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ANALYSIS OF DIGITAL HYDRAULIC SYSTEM FOR AIRCRAFT WITH FOCUS ON ENERGY EFFICIENCY

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Abstract. Hydraulics is a technology typically used in applications that require control of large loads and high-power density. However, hydraulic systems are known for their low energy efficiency. As a consequence, a concept known as More Electric Aircraft-MEA proposes that the design of new aircraft can be done using more electrical equipment. Nevertheless, in aircraft applications, due to safety factors and reliability, the control of the primary control surfaces still prioritizes the use of hydraulic actuators. According to recent research results, digital hydraulics is a technology that has been proven to be an alternative for reducing energy dissipation in hydraulic systems. The main objective of this paper is the modeling and experimental analysis of a digital hydraulic system, with a special focus on energy efficiency. The actuator used in this study is the Digital Hydraulic Actuator - DHA and is based on a set of on/off valves, a multi-chamber cylinder, and three pressure lines. A model was developed in the software Hopsan, and validated experimentally. In addition, two equivalent models were developed for the servo-valve actuation system, in order to compare the efficiency of these systems. The first model considers the internal leakage of the servo valve and the second model the leakage is neglected. For the internal leakage model, the servo-valve was modeled using a full Wheatstone bridge with hydraulic resistances, which was validated based on experimental results. The results obtained show a considerable increase in energy efficiency of the digital system, due to the absence of resistive control by orifices and reduction of internal and pilot leakages. The system with servo-valve has an efficiency of 1,2% and the digital system of 37.2%, with a decrease of the input energy from 16.6 to 1.7 kJ and a reduction of the energy loss of 93%. These results demonstrate that DHA can be a promising solution for obtaining more efficient hydraulic systems.

Keywords: Digital hydraulics, energy efficiency, aircraft actuation systems.

1. INTRODUCTION

Hydraulics is a technology widely used in applications that require great load control, high power density, and fast dynamic response. However, hydraulics is also known to have low energy efficiency when compared to electrical systems (TANAKA & SAKAMA, 2013). In this context, in relation to the aeronautical field, there is an initiative known as More Electric Aircraft - MEA, whose objective is the use of electrical systems in replacement of mechanical, hydraulic, and pneumatic systems (CAO *et al*., 2012). However, due to various safety and reliability factors, the control of primary flight control surfaces still uses hydraulic actuators. This contributes to research into hydraulic systems to achieve more efficient solutions.

According to recent research results, digital hydraulics is a technology that has proven to be an alternative to reduce energy dissipation in hydraulic systems. According to Linjama (2011), Digital Hydraulics can be defined as hydraulic systems that have discrete components, which are able to actively control the system output. These systems aim to increase energy efficiency by reducing resistive and dissipative effects in flow and pressure control actions (LINJAMA, 2011; SCHEIDL, *et al*., 2008; DE NEGRI, *et al*., 2014).

Applying the concepts of digital hydraulics, a proposal was developed by Belan (2018), which was called DHA - Digital Hydraulic Actuator (BELAN, *et al*., 2016b). Belan (2018) proposed an architecture for more efficient actuation hydraulic systems for aircraft, based on replacing the servovalve with a set of on/off valves, associated with a multichamber hydraulic cylinder and three pressure lines. This concept was implemented on a test bench at the Laboratory

of Hydraulic and Pneumatic Systems (LASHIP) at the Federal University of Santa Catarina (UFSC) where the results obtained are promising.

Several studies in recent years have investigated increasing the efficiency of digital hydraulic systems. Although many ideas of digital hydraulics have been developed for decades, only a few years ago research in this field reached a relevant development. In this context, this paper aims to present an energy comparative analysis between the Digital Hydraulic Actuator – SHA, which was developed by Belan (2018) and the Servo Hydraulic Actuator, which is the commonly used solution on aircraft flight control surfaces, in order to verify the energy gains when the digital solution is used. This paper is divided in five sections. Section 2 presents the models of the Digital Hydraulic Actuator and the Servo Hydraulic Actuator. Section 3 presents the main simulation results. In the Section 4, the main conclusions are presented and in Section 5 the main references.

2. NUMERICAL MODEL

In this section of the paper, the numerical model developed for the Digital Hydraulic Actuator – DHA and for the Servo Hydraulic Actuator will be presented.

2.1 Digital Hydraulic Actuator – DHA

The system developed by Belan (2018) uses the technique known as secondary control for linear actuators and is composed of three pressure lines, a set of on/off valves, and a multichamber cylinder. The description presented in this section is based on the work developed by Belan (2018).

