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Redundant Digital Hydraulic Actuators for Flight Control Surfaces

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Abstract

The aircraft industry is continually driven to improve energy efficiency in response to environmental concerns and cost reduction. Among solutions available in the field, hydraulics is commonly chosen to deliver crucial functions for its known reliability, precise controllability, and high stiffness. Additionally, when compared to competing technologies in development, hydraulic systems are far less susceptible to jamming, heat rejection problems, and premature wear. In the current context, digital hydraulics emerges as a promising alternative to conventional hydraulics, greatly increasing energy efficiency while keeping the robustness of fluid power systems. Aiming to apply this technology to aircraft systems, this paper introduces enhancements for the digital hydraulic topologies developed at LASHIP/UFSC that allow them to be applied in critical tasks, such as flight control actuation, achieving reliability and performance criteria, beyond the increase in efficiency. These topologies were refined with segregation and independence principles, as is standard in aircraft. The solutions address both centralized (easier to adapt to existing aircraft designs) and distributed hydraulic systems (coherent with the More Electric Aircraft concept). Furthermore, to evaluate the feasibility of the systems, the study correlates industrial components and aeronautical systems through systematic analogy, resulting in an estimate of the size and weight of digital hydraulic systems if designed for the aeronautical industry. The resulting digital hydraulic systems adhere to the reliability practices and safety standards employed in aircraft flight control while showing similar sizes and weights to the current solutions.

Keywords: Digital hydraulics; Redundancy; Flight control surfaces; Efficiency.

1 Introduction

Aircraft are heavily reliant on hydraulic systems. Such systems are most often responsible for braking systems, cargo doors and ramps, wheel steering, landing gear management, and flight control surfaces operation [1]. Despite the continuous efforts to develop More Electric Aircrafts, the reliability, precise controllability, and high stiffness of hydraulic systems ensure their ongoing engagement in critical tasks, especially in the context of flight control surfaces [2].

Conventional hydraulic systems applied for position control in aircraft are based on Servo Hydraulic Actuators (SHA). This kind of system, although mature and very reliable, can have improvements in efficiency. The main factors are throttle losses and internal leakages, inherent to dissipative control systems [2], which must be addressed in order to improve energy efficiency.

An alternative that has gained popularity over the past decades is the Electro-Hydrostatic Actuator (EHA). The concept consists of a local source of hydraulic power, based on an electric motor coupled with a bi-directional pump, and a conventional hydraulic cylinder for actuation [3]. With this configuration, the actuation system achieves lower overall weight, improved maintainability, reduced complexity in aircraft design and reduced power consumption. Although several advantages, EHA systems may suffer from limited life span due to pump wear, difficulties in heat rejection and efficiency loss in low-speed high-load situations [4][5][6].

Another alternative in study over the last few years is the Electro-Mechanical Actuator (EMA). These systems rely on an electric motor, normally associated with a screw, to generate mechanical movement directly from electric energy, resulting in higher efficiency than other solutions. In a reliability analysis, however, this solution is yet to comply with requirements for critical system use.

EMAs are, unfortunately, susceptible to jamming, which could render the aircraft uncontrollable. Antijamming devices could be implemented, but their impact on installation, weight, cost, and reliability cannot be neglected. In contrast, linear hydraulic actuators are, by design, a jam-free solution [7][8]. Furthermore, according to [7], the evolution of electric technology leads to increased weight and cost when compared to hydraulic solutions and [8] estimates that the overall actuator mass of EMAs would be 1.8 to 3.8 times higher than conventional SHAs.

In this scenery, digital hydraulics emerges as a promising alternative for primary flight control. Digital hydraulics systems are those composed by hydraulic components capable of discretizing fluid flow [9]. The main components of such systems are the digital hydraulic valves, typically on/off valves, which have only two stable positions. Because of that, these valves can have a simpler structure, like poppet valves and, therefore, have lower cost, increased robustness, minimal leakage and reduced pressure drops [10].

