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A STUDY OF AN ELECTRO-HYDROSTATIC ACTUATOR FOR AIRCRAFT APPLICATION

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Abstract. *Hydraulic systems are known for their robustness and high power density, which makes them a good solution for mobile applications, including aerospace ones. In aeronautical applications, recent technological developments have led to a trend towards the use of electrical systems, aiming to improve energy use, reduce maintenance, reduce weight, increase payload capacity and decrease life cycle costs. The Electro-Hydrostatic Actuator - EHA stands out as a key solution in the transition to more electric actuation systems. EHAs are decentralized power-by-wire actuators that eliminate the need for extensive hydraulic pipelines, reducing complexity and the risk of leakage, allied to a compact design, high power density, controllability, and weight reduction. This study focuses on an EHA with a fixed displacement pump and a variable speed motor. The actuator design is based on aircraft requirements, and a model is implemented to assess its dynamic behavior and energy consumption. The results demonstrate the ability of the EHA to achieve precise position control within the specified settling time, which show their good dynamic response. The power consumption analysis reveals efficient power conversion during cylinder movement, however the efficiency decreases when holding high loads for extended periods. High torque requirements for cylinder position holding result in increased electric current and heat generation. The research provides a foundation for the development of EHAs in aircraft applications, emphasizing the need for further investigation into heat dissipation and system efficiency during prolonged high-load conditions.*

Keywords: *Electro-Hydrostatic Actuator, Power consumption, Aircraft application*

1. INTRODUCTION

Hydraulic systems have played a crucial role in actuation systems in both industrial and mobile applications. These systems possess several key characteristics that contribute to their widespread use, including robustness, excellent dynamic response, reliability, and notably, high power density. It is this exceptional power density that renders hydraulic systems nearly unparalleled when compared to alternative actuator solutions. However, in recent decades, with the continuous evolution of electrical components, new approaches incorporating electrical systems concepts have begun to emerge. This paradigm shift has given rise to the concept of More Electric Aircraft (MEA), which first emerged nearly ninety years ago. The MEA concept focuses on gradually replacing traditional hydraulic and pneumatic systems with electrical systems (BOZHKO *et al.*, 2018; CHAKRABORTY *et al.*, 2013; SARLIOGLU; MORRIS, 2015).

The integration of electrical systems into aircraft design brings forth numerous advantages. It enables improved energy utilization, as electrical systems can more precisely tailor power delivery to match demand, resulting in enhanced efficiency. Additionally, the shift towards electrical systems reduces the reliance on hydraulic and pneumatic components, leading to reduced maintenance requirements and increased operational reliability. Furthermore, the adoption of electrical systems contributes to weight reduction, which is of utmost importance in the aerospace industry. The reduction in weight not only positively impacts fuel efficiency, but also allows for increased payload capacity and improved overall performance. Moreover, the incorporation of electrical systems in aircraft design offers the potential for decreased life cycle costs. Electrical components often exhibit longer lifespans and require less frequent maintenance, resulting in reduced operating expenses over the aircraft's lifetime.

In the context of transitioning from conventional servo-hydraulic actuators to more electric solutions, the Electro-Hydrostatic Actuator (EHA) stands out as a key solution. The EHA represents a decentralized power-by-wire actuator, eliminating the need for hydraulic pipelines that would transport hydraulic power from a centralized hydraulic power unit

to the hydraulic cylinder. This not only reduces the number of pipelines within the aircraft, but also mitigates the risk of leakage associated with hydraulic systems. In this solution, electric power is converted into hydraulic power in close proximity to the final application (MARÉ, 2017; MOIR; SEABRIDGE, 2008).

The EHA combines the compactness and high power density provided by hydraulic cylinders with the controllability offered by electrical systems and electric motors (MARÉ; FU, 2017). Various architectures of EHAs can be found in the literature, typically classified into three main groups based on the speed of the electric motor and the volumetric displacement of the pump. These groups include configurations with both variable and fixed options, such as variable pump and fixed motor, fixed pump and variable motor, and variable pump combined with a variable motor (ALLE *et al.*, 2016). In a comprehensive review of electro-hydrostatic actuators focusing on flight control, Alle *et al.* (2016) emphasize that EHAs with a fixed pump and variable motor are simpler and exhibit better efficiency compared to systems that use a variable pump combined with a fixed-speed motor. The latter offers an improved dynamic response, while EHAs with a variable pump combined with a variable motor allow for simultaneous adjustment to leverage the advantages of both configurations.

