DIGITAL HYDRAULIC ACTUATORS: A RESEARCH OVERVIEW FOR AIRCRAFT CONTROL SURFACES

Dimitri Oliveira e Silva
Federal University of Santa Catarina
dimitri.oliveira@unifesspa.edu.br
Florianópolis, Santa Catarina, Brazil

Marcos Paulo Nostrani
Federal University of Santa Catarina
marcos.nostrani@gmail.com
Florianópolis, Santa Catarina, Brazil

Rodrigo Simões Lopes Junior
Federal University of Santa Catarina
rodrigo_lopesjr@hotmail.com
Florianópolis, Santa Catarina, Brazil

Victor Juliano De Negri
Federal University of Santa Catarina
victor.de.negri@ufsc.br
Florianópolis, Santa Catarina, Brazil

ABSTRACT

In the last decades, digital hydraulics has emerged as a new alternative for the development of more efficient hydraulic systems, where the effects of throttling losses and internal leakages are minimized through the use of conventional hydraulic components associated in parallel or through switching hydraulics. In the aviation industry, hydraulic systems are commonly applied to control highly relevant systems, such as landing gear and flight control surfaces. In this context, digital hydraulics can be used as an alternative solution to improve the energy efficiency of aircraft hydraulic systems. Based on that, this paper aims to present three new hydraulic actuators for application on aircraft flight control surfaces using digital hydraulics. The actuators are being studied by the Laboratory of Hydraulic and Pneumatic Systems - LASHIP of the Federal University of Santa Catarina - UFSC and are called Digital Hydraulic Actuator - DHA, Digital Electro Hydrostatic Actuator - DEHA and Variable Speed Digital Electro Hydrostatic Actuator - VSDEHA. The simulation results show that the actuators developed can be 23 times more efficient than conventional servo-hydraulic actuators, with equivalent dynamic characteristics, demonstrating the potential for application of these new actuators in aeronautical systems.

[DOI: https://doi.org/10.3384/ecp196002]

Keywords: *Digital hydraulics, Digital hydraulic pump, Efficiency, Variable speed, Dynamic simulation.*

INTRODUCTION

Hydraulic systems are mainly applied when it is necessary to develop a large amount of power combined with a compact volume. This characteristic makes hydraulic systems be applied in several areas, such as in construction machinery, hydroelectric plants, and the aeronautical industry. In the aviation industry, hydraulic systems are used in aircraft flight control surfaces, cargo doors, steering, landing gears. [1]. Additionally, hydraulic systems are known for their high reliability and fast dynamic response, making these systems suitable for aircraft application. However, one of the disadvantages of using hydraulic systems is the low energy efficiency, which is caused by the use of valves that throttle the flow and by the internal leakage of the hydraulic components. In order to develop a more efficient actuator solution, studies using digital hydraulics began to be carried out aiming at aircraft applications [2 – 6]. In this technology, components such as the servo or proportional valves are replaced by a set of on/off valves connected in parallel or by a fast switching on/off valve, which is capable of delivering discrete outputs, avoiding the throttling control and minimizing the internal leakage. On/off valves can also be applied to control the pump output, in cases of parallel connection two or more fixed displacement pumps can be connected through the same shaft to provide different flow levels in place of variable displacement pumps. Therefore, using the digital hydraulics approach, throttle losses and internal leaks can be reduced and the system is controlled by the interaction of simple on/off hydraulic components.

In this paper, an overview of researches provided by the Laboratory of Hydraulic and Pneumatic Systems - LASHIP of the Federal University of Santa Catarina – UFSC in the development of digital hydraulic actuators for aeronautical applications will be presented.

STUDIES ON DIGITAL HYDRAULICS TOPOLOGIES

The Laboratory of Hydraulic and Pneumatic Systems at the Federal University of Santa Catarina is one of the main centers in Latin America in the development of hydraulic and pneumatic systems. Currently, the laboratory has a research line focused on the study of different topologies for aircraft actuators applying digital hydraulics to flight control surfaces. In this context, three digital hydraulic topologies are being studied, which are called Digital Hydraulic Actuator – DHA, Digital Electro Hydrostatic Actuator – DEHA, and Variable Speed Digital Hydrostatic Actuator – VSDEHA. These solutions will be presented according to the chronological development in the laboratory.

