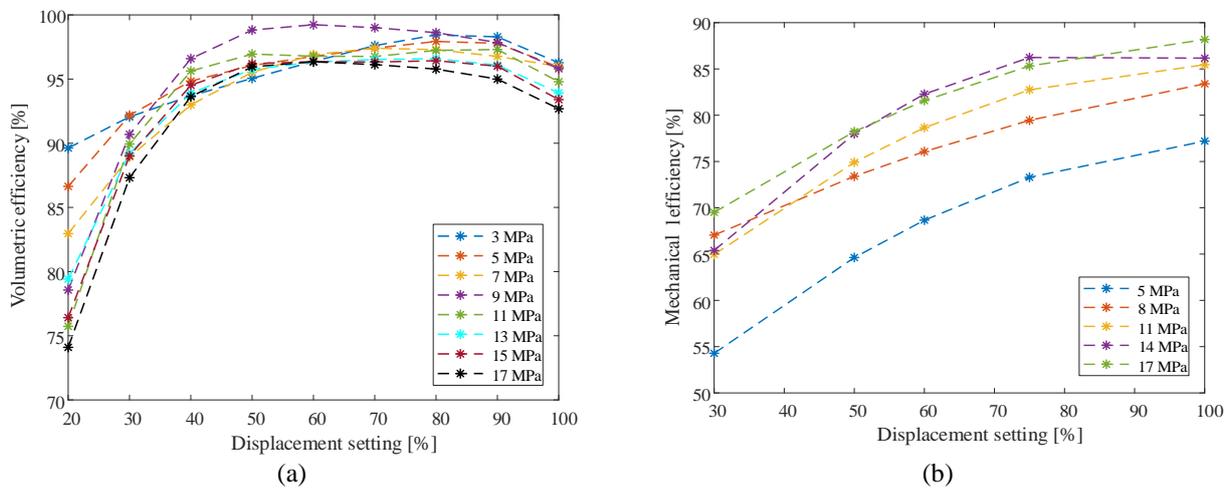


Figure 8. a) The pump volumetric efficiency, b) The pump mechanical efficiency.

#### 4. RESULTS AND DISCUSSION

It was created a flow rate demand cycle to analyze the hydraulic pumps at different load conditions. The flow rate results and the global efficiency to the variable rotational speed digital hydraulic pump are presented in Fig. 9.

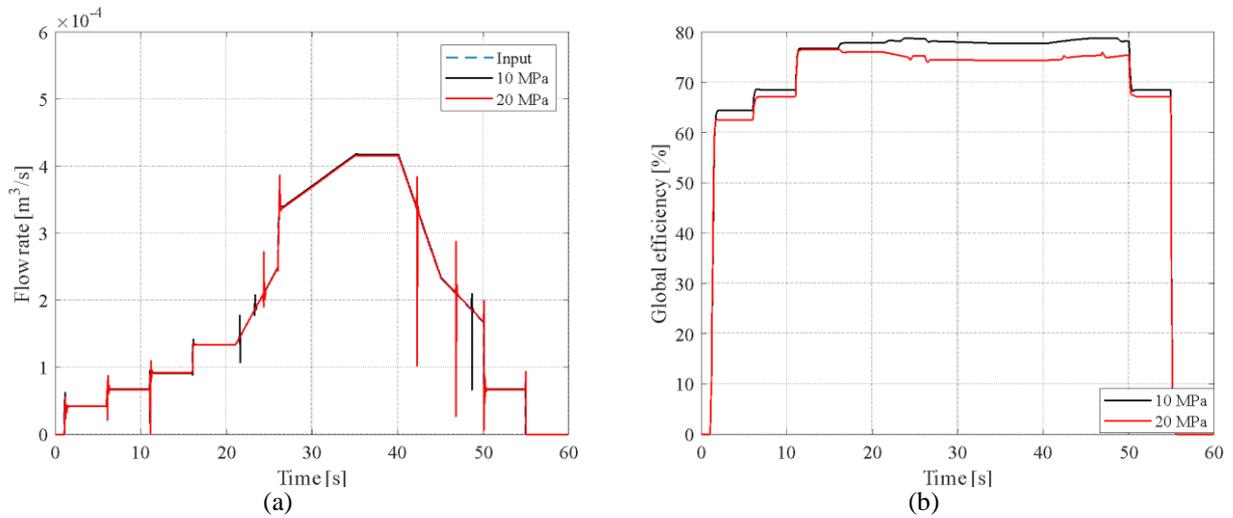


Figure 9. a) The digital hydraulic pump flow rate output, b) The global efficiency.

Figure 9a, shows that the digital hydraulic pump can follow the reference input in both pressure conditions without a large error due to the real-time volumetric efficiency calculation using the lookup tables. It is possible to observe some instantaneous peaks at some points, it could be explained by the system pressure changes due the pump commutation. During the transition time of the pump commutations, the flow rate varies elevating or reducing the pressure differential at the relief valve increasing or reducing the output flowrate until occur the pressure stabilization.

Figure 10 presents the pump angular velocity for each pressure condition during the flow rate demanded cycle. It can be noticed that at the load pressure condition of 20 MPa the pump angular velocities were greater than for the 10 MPa. It could be justified due to the lower volumetric efficiency in this condition, making the digital hydraulic pump use the variable angular velocity to compensate it. Further studies have to be conducted to verify the motor dynamics influence. In this case, when the digital hydraulic pump is on standby, the angular velocity is kept at 104.72 rad/s (1000 rpm).