By adopting EHAs, aircraft systems can benefit from their compact design, high power density, controllability, and flexibility. The localized conversion of electric power into hydraulic power near the final application not only reduces the reliance on extensive hydraulic pipelines, but also simplifies system architecture, enhances controllability and increases overall reliability. Additionally, EHAs contribute to weight reduction, fuel savings, improved maneuverability and operational performance. The decentralized nature of EHAs also enhances safety by minimizing the risks associated with hydraulic leaks and facilitating localized maintenance and troubleshooting. In this paper, a model of an Electro-Hydrostatic Actuator (EHA) with a fixed displacement pump and a variable speed motor is presented. The design of the actuator is based on aircraft requirements documented in the literature. The model is implemented to assess the dynamic behavior of the actuator for control position response. Furthermore, an energy evaluation is conducted. This study represents the initial step towards the development of a test bench.

2. AIRCRAFT CONTROL SURFACES AND ACTUATOR REQUIREMENTS

Control surfaces play a vital role in maneuvering an aircraft and, in conjunction with flight control systems, enable pilots to maintain control during flight (MOIR; SEABRIDGE, 2008). These surfaces can be categorized into primary and secondary control surfaces based on their priority level. Primary control surfaces are responsible for controlling the aircraft's trajectory, while secondary control surfaces modify the aerodynamic configuration during specific flight phases (MARÉ, 2016).

The requirements for control surface actuation systems can vary significantly depending on factors such as aircraft type, size, maneuverability and application. The development of these actuation systems aims to meet various requirements, including controllability, power, dynamics, environmental considerations, service life, reliability and integration with the aircraft structure. The latter is closely related to the architecture, size and volume occupied by the actuation solution (MARÉ, 2016; MOIR; SEABRIDGE, 2008).

Information regarding actuator requirements is often limited due to technological and commercial considerations. Maré (2016) provides a summary of power and dynamics requirements, where typical stroke ranges from 20 to 700 mm, speed ranges from 20 to 500 mm/s, force ranges from 20 to 350 kN and bandwidth ranges from 1 to 20 Hz. Table 1 presents examples of requirements for actuators and their respective applications.

Table 1 – Example of actuator requirements.

	Actuator function			
	Aileron Airbus A320	Nose landing gear steering A320	Tilt rotor Boeing V22	Thrust vector control Ariane V
Stroke (mm) (degree)	44	± 75	1143	± 160
Speed (mm/s) (degree/s)	90	20	97	972
Force (kN) (Nm)	44	7000	80	347
Bandwidth (Hz)	1	1.5	3.2	7.9

Source: Adapted from Maré (2016).

3. ELECTRO-HYDROSTATIC ACTUATOR MODEL

In this study, an Electro-Hydrostatic Actuator was developed to generate a force of 20 kN. Following a hydraulic positioning system design method proposed by De Negri *et al.* (2008), the boundary conditions applied were a settling time of 1 second for a maximum step of 0.05 m, a maximum pressure of 21 MPa, an actuator stroke of 0.1 m and a cylinder area of $A_{EHA} = 23.72 \times 10^{-4} \text{m}^2$. This method was utilized to determine the maximum flow rate required by the

system, resulting in a required flow rate of $2.63 \times 10^{-4} \text{m}^3/\text{s}$. For the primary rotational moving source, a four-pole three-phase induction motor was considered. Taking into account a maximum available angular velocity of 188 rad/s, a sizing method for digital hydraulic pumps proposed by Silva (2023) was adapted to select a fixed displacement pump. As result, a pump with a volumetric displacement of 9.94 cm³/rev was chosen.

In order to model the pump, it was assumed that the output flow rate of the pump is a function of the angular velocity (ω), volumetric displacement (D), and pressure differential across the pump (Δp). This relationship can be expressed as follows

$$q_{Vreal} = \omega D - q_{Vloss}, \tag{1}$$

where q_{Vloss} represents the internal leakage of the pump, which is modeled using the laminar orifice equation, being

$$q_{Vloss} = k_{vin}\Delta p, \tag{2}$$

where k_{vi} is the internal leakage coefficient and Δp denotes the pressure differential at the pump ports.
The q_{Vreal} is obtained from the manufacturer datasheet (Figure 1), where the flow curves are used to calculate the pump flow rate for a different pressure conditions and angular velocities obtaining a flow rate map and the angular velocity map. During the simulation, the flow rate map is employed as a lookup table, with pressure and angular velocity serving as input variables and the corresponding real flow rate as the output. The k_{vin} is calculated in real-time simulation by

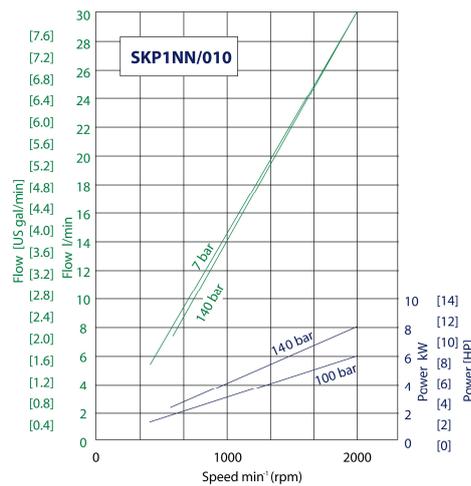$$k_{vin} = \frac{(\omega D - q_{Vreal})}{\Delta p} \tag{3}$$

Figure 1 – Pump information. Source: Adapted from DANFOSS (2019).

A drain is modeled using the laminar orifice equation, taking into account a fixed flow rate coefficient (k_v) of 2.5×10^{-1} m⁵/Ns, given by

$$q_{Vd} = k_{vin}\Delta p. \tag{4}$$

Figure 2 illustrates the pump maps derived from information in the manufacturer datasheet. Figure 2a represents the flow rate map, which is utilized to determine the actual flow rate for calculating the internal leakage coefficient. Figure 2b depicts the angular velocity map, which assists in identifying the required angular velocity to achieve the desired flow based on the system pressure and, Figure 2c shows the torque map, which is used to determine the torque under specific pressure and angular velocity conditions.
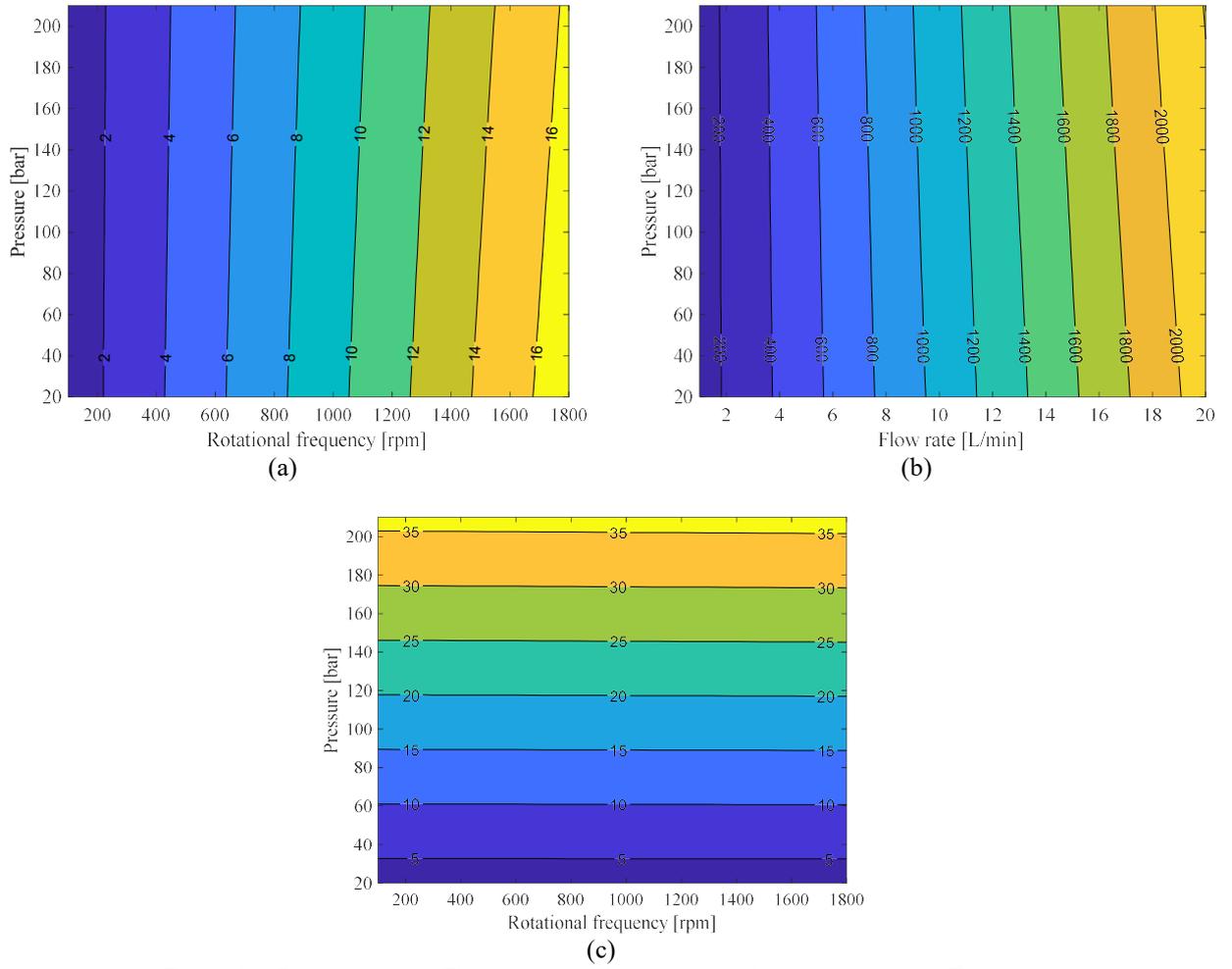
Figure 2 – Pump maps. a) Flow rate map, b) Angular velocity map, and c) Torque map.

The dynamics of the electric motor were approximated using a second order transfer function, considering natural frequency of 20 rad/s and a damping coefficient of 1. The cylinder is modeled as a symmetric dual chamber cylinder, using the continuity equation to describe the inlet and outlet flow rate in the cylinder chambers,

$$q_{V\,in} - q_{V\,out} = Av + \frac{V}{\beta_e}\frac{dp}{dt}, \tag{5}$$

where $q_{V\,in}$, $q_{V\,out}$, and q_{vleak} are the input and output flow rates, respectively, A is the chamber area, v is the cylinder velocity, V is the chamber volume, β_e is the effective bulk modulus, and p is the pressure.

The equation of motion (Second Newton's Law) was used to describe the cylinder rod movement as

$$M_T\ddot{x} = p_A A_A - p_B A_B + p_c A_c - p_D A_D - F_{fric} - F_L , \tag{6}$$

where M_T is the total mass moved, $\ddot{x}$ is the acceleration, $p_A, p_B, p_C, p_D, A_A, A_B, A_C$ and A_D are the chamber pressures and areas, respectively; F_{fric} and F_L are the friction and external load forces, respectively.

The LuGre friction model (ASTROM; DE-WIT, 2008; DE WIT *et al.*, 1995) was adopted using parameters obtained experimentally by Silva (2023) for a hydraulic cylinder (Table 2).

Table 2 – LuGre parameters

Parameter	Positive velocities	Negative velocities	Unit
Coulomb Force (F_c)	271.65	235.29	N
Static force (F_s)	1364.15	1124.50	N
Stribeck velocity (v_s)	0.006968	0.008257	m/s
Stiffness coefficient (σ_0)	5×10^6	2.5×10^6	N/m^2
Damping coefficient (σ_1)	0.1	0.1	Ns/m
Viscous coefficient (σ_2)	1712.65	1183.28	Ns/m
α	0.48	0.67	

Source: Silva (2023).

Figure 3 presents the hydraulic circuit of the EHA. The circuit is based on a single pump configuration with a pressurized reservoir (Figure 3a) (COSTA; SEPEHRI, 2015; MARÉ, 2017). A symmetric hydraulic cylinder is connected to a pump, and two relief valves are employed to connect the high and low-pressure lines for safety purposes. To prevent cavitation and replenish the hydraulic system due to internal leakage in system components, the pressurized reservoir is connected to the system through two relief valves. The software Hopsan was utilized for the implementation the EHA system (Figure 3b).

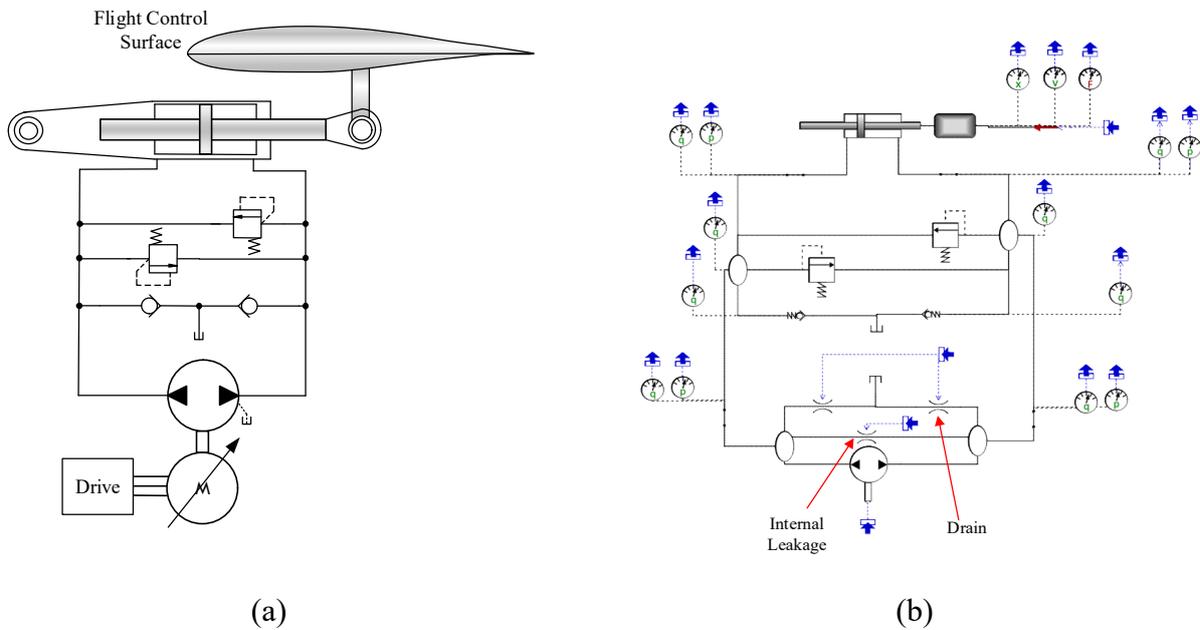(a)   (b)

Figure 3 – EHA implemented in Hopsan. Source: Author.

Table 3 presents other parameters used to implement the model in Hopsan, which were adopted considering generic information from manufacturers datasheets.

Table 3 – Parameters of EHA model.

Parameters	Unit	Value
Bulk Modulus	Pa	1.3×10^9
Check valve restriction coef.		7.5×10^{-7}
Check valve crack pressure	Pa	1×10^5
Cylinder Area	m^2	2.372×10^{-3}
Cylinder Stroke	m	0.1
Cylinder dead volume	m^3	3×10^{-5}

Cylinder leakage coefficient		1×10^{-14}
Drain flow rate coefficient	m^5/Ns	2.5×10^{-12}
Mass moved	kg	100
Relief valve opening pressure	Pa	2.5×10^7
Relief valve Nominal flow rate	m^3/s	1.667×10^{-3}
Reservoir pressure	Pa	1×10^6
Volume lines	m^3	1×10^{-3}

<div align="center">Source: Silva (2023).</div>

Considering the application on an aircraft control surface, the external load is modeled take into account a spring force, as aerodynamic loads tend to increase proportionally to the displacement of the control surface, given by

$$F_L = kx, \tag{7}$$

where k is a spring constant, which is configured to produce the maximum force at the maximum cylinder displacement, and x is the cylinder position, where the initial position is centralized.

Figure 4 presents the system block diagram, a position reference (x_{ref}) is compared with cylinder position (x_{A1}), resulting in a position error(e), a Proportional Integral controller is used to control the cylinder position, where a proportional gain of 2.2 and integral gain of 0.3 were used. In addition, a gain of $5.33 \times 10^{-3} m^2/s$ is used to convert the position error signal in to a flow rate requirement signal (q_V). The signals of required flow rate and pressure are used as input to the angular velocity map, implemented as a lookup table, which gives as output a signal of angular velocity necessary to the pump achieve the required flow rate. The angular velocity signal is sent to the electric motor as a command signal (ω_{cmd}). Rotor angular velocity (ω_r) is the electric motor output, which is used in the flow rate map, to calculate the pump internal leakage coefficient (k_{vin}), and in the torque map to obtain the torque demanded by the pup (T) used in the energy evaluation. System pressure (p_{sys}) is the pressure differential at the pump ports, used in the look up tables as second input variable.
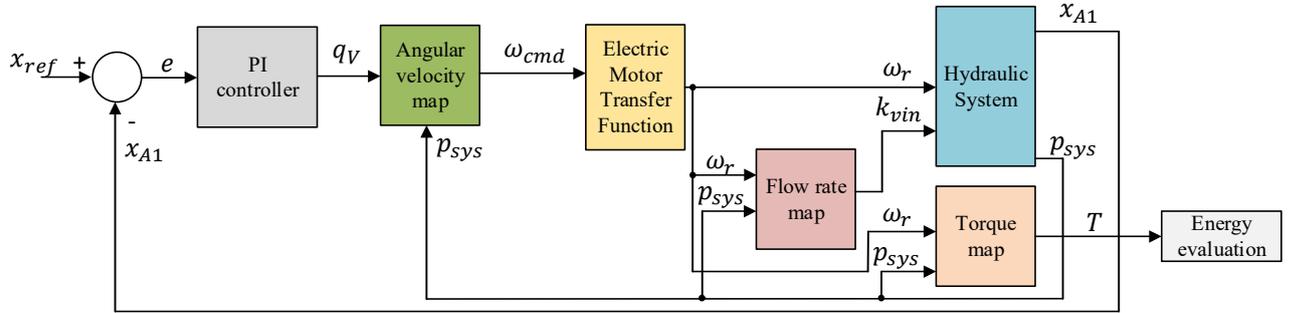

Figure 4 – System block diagram.

3.1 Power consumption evaluation

During the simulation, power consumption evaluation was performed to observe the behavior of the system. Mechanical power inputted to the system (P_{Sin}) was computed based on torque required by the pump (T) and its rotational frequency (ω_r), given by

$$P_{Sin} = T\omega_r. \tag{8}$$

The hydraulic power of the pump (P_p) was calculated using the pressure and flow rate information given by

$$P_p = \Delta p q_V \tag{9}$$

The system output power (P_{Sout}) was obtained using the output force (F) and cylinder rod velocity (v_r), calculated as

$$P_{Sout} = Fv_r. \tag{10}$$

The energy was calculated by integrating the power in time. As the actuator is controlled based on position reference, three different steps were used to evaluate the energy consumption, in order to evaluate the energy consumption in a small medium and maximum displacement condition.

4. SIMULATION RESULTS

Figure 5 presents the position control response for three different steps, which were used to evaluate the behavior and power consumption of the EHA. The actuator was able to achieve a maximum step of 0.05 m inside the stablished time of 1 s, and also complete the tasks for smaller steps, the PI controller gains used in each step are the same. Figure 6 present the mechanical power input and output of the actuator. Observing the graphs of Figure 6a and Figure 6b, in the time between 1 and 2 s the peak of inputted power in the shaft of the pump is almost totally converted to output power in the cylinder rod, presenting an efficiency of 66% on that point. The simulation keeps running until the time of 10 s after the step input. This time simulation is used to observe the effect of the external load in the power consumption of the actuator. In this configuration of EHA, to maintain cylinder position, the pump must supply the necessary flow rate to reach a pressure level capable of balancing the external load and supplying internal leaks, which are proportional to the pressure differential on the pump. In this case, the pressure resulting from the external load has a direct effect on the pump, which requires a higher torque from the electric motor, increasing the power consumption (Figure 6a). Figure 6b, shows the cylinder output power, after the step response, as the cylinder is kept holding position, the power output is zero for all simulations. In this case, after the movement, if the actuator is stopped holding load the energy efficiency of the system decrease as the output power is zero.
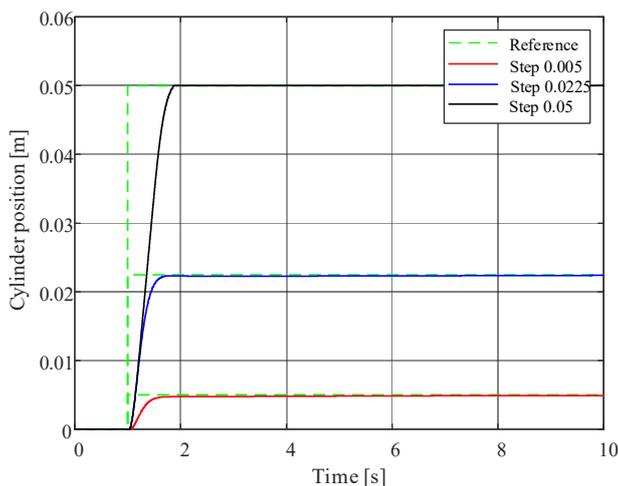

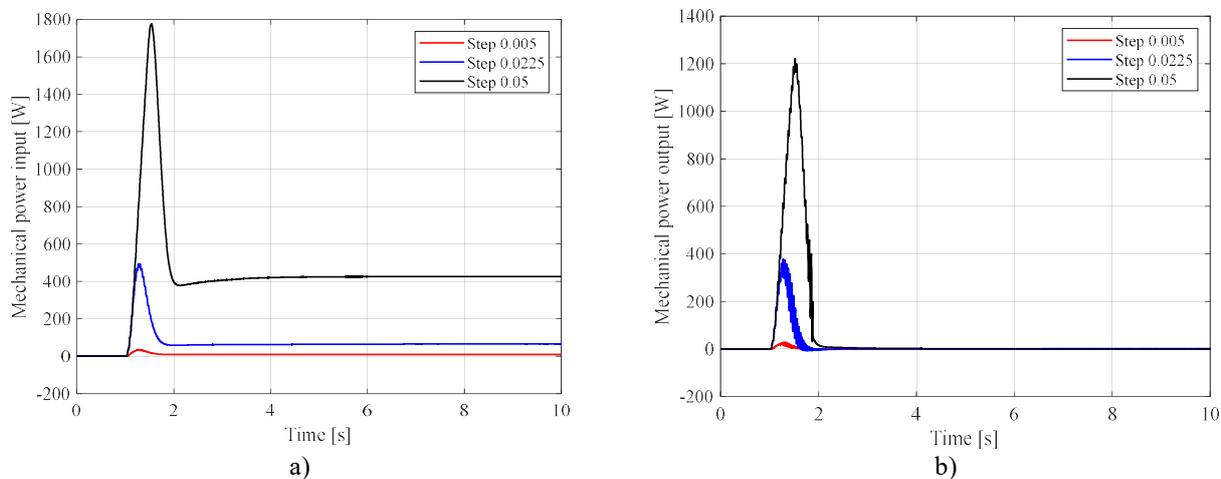Figure 5 – EHA different step responses.

Figure 6 – EHA mechanical power. a) Input, b) Output.

Looking forward to electric systems employed to aircraft, in order to maintain position under high loads, the electric motor of the EHA must keep a high torque under low or zero rotational frequency. Following the equations of electrical machines, the electromagnetic torque needed to maintain the cylinder position is proportional to the current (BOSE, 2002; KRAUSE *et al.*, 2013). According to Gundabattini *et al.* (2021), the temperature of the electric machine increases non-linearly with the load due to the losses in the motor, such as the stator cooper losses. The cooper losses are produced by the flux of current in the stator windings, which generates heat and these losses are dependent on the square of stator current. For aircraft applications the operating temperature of the components determines their service life and reliability, dissipate the heat is one of the challenges nowadays (MARÉ; FU, 2017).

5. CONLUSIONS

In this paper, a study of an Electro-Hydrostatic Actuator for aircraft application was developed. A research to obtain requirements for aircraft actuator systems was carried out and a set of requirements were used as boundary conditions to design an EHA. A method to design hydraulic systems for position control was used, to calculates a maximum flowrate required by the system. In sequence, a method to select hydraulic pump was adapted to select the volumetric displacement of the pump, based on the manufacturer datasheets.

After implementation, the model was used to simulate the EHA in different conditions, in order to evaluate the behavior and energy consumption. The results shown the good controllability of the EHA, which was able to follow the input reference with accuracy within the settling time established. The power consumption evaluation demonstrates that the conversion of power during the cylinder movement present a good efficiency, as the hydraulic power is not controlled by throttling control the hydraulic energy is directed directly to the cylinder avoiding energy dissipation to meter the hydraulic power. However, for long times holding high loads, the system efficiency is deteriorated as it is necessary to use power to hold position under high loads. In addition, if high torque is required to hold a cylinder position, high current of the electric source is also required, which impacts in heat generation that must be further investigated.

6. ACKNOWLEDGEMENTS

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