Digital Hydraulic Actuator (DHA)

In this topology, a multi-chamber cylinder with different areas is supplied by different pressure lines (Figure 1). The on/off valves are used to direct the flow rate from the supply lines to the cylinder chamber, where each cylinder chamber can be connected to each supply line independently [2]. The secondary control system of this solution is based on the combination of the pressure lines with the areas of the cylinder chambers to produce the necessary force to move the cylinder, according to the load condition estimated by the system [4]. In this solution, a centralized hydraulic power unit is used to supply the pressure lines.

In [4], the authors proposed a way to define the areas of the multi-chamber cylinder and the pressure values of the supply lines, with a focus on the use for aircraft control surface applications. In the experimental study developed by [2], a four-chamber cylinder connected to three pressure lines through twelve on/off valves was used. Using the combinations of areas and pressures, it was possible to obtain 81 discrete output forces values.

The study carried out by [2], the authors presented an evaluation of the energy saving potential of the solution, where it was possible to reach levels between 80% and 96% of reduction in energy dissipation using the DHA solution when compared to a Servo Hydraulic Actuator under the same simulation conditions. In [6], the simulations performed by the author showed a reduction in energy dissipation of 15.7 times.

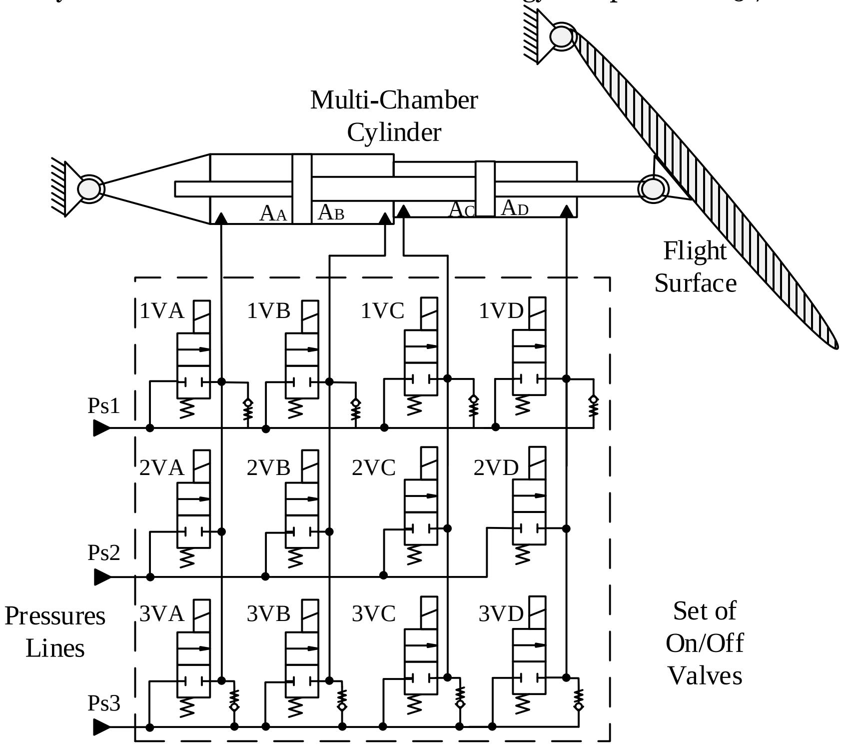

Figure 1 – Digital Hydraulic Actuator [10].

Digital Electro Hydrostatic Actuator (DEHA)

In this topology, a digital hydraulic pump (DHP) is used to provide different flow rate levels, which combined with different areas of the cylinder chamber, produce different cylinder velocities, for the cylinder control [3] (Figure 2). The on/off valves are used to control the output combination of the digital hydraulic pump and direct the flow rate to the cylinder chambers. In [3], the author proposed a DEHA using a digital hydraulic pump with three pump units and a four-chamber cylinder, using a block valve with 8 valves to connect the DHP and the cylinder chambers.

With the use of three pump units, seven different flow rates are obtained, which combined with the four-chamber cylinder areas, it is possible to obtain 28 cylinder velocities. However, as in the DHA solution, in the DEHA is possible to connect each cylinder chamber to each supply line. In [7], the same configuration is used and the authors propose the use of the DEHA in regenerative mode, increasing the number of different cylinder velocities to 43.