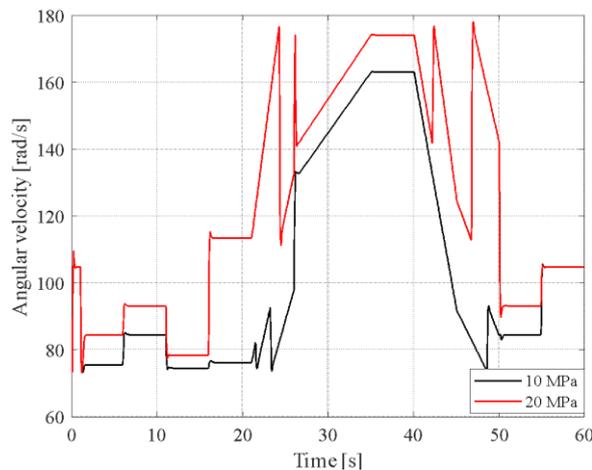


Figure 10. Angular velocity of the digital hydraulic pump.

The results of the flow rate and the overall efficiency of the variable displacement pump are shown in Fig. 11, it can be seen through Fig.11a that the leakage of the pump is more severe in low displacement regions, it is also possible to visualize a larger leakage in the 20 MPa test, what is expected since the increase in pressure differential. Fig.11b shows the overall efficiency of the pump, a better overall efficiency is noted for the 20 MPa test, this is due to the predominance of high mechanical efficiency at the point of operation. However, it should be noted that due to the flow demand the pump did not operate at more than 86% of its maximum displacement, thus a higher overall efficiency was expected in higher flow rates.

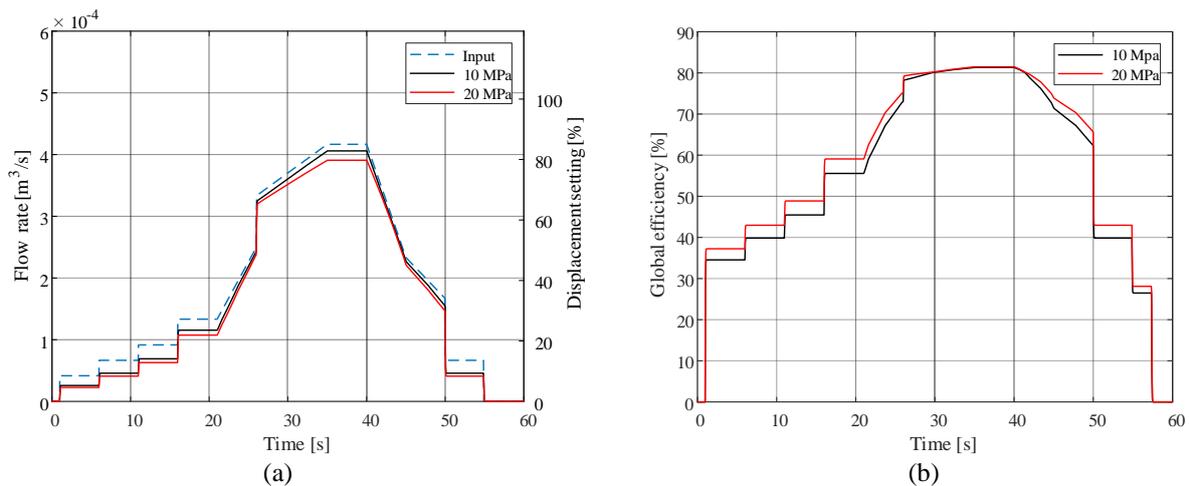


Figure 11. a) The variable displacement pump flow rate output, b) The global efficiency.

## 5. CONCLUSION

In this paper, the mathematical models of a variable rotational speed digital hydraulic pump and fixed rotational speed variable displacement pump were developed. The models were used to perform the global efficiency analysis of the pumps working at same load condition. The results demonstrated that the digital hydraulic pump reached a better global efficiency at low flow rate demand conditions, keeping a global efficiency above 60% for both load conditions, while the variable displacement pump presented a global efficiency lower than 40% at the lowest flow rate requested. In the high flow rate demand condition, the variable displacement pump presented a global efficiency close to 80% while the digital hydraulic pump does not reach 80% of global efficiency but still presents a good efficiency, around 75%.

The efficiency of the variable displacement pump drastically deteriorates when it operates far from its rated operating conditions. It is possible to note that the global efficiency very quickly reduces as the displacement decreases. In other hand, the digital hydraulic pump can change to a smaller pump combination to supply low flow rates with a smaller reduction in global efficiency.

The proposed variable rotational speed digital hydraulic concept showed that it is possible to obtain a better global efficiency for different flow rate conditions. For both cycles the mean global efficiency of the digital hydraulic pump was 67% and 65%, while the variable displacement pump was 55% and 57%, to load pressure of 10 MPa and 20 MPa, respectively. This demonstrate that the variable speed digital hydraulic pump can be a good alternative solution to replace variable displacement pumps at systems with low demand cycles, once that this solution could increase the system global efficiency. These results demonstrate the potential for energy improvement of the variable speed digital hydraulic pump.

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