Figure 1 shows the proposed design for the actuation system, already including the multichamber actuator. In this configuration, the system servovalves are replaced by a set of 12 discrete valves (on/off) to perform position control and force control. In this configuration, three constant pressure lines, which can operate at different values are considered. The lowest pressure line (p_{S3}) will always be fixed (7.5 bar) and the other two (p_{S1} and p_{S2}) can be adjusted within a range of 20 bar to 300 bar. The high and medium pressure lines (p_{S1} and p_{S2}, respectively) can be fed by independent units, in correspondence with the redundant pumps currently available on the aircraft. The third supply line (p_{S3}), of low pressure, will possibly be connected to the reservoirs, which in aircraft are redundant and pressurized (BELAN, 2018). The design requirements of the DHA used in this paper were based on those presented by Belan (2018).
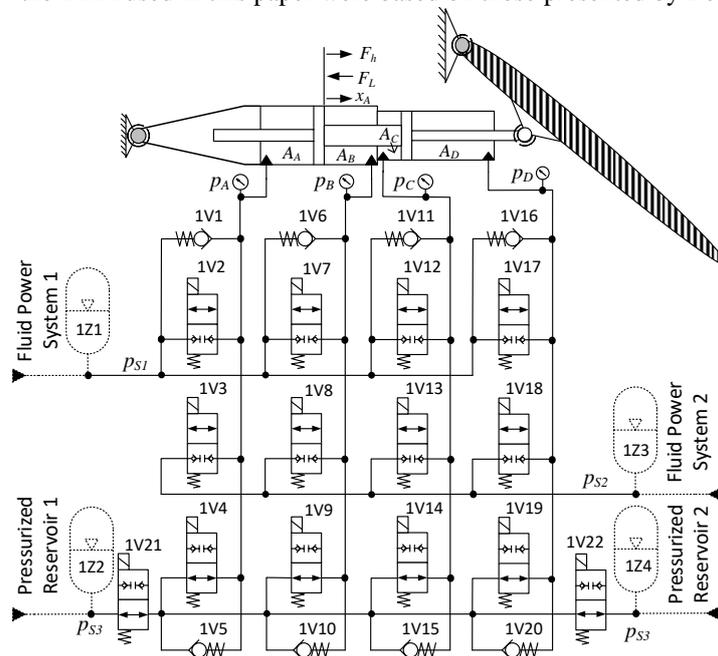

Figure 1 - Digital Hydraulic Actuator (Adapted from Belan (2018)).

Each cylinder chamber can be powered by one of the pressure lines, activating a specific on/off valve. It should be noted that it is permissible for the same supply pressure line to be connected to two or more actuator chambers at the same time, however two pressure lines cannot be connected to the same chamber.

For this proposal, the discrete number of forces provided by the actuator depends on the number of actuator chambers, which in this case is four, and the number of supply pressures lines, being three for the topology presented in Figure 1. Therefore, the total number of forces that the actuator can provide is 3^4, for a total of 81. Each force can be calculated as

$$F_H = A_A p_A - A_B p_B + A_c p_c - A_D p_D. \tag{1}$$

Using Eq. (1) and considering the sizes of the areas of chambers A, B, C and D being 13.48×10^{-4}, 7.07×10^{-4}, 11.20×10^{-4} and 15.72×10^{-4} m², respectively, and the values of the pressure lines 1, 2 and 3 being 45×10^{5}, 35×10^{5} and 7.7×10^{5} Pa, the distribution of the available forces are presented in Figure 2.
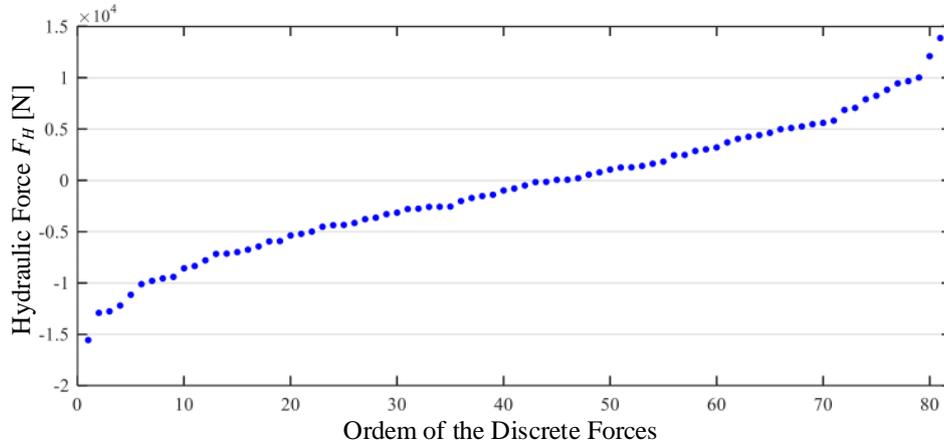
Figure 2 - Distribution of the Hydraulic Forces (Adapted from Belan (2018)).

As can be seen in the results presented in Figure 2, with the values of the areas and pressure lines used, the distribution of the forces tends to be linear with the maximum positive and negative forces with an equivalent value. These features improve the controllability of the system.