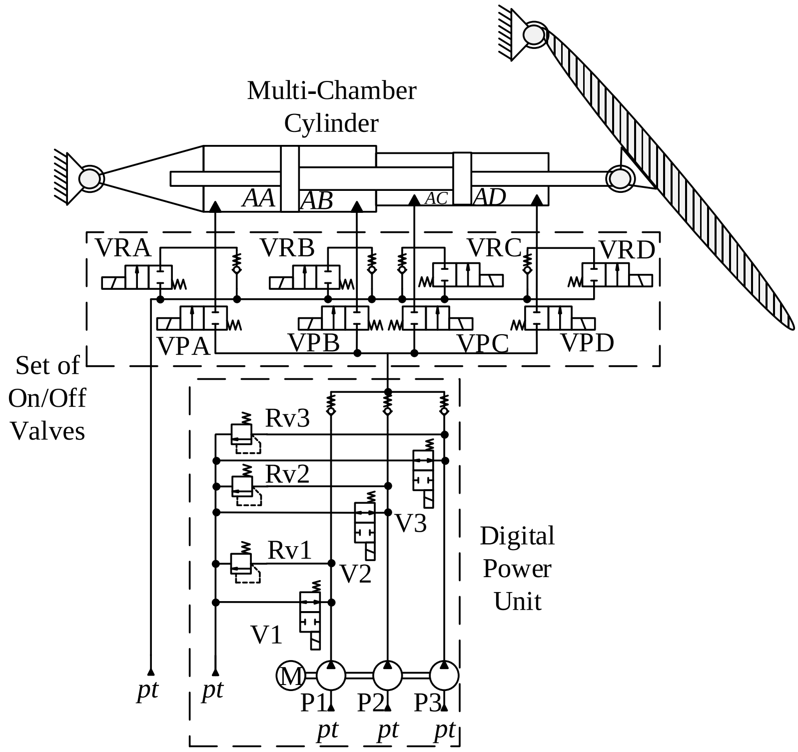

Figure 2 – Digital Electro Hydrostatic Actuator [10].

Variable Speed Digital Electro Hydrostatic Actuator (VSDEHA)

This topology is an evolution of the two topologies presented previously, where a variable-speed digital hydraulic pump is used to supply a cylinder (Figure 3). Unlike the DEHA topology, the flow rate can be changed continuously, where it is not mandatory to have a combination of chamber area and flow rate to increase or decrease the cylinder speed. Speed control is performed by the combination of the angular speed source and pump unit. According to [8], the use of the variable speed increases the number of different flow rates of the DHP, which becomes a continuous flow rate source and allows using the power-on-demand concept to adjust the angular speed for each pump unit combination. This strategy aims to achieve the best operating point for each work condition.

The use of a variable speed digital hydraulic pump is justified by the possibility of changing the pump unit combination to supply a certain operation point or flow rate range without sacrificing efficiency [8]. For example, under low demand conditions, the smaller pump unit can be used more efficiently to supply the low flow rate demand, and under high demand conditions, the higher pump unit combination can be used to achieve this point. Whereas, in a variable displacement pump, the volumetric efficiency generally decreases drastically with the reduction of the volumetric displacement [8; 9].

In this topology, during cylinder movement, there is no cylinder chamber switching to change cylinder speed. This is an advantage from a valve-commutation number perspective, as valve-commutation is only used to change the direction of the cylinder, reducing the number of valve cycles per operating time. However, when the external load is acting in the same direction as the cylinder movement, there is a risk of cylinder overspeed, which may impair the controllability of the system. To overcome this risk, during this condition a second set of on/off valves (V_{bA}, V_{bB}, V_{bC}, and V_{bD}) is used to limit the maximum cylinder velocity by dissipating the extra energy supplied by the external load.