In this scenario, three main architectures of digital hydraulic systems for aircraft application have been proposed and tested at the Laboratory of Hydraulic and Pneumatic Systems - LASHIP, considering both centralized and distributed systems. The concepts were named Digital Hydraulic Actuator (DHA), Digital Electro-Hydrostatic Actuator (DEHA), and Variable Speed Digital Electro-Hydrostatic Actuator (VSDEHA), all of which showed exceptional gains in energy efficiency ([11], [12], [13], [14], [15], [16], [22]). Further, in [18], all three topologies were simulated in an aircraft model performing different missions and showed, during longitudinal mission, an increase of up to 90 times the energy efficiency when compared to typical SHA. Additionally, the digital hydraulic systems were shown to be more reliable and fail tolerant than typical systems [19] [20].

In order to use digital hydraulic technology in the most critical functions of aircraft, further compliance with sector regulations and standards is necessary. Therefore, this paper proposes topology adaptations that hold the advantages of the developed digital hydraulic systems while allowing for greater redundancy, hydraulic system isolation, and single system operation. In addition, a new topology is presented, aiming to perform the same functions with a significant reduction in the number of valves used. Furthermore, the possible size and weight of such systems, if produced for the aircraft industry, are calculated.

2 Topologies

Primary flight control surfaces refer to ailerons, rudders and elevators, which control the aircrafts roll, yaw and pitch movements, respectively. Loss of control of these surfaces results in loss of aircraft control. Regulations require failures as such to be extremely improbable, which translates to a failure rate smaller then 10^{-9} per flight hour. [5]

To achieve extremely low failure rates, designs include redundant systems. An important characteristic for that is segregation. This property consists in the absence of shared elements between channels and removes common mode failures. In hydraulics, this means the absence of hydraulic connections between parts of the system, thus preventing the propagation of fluid contamination and leakage. [1]

Another characteristic to be considered in the effort for redundancy is independence. This property defines that a failure in one part of the system should not spread to others. In tandem hydraulic cylinder, this is obtained employing a bypass valve between the chambers of each cylinder. This element ensures that, in case a failure renders one actuator uncontrollable, it can be switched to move freely, allowing a redundant actuator to control the surface with no obstacle. [1]

Both segregation and independence will be applied to the three previously developed architectures of digital hydraulics.

2.1 Digital Hydraulic Actuator

The first topology proposed is the design named DHA, presented in [12] and [13]. Belan defined a 12 on/off valve manifold that would handle three pressure lines: one from the pressurized reservoirs, and each other from the two pressure systems present on the aircraft. This manifold would be responsible for connecting the different pressures to each of the chambers of an asymmetric multi-chamber cylinder.

The DHA can produce 81 different possible force outputs on the actuator rod. The actuator areas and supply pressures are defined aiming in a close-to-linear discrete force output distribution. It is a force control system based in a cost function and yields the valve combination that delivers the closest force option to the required. When the control loop is implemented, this system performs a position control (standard in the area). [12][13]

Although already modelled in aircraft conditions, the concept allowed for oil mixing between supply systems and had no way to isolate cylinder chambers from supply line without blocking the actuator. A new configuration taking into account both considerations is presented in Figure 1.

This actuator receives three pressure lines from each of two supply systems. Even in case of component failure, there is no connection between supply lines. Additionally, all supply pressure lines must be able to provide flow rate for the actuator and, therefore, no line can be considered only as a return.

The position control is achieved by rapid switching of pressure combinations in the actuator chambers. Since no proportional valve is used to perform the control, the throttle losses and leakage are reduced to a minimum during the operation. Also, since the system can switch between two pressure levels that are higher than reservoir pressure, the energy associated with the switch is not lost entirely. Thus, the system is capable of using 5 times less energy when compared to conventional hydraulic systems in closed-loop operation. [12][13]

The afore mentioned result, however, may not be representative of the usual paths and forces required in primary flight control actuation. In [21], [14] and [18], the system was implemented in an aircraft model set for performing customary aircraft manoeuvres. Besides showing no significant performance loss, it achieved on average an increase of 6.4 times in energy efficiency when compared to SHA.

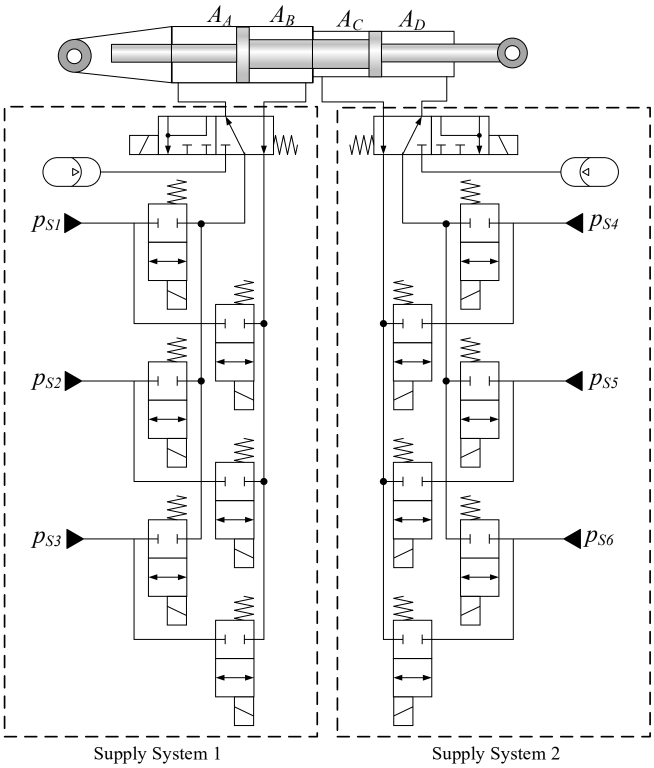

Figure 1: Redundant DHA topology.

The bypass 5 way 2 position valve (5/2 valve), present at the top of Figure 1, implemented in each actuator side ensures that it can be moved freely and isolated from the rest of the system in case of failure. In this way, the remnant system can continue to control the surface. For a simple bypass to perform this, the actuator must be symmetric regarding the chambers connected to the same supply line. If not, the interconnection between chambers with different volumes would bring pressure forces that would immobilize the piston and, along with it, the control surface. A symmetry in this component, however, is detrimental for system performance, as it diminishes the force output possibilities to only 75 outputs.

To allow using an asymmetric actuator, the bypass should be able to compensate the difference in volume between chambers. For that, when bypassed, the chambers would be connected to a small accumulator or reservoir (as shown in Figure 1), which is used only in failure case, or possibly to a return line. Depending on the size of the aircraft and, more specifically, the distance between actuator and supply, either option can be viable. The redundant DHA topology can generate 81 possible force outputs, the same as the original system.

2.2 Digital Electro-Hydrostatic Actuator

Next proposed topology was published on [15] and [22]. Nostrani presents a system, named DEHA, that associates three different fixed displacement pumps coupled in line with three corresponding on/off valves that can direct fluid back to the reservoir. This configuration can supply different combinations of flow rates and defines a digital hydraulic pump (DHP). An eight on/off valve manifold establishes the connection of the actuator chambers to the DHP output or to the reservoir. The design presents a velocity-based control. The 43 possible actuator velocities are compared through a cost function to the required value and the valve combination that achieves the best fit is selected. [15][22]

To allow for redundancy, an isolated supply system for each of the actuators in tandem is proposed. This essentially doubles the supply components presented in the original topology but, considering the same use case, the parts selected could be substantially smaller as the flow rates required are also divided. The directional valve manifold remains mostly the same, simply allocating half of the valves for each supply line. Moreover, bypass valves are added to perform the required redundancy when maintaining a single actuator for surface control. The result is shown in Figure 2a. Figure 2b illustrates the same circuit with a simplified, more concise representations of the DHPs, as depicted in [25] and [13], which will be used in the subsequent diagrams.