In order to verify the dynamic behavior of the digital hydraulic actuator, a mathematical model was developed in the software Hopsan. Figure 3 shows the Hopsan model.
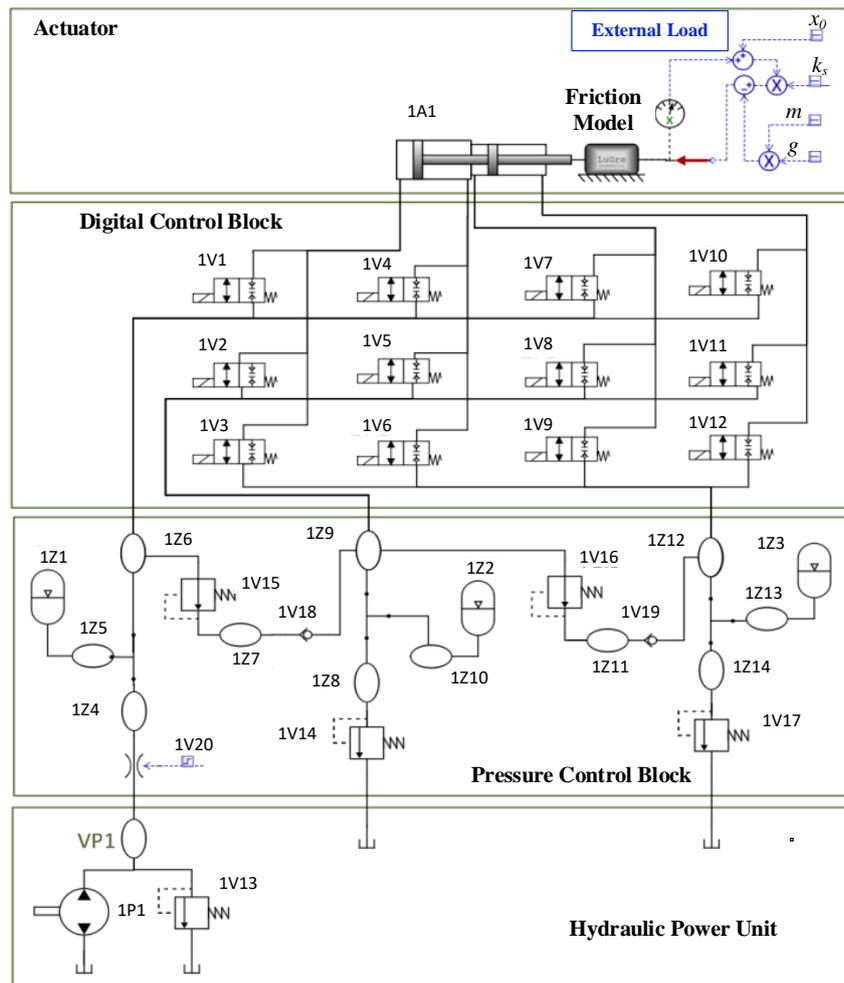

Figure 3 - Hopsan Model for the Digital Hydraulic Actuator.

Model details about the parameters used in the model for the valves, cylinder, external load, and friction model can be seen in Belan (2018) and Cruz (2018).

2.2 Servo Hydraulic Actuator - SHA

To compare the energy efficiency and performance of the proposed digital system with a conventional proportional system, a model of a Servo Hydraulic Actuator -SHA was developed considering the internal and pilot leakage of the servovalve and another one without considering these leakages. The Servo Hydraulic Actuator modeled is presented in Figure 4.
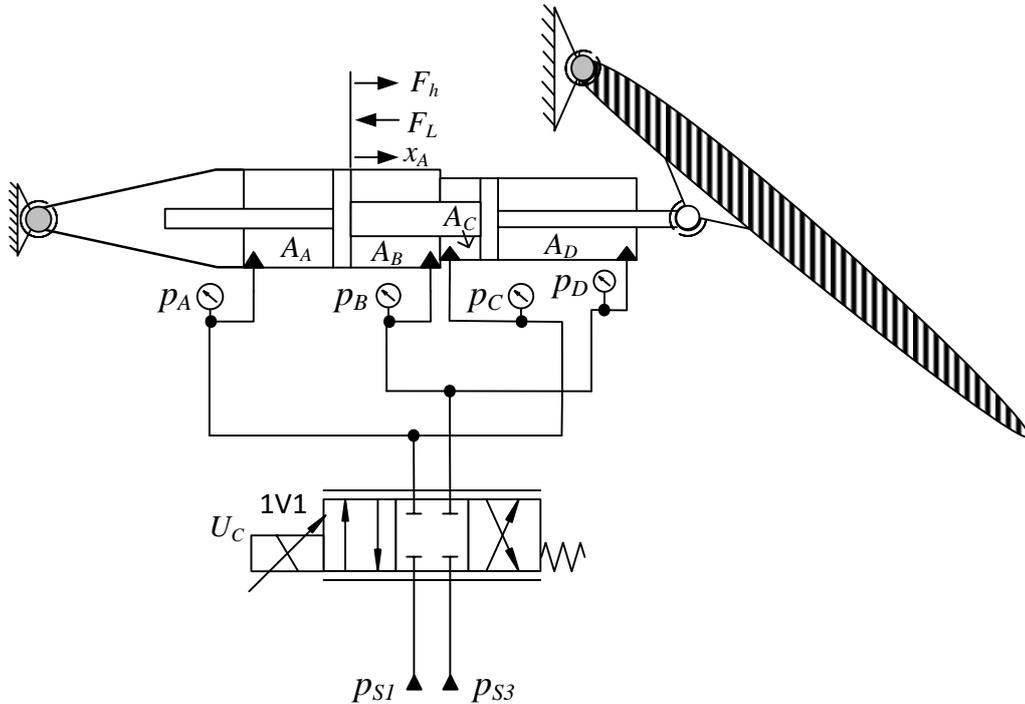
Figure 4 - Servo Hydraulic Actuator - SHA.

The study proposal is based on the specification of a servovalve so that it is equivalent to the set of valves in the digital control block of the digital system. In this context, the model developed in Hopsan for the SHA without considering the internal and pilot leakage of the servo valve is presented in Figure 5.
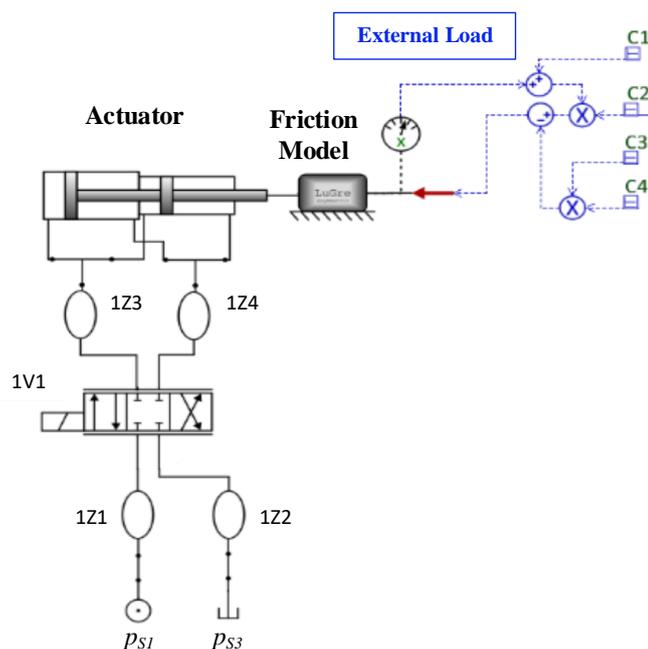

Figure 5 - Servo Hydraulic Actuator without Internal and Pilot Leakage.

One of the parameters to specify a servovalve is to identify the total flow rate coefficient (K_V). This coefficient can be obtained from the ratio of the control flow rate to a nominal inlet and to a test pressure, considered as the nominal pressure. This relation is provided in catalogs from various valve manufacturers or can be extracted from flow rate versus input signal curves (FURST, DE NEGRI, 2002).

To identify the total flow rate coefficient (K_V), the following process was performed: In the model of the digital hydraulic system, the pressure control block and the hydraulic power unit were removed and constant pressure lines were added. This model with constant pressure lines was simulated at maximum velocity and the actuator response is shown in Figure 6. This actuator response was considered as a reference to parameterize the servovalve.
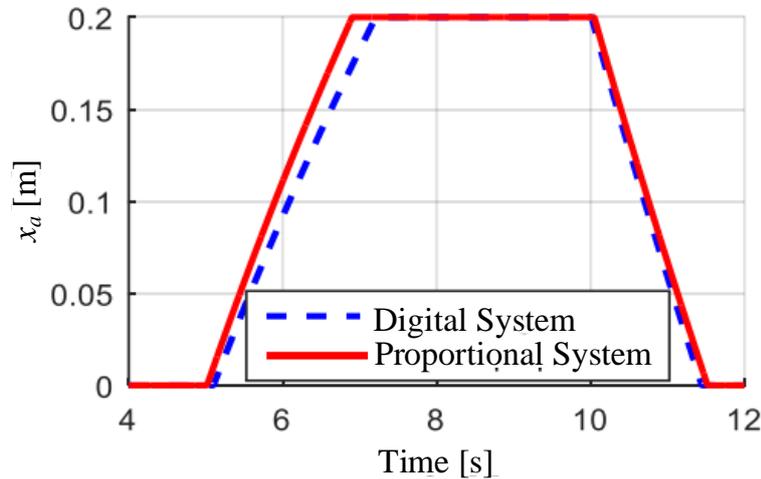

Figure 6 - Comparison Between the Digital and the Proportional Systems.

The model in Figure 5 was simulated in the situation of maximum velocity, for the advance moviment the total opening of the servovalve from port P to A and for the retreat moviment the total opening of the port P to B. The parameters of the servovalve were identified (diameter and maximum displacement spool) to obtain the same actuator response (Figure 6). A comparison of the actuator displacement responses was performed to determine the total servovalve flow rate coefficient (K_V). With the flow curve and pressure differential between ports P and A of the servovalve, the total flow rate coefficient of the servovalve (K_V) of 1.1×10^{-7} m³/(sPa$^{1/2}$) was identified.

To select the flow rate coefficient of the servovalve, Furst & De Negri (2002) recommend that this coefficient should be chosen according to

$$\frac{K_V}{2} \leq K_{V_{cat}} \leq 2K_V. \tag{2}$$

According to Eq. (2) and the information provided by the Moog servovalve catalog, a servovalve with a nominal flow of 3.15 x10-4 m³/s, with a flow rate coefficient of 1.2×10^{-7} m³/(sPa$^{1/2}$) at 70 MPa pressure drop, was chosen. This servovalve was used to perform simulations and analysis of the performance and efficiency of the proportional system.

The model available in the Hopsan software library does not consider internal and pilot leakages. Thus, a model of the servovalve considering the internal and pilot leakages was developed using a Wheatstone bridge. This model was parameterized with data provided by the manufacturer's catalog and with data from experiments carried out at LASHP. Figure 7 presents the model of the servovalve considering the Wheatstone bridge.
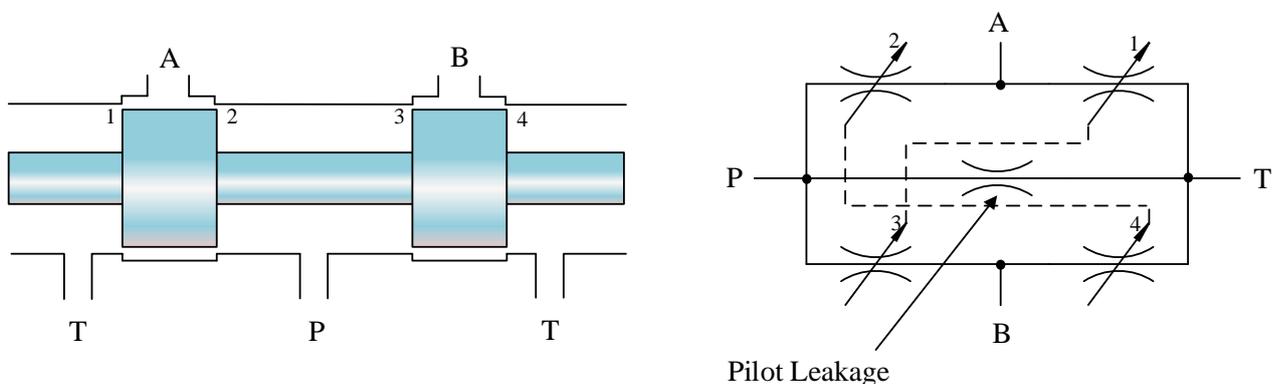

Figure 7 - Servovalve Modeled as a Wheatstone Bridge.

The experiments to provide the internal leakage curve of the servovalve were performed according to ISO 10770-1, with the control ports blocked. For the experiment, the servovalve is supplied with a voltage input signal of -3 to 3 V, with ports A and B closed. The parameterization of the servovalve pilot leakage was carried out with reference to the internal leakage curve determined with the experiments. Figure 7 presents the servovalve leakage considering the pilot leakage. More details about the servovalve model can be found in Cruz (2018).
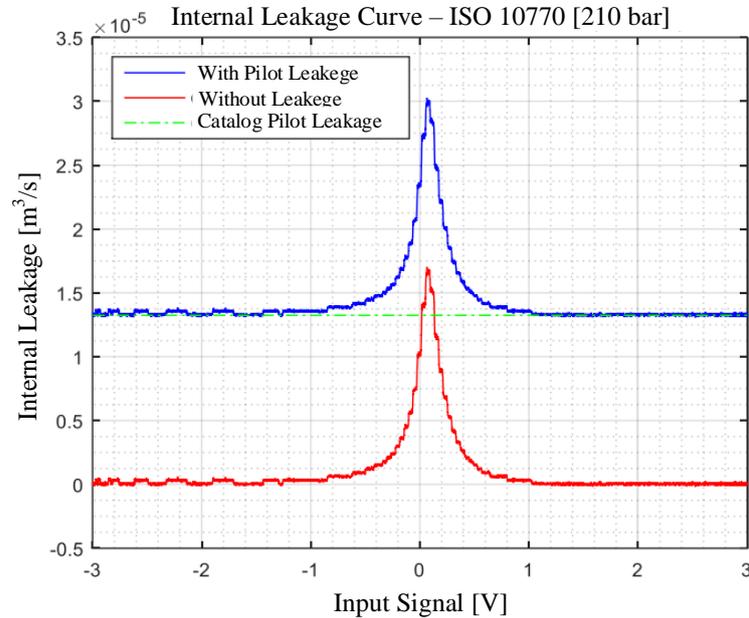

Figure 8 - Internal Leakage of the Servovalve (Adapted from Cruz (2018)).

The model developed for the Servo Hydraulic Actuator considering the internal leakage of the servovalve is presented in Figure 9.
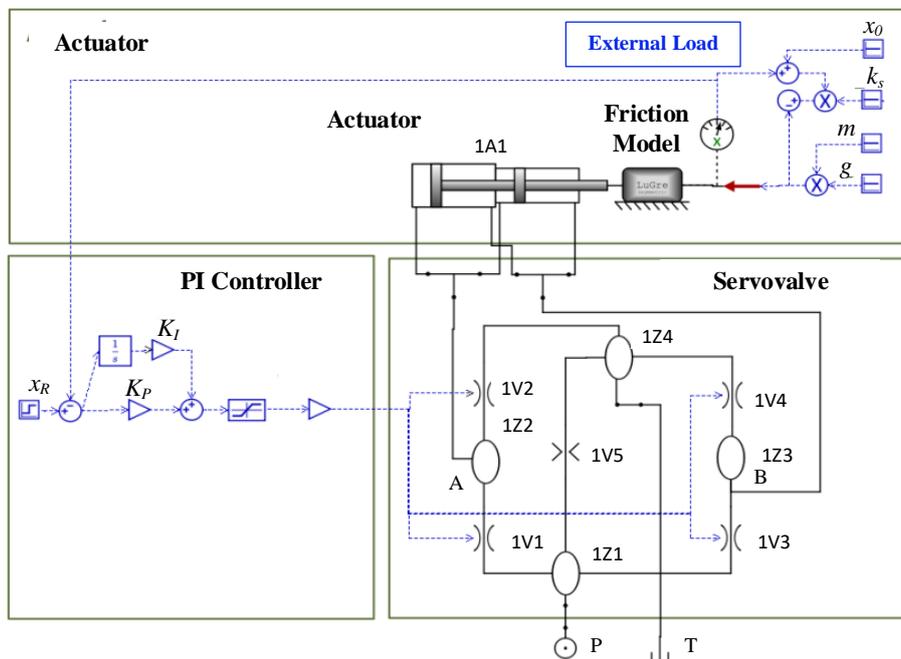

Figure 9 - Servo Hydraulic Actuator Model with Internal Leakage.

3. SIMULATION RESULTS

In this section, the simulation results considering the SHA and DHA operating in position control will be presented. The results of the simulations for the analysis of the energy efficiency of each system and the comparison between the three systems, SHA with leakage, SHA without leakage, and DHA, will also be presented.

For the digital system, the input energy is calculated as

$$E_{in\_D} = \int (P_{ps1} + P_{ps2} + P_{ps3})dt, \tag{3}$$

where P_{ps1}, P_{ps2} and P_{ps3} are the power of the pressure sources 1, 2 and 3, respectively.

For the proportional system, the input energy is calculated as

$$E_{in\_P} = \int (P_P + P_T)dt, \tag{4}$$

where P_P and P_T are the power of the ports P and T of the servovalve, respectively.

The output energy for both systems is calculated as

$$E_{out\_D}, E_{out\_P} = \int (P_A + P_B + P_C + P_D)dt, \tag{5}$$

where P_A, P_B, P_C and P_D are the power of the chamber A, B, C and D of the cylinder, respectively.

The dissipated energy for both systems is expressed as

$$E_{dis\_D} = E_{in\_D} - E_{out_D}, \tag{6}$$

$$E_{dis\_P} = E_{in\_P} - E_{out_P}. \tag{7}$$

Figure 10 presents the results obtained for the DHA in position control. More details about the controller used can be found in Belan (2018) and Cruz (2018).
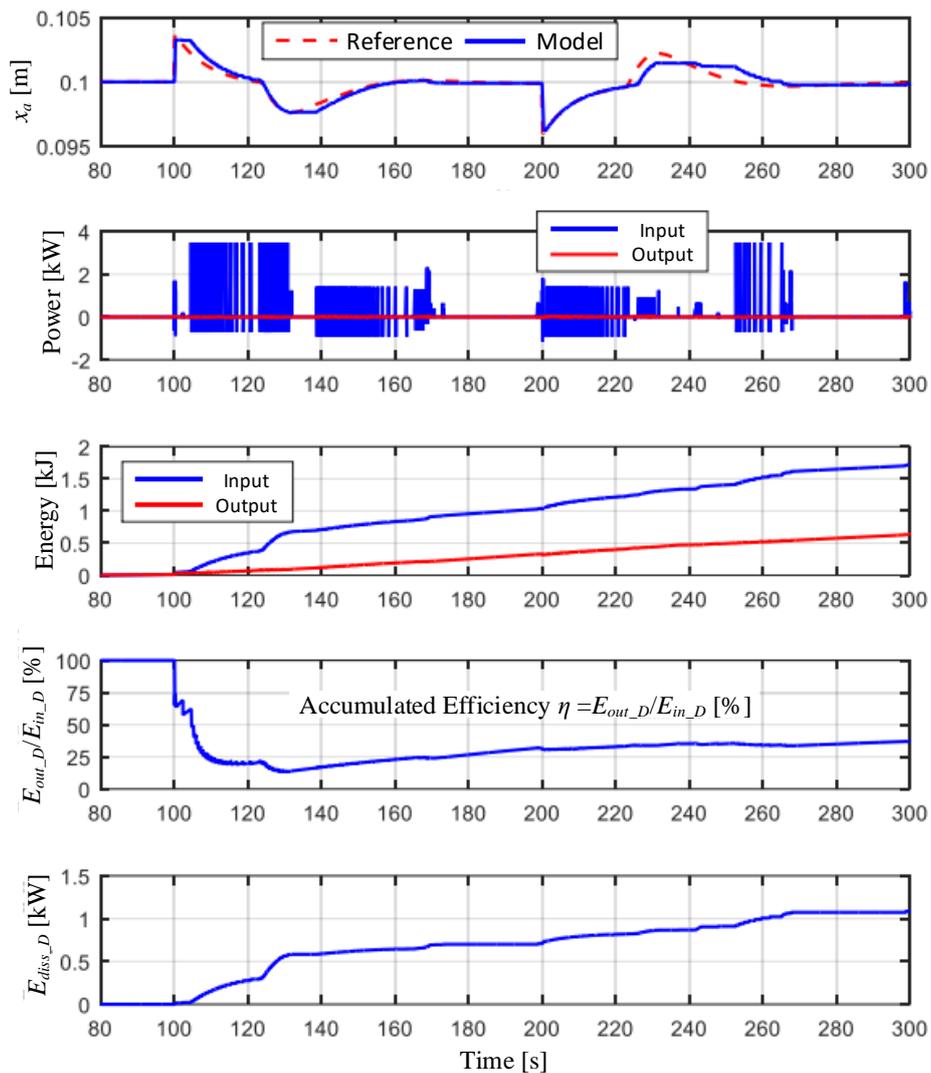

Figure 10 – Energy Results for the DHA.

As can be seen in the results shown in Figure 10, the DHA can control de position with an energy efficiency of around 40%. This is due to the on/off valves that present zero internal leakage when closed. Therefore, with a more efficient hydraulic system, the dissipated energy becomes lower end consequently, other components can be reduced as the hydraulic fluid cooling system. Figure 11 presents the results obtained for the Servo Hydraulic Actuator considering the internal and the pilot leakage.
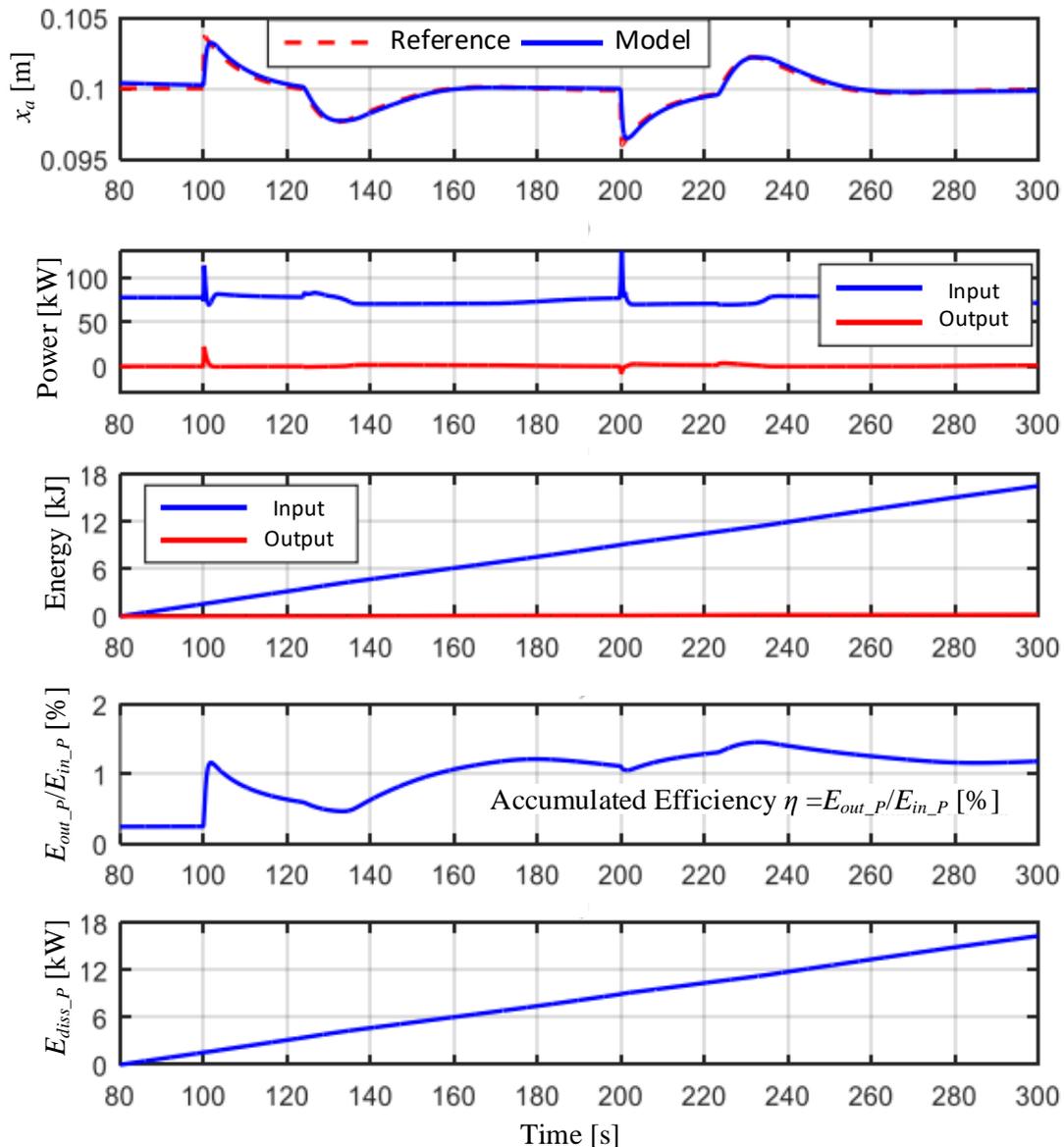

Figure 11 – Energy Results for the SHA with Internal and Pilot Leakage.

As can be seen in the results presented in Figure 11, the servo hydraulic actuator can also control the position of the cylinder. It is observed that there is a constant input power in the system, approximately 70 kW, throughout the simulation. This constant power is due to constant leakage through the servovalve pilot stage. At the end of the simulation, there is an efficiency of approximately 1.2%. This low efficiency is mainly due to leakage through the pilot stage.

The servovalve, in addition to being a resistive element that dissipates energy, also has internal leakage and a pilot that generates a considerable loss of energy. Even if the servovalve does not have any control action, internal and pilot leakages are always present, being in the central point of the servovalve where there is greater internal leakage. Thus, the dissipated energy curve is a straight line with a constant slope that is due to constant leakage through the servovalve pilot stage. In this case, almost all input energy is converted in heat which is transferred to the environment, components, and hydraulic fluid, increasing considerably the temperature of the hydraulic system, which demands a bigger cooling system when compared to the DHA.

Figure 12 presents the input, output, and dissipated energy for the digital system and proportional system.
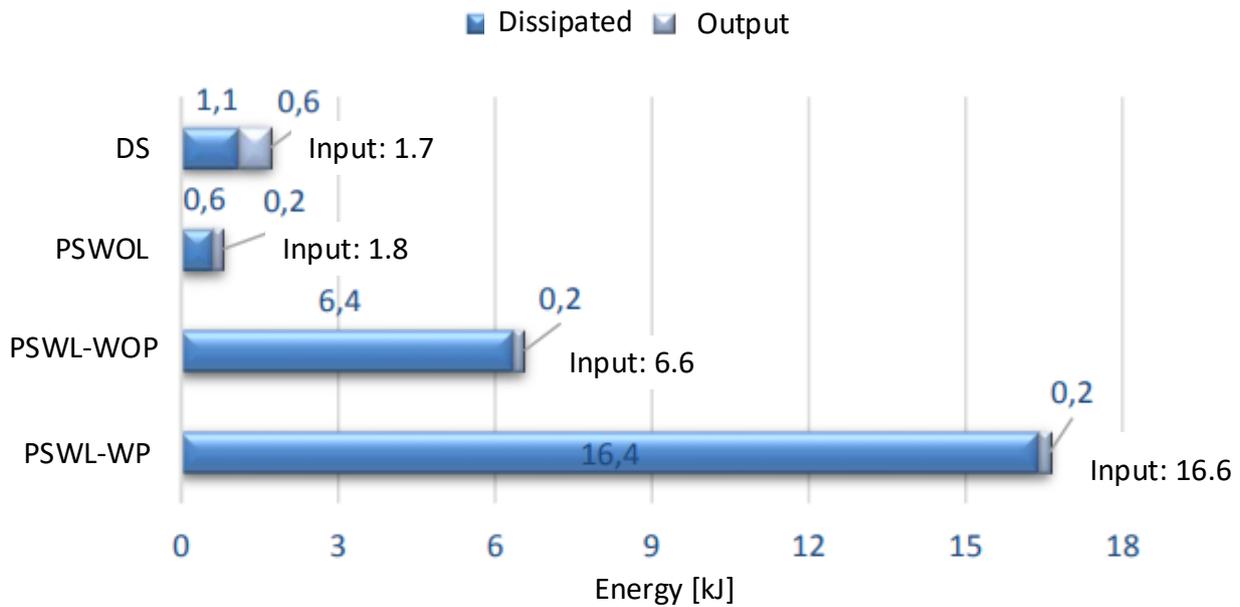
DS – Digital System
PSWOL – Proportional System without Leakage
PSWL-WOP – Proportional System with Leakage without Pilot Leakage
PSWL-WP – Proportional System with Internal and Pilot Leakage
Figure 12 – Input, Output and Dissipated Energy.

It is observed in the results presented in Figure 12 that the energy dissipated by the proportional system with internal leakage (PSWL-WP) is greater than the other systems, due to the internal leakage and pilot leakage of the servovalve. The value of energy dissipated only by the pilot leakage is approximately of 9.8 kJ. Since the total energy dissipated in the servovalve is 16.6 kJ, then the energy dissipated by the pilot is approximately 60% of the total energy dissipated in the servovalve. The proportional system considering only the internal leaks without considering the pilot stage (PSWL-WOP) has a higher energy dissipation than the digital system (DS).

4. CONCLUSIONS

In this paper, a comparative energy analysis of a Digital Hydraulic Actuator – DHA and a Servo Hydraulic Actuator – SHA was presented. The DHA is a hydraulic actuator topology developed to be a more energy efficient solution for application in aircraft flight control surfaces, since the SHA, which is the most common solution applied, has low energy efficiency due the internal and pilot leakages of the servovalves. The study carried out in this paper shows a considerable increase in the energy efficiency of the analyzed digital system. When relating the output energy to the total input energy, from 1.2% of the proportional system considering the internal and pilot leakage (PSWL-WP) to 37.2% of the digital system (DS). This increase in efficiency results in a reduction of input energy to the system from 16.6 kJ to 1.7 kJ.

Considering the proportional system only with internal leaks (PCV-SP), without pilot leakage, with the digital system (DS), when relating the output energy to the total input energy, of 2.9% of the proportional system considering leakages (PSWL-WOP) to 37.2% of the digital system (SD), the input energy reduction is 6.6 kJ to 1.7 kJ given that the pilot dissipation of 9.8 kJ.

The results presented demonstrate that the Digital Hydraulic Actuator can be a good solution to obtain a more efficient hydraulic system for application in aircraft, where the other components can be reduced as the cooling system, saving weight and consequently fuel.

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6. ACKNOWLEDGEMENTS

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