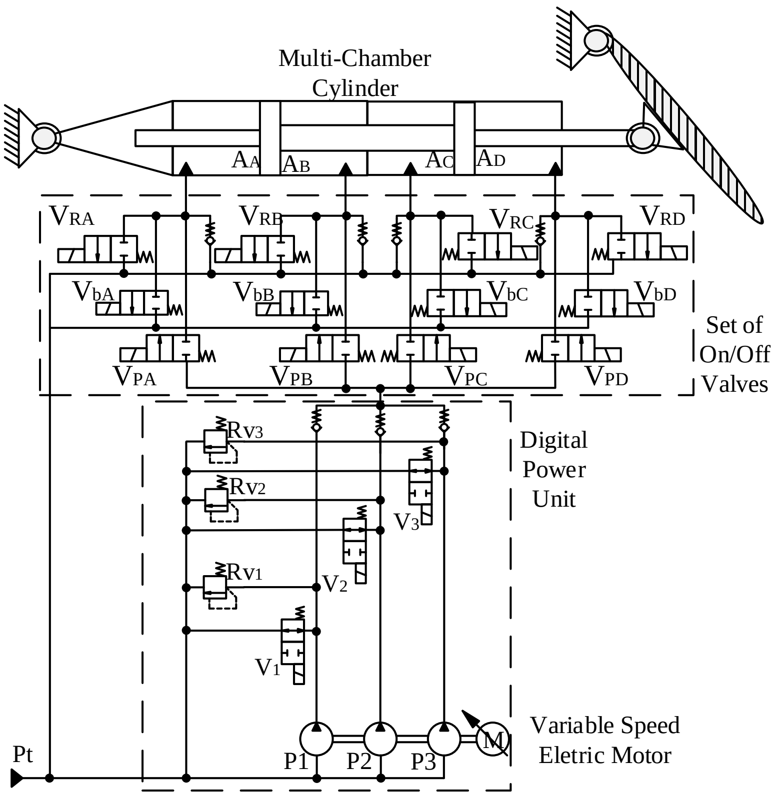

Figure 3 – Variable Speed Digital Electro Hydrostatic Actuator [10].

TOPOLOGY COMPARISON

With the development of new solutions, it is natural to perform some comparisons between their characteristics and research evolutions. Table 1 presents a comparison of the main characteristics of the digital solutions presented in this paper.

Table 1 – Characteristics of the digital hydraulic actuators studied.

Characteristic	DHA	DEHA	VSDEHA
Controlled hydraulic variable	Pressure	Flow rate	Flow rate
Controlled mechanical variable	Force	Velocity	Velocity
Hydraulic supply unit	Not considered	Digital Hydraulic Pump	Digital Hydraulic Pump
MEA concept	Not considered	Considered	Considered
Electric motor control	Not considered	Fixed angular speed	Variable angular speed
Cylinder valve commutation	To change force and direction	To change velocity and direction	To change direction
Pump valve commutation	Not considered	To change the pump unit combination	To change the pump unit combination
Number of forces or velocities	Limited by the number of pressure lines and cylinder chamber combinations	Limited by the number of discrete flow rate and cylinder chamber combinations	Limited by the angular speed range available for each pump unit combination

Dynamic and energy saving potential

In [10], the authors present a comparison between DHA, DEHA, and VSDEHA topologies, which were designed for the aircraft primary control surfaces. The three topologies were implemented in a generic aircraft model called Aero-Data Model in a Research Environment (ADMIRE) [11]. The ADMIRE implemented in MatLab/Simulink ® was used to perform simulations of the actuators in a virtual aircraft environment to simulate flight commands, behavior, and load conditions. Different flight maneuver missions were used to verify the behavior of the digital hydraulic solutions and perform dynamic and energetic analyses of the systems. The control surfaces analyzed were the left inner elevon (LIE) and left outer elevon (LOE) [10].

Table 2 presents a summary of the dynamic evaluation results highlighted by [10] in relation to the reference, where the overshoot and response time presented are in the maximum condition for the evaluated maneuver, which in this case was the roll-turn flight maneuver. Due to the non-linearities of the system, the dynamic behavior is not the same for different input signals [10].

Table 2 – Dynamic characteristics of digital hydraulic actuators. Adapted from [10].

	ADMIRE	DHA	DEHA	VSDEHA
Overshoot (%)	-	13.8%	4.8%	10.9%
Time response (s)	0.168	0.241	0.351	0.241

Table 3 presents the energy efficiency of the systems during three different maneuvers, landing, roll-turn, and longitudinal, for each digital actuator. The servo hydraulic actuator is a conventional hydraulic system used in aircraft control surfaces, which are known for their low energy efficiency caused by the throttling control and internal leakage of the system components. In [10], a servo hydraulic actuator model was used as a baseline and presented an energy efficiency lower than 2% for the maneuvers. This demonstrates the high energy-saving potential of the digital hydraulic solutions, where energy efficiency values above 30% have been achieved during some maneuvers.

Table 3 – Energy efficiency of digital hydraulic actuators. Adapted from [10].

	DHA		DEHA		VSDEHA	
Control surface	LIE	LOE	LIE	LOE	LIE	LOE
Landing	1.93 %	1.86 %	8.49 %	8.04 %	5.85 %	6.06 %
Roll-turn	6.2 %	6.23 %	14.41 %	14.86 %	35.05 %	34.95 %
Longitudinal	11.3 %	6.47 %	34.87 %	41.63 %	39.9 %	27.9 %

CONCLUSIONS

This paper presented an overview of three digital hydraulic topologies developed at the Laboratory of Hydraulic and Pneumatic Systems of the Federal University of Santa Catarina, designed to be applied to primary control surfaces of aircraft. The use of digital hydraulic solutions is focused on reducing the use of dissipative control strategies and improving system efficiency by using simpler components, reducing costs, and improving reliability.

One of the main features of digital hydraulics is the use of intelligent control to control the output of the system. In this aspect, it is possible to notice that the three topologies presented have almost the same physical structure. However, due to the different control strategies adopted for each one, the results obtained were quite different for each simulated condition.

From an aircraft design point of view, more experimental studies using prototypes should be developed to validate the dynamics and energy savings presented by the proposed systems. In addition, with the use of prototypes, other characteristics such as occupied volume and weight can be evaluated.

ACKNOWLEDGMENTS

The authors are grateful for all the support offered by the entities CISB, CNPq, Saab AB and Linköping University for the sandwich doctorate scholarship CNPq 201325/2020-9, the Federal University of South and Southeast of Pará and the Federal University of Santa Catarina. The research is supported also by the CNPq Grant 315239/2018-2.

REFERENCES

[1] Ward, S. Digital Hydraulics in Aircraft Control Surface Actuation. Fluid and Mechatronic Systems Master Thesis. Linköping University. 2017.

[2] Belan, H. C. "Sistemas de atuação hidráulicos digitais para aviões com foco em eficiência energética," Doctoral thesis, Federal University of Santa Catarina, Florianópolis, Brazil, 2018.

[3] Nostrani, M. P. Development of a digital electro hydrostatic actuator for application in aircraft flight control surfaces. 2021. 1–192 f. Federal University of Santa Catarina, 2021.

[4] Belan, H. C.; Locateli, C. C.; Lantto, B.; Krus, P.; De Negri, V. J. Digital Secondary Control Architecture for Aircraft Application. The Seventh Workshop on Digital Fluid Power. p. 21–39, 2015.

[5] Lopes, R. S. "Avaliação do desempenho dinâmico de um atuador hidráulico digital para aplicações aeronáuticas em condição de falha". Master thesis, Federal University of Santa Catarina, Florianópolis, Brazil, 2021.

[6] Lopes, R. S.; Nostrani, M. P.; Carvalho, L. A. B.; Dell'Amico, A.; Krus, P. and De Negri, V. J., "Modeling and Analysis of a Digital Hydraulic Actuator for Flight Control Surfaces," Symposium on Fluid Power and Motion Control FPMC2021. online, October, 2021, doi: 10.1115/FPMC2021-68923

[7] Nostrani, M. P.; Raduenz, H.; Dell'amico, A.; De Negri; V. J.; Krus, P. Multi-Chamber Actuator Using Digital Pump for Position and Velocity Control Applied in Aircraft. Global Fluid Power Society - GFPS 2020 PhD Symposium., 2020.

[8] Silva, D. O.; Carvalho, L. A. B.; De Negri, V. J.; Waltrich, G. Digital Hydraulic Pump: an energy efficiency study. 2021. Proceedings of the 26th International Congress of Mechanical Engineering: ABCM, 2021. https://doi.org/10.26678/ABCM.COBEM2021.COB2021-1613.

[9] Maré, J.C. Aerospace Actuators 1: Needs, Reliability and Hydraulic Power Solutions. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2016.

[10] Lopes, R. S; Silva, D. O.; Nostrani, M. P.; Dell'amico, A.; KRUS, P.; De Negri, V. J. A comparative analysis of innovative digital hydraulic actuators for primary flight control. 2022. 33RD Congress of the International Council of the Aeronautical Sciences. Stockholm, 2022. p. 18.

[11] Forssell, L. and Nilsson, U. "ADMIRE The Aero-Data Model. In a Research Environment Version 4.0, Model Description," FOI Report No. FOI-R-1624-SE, December, 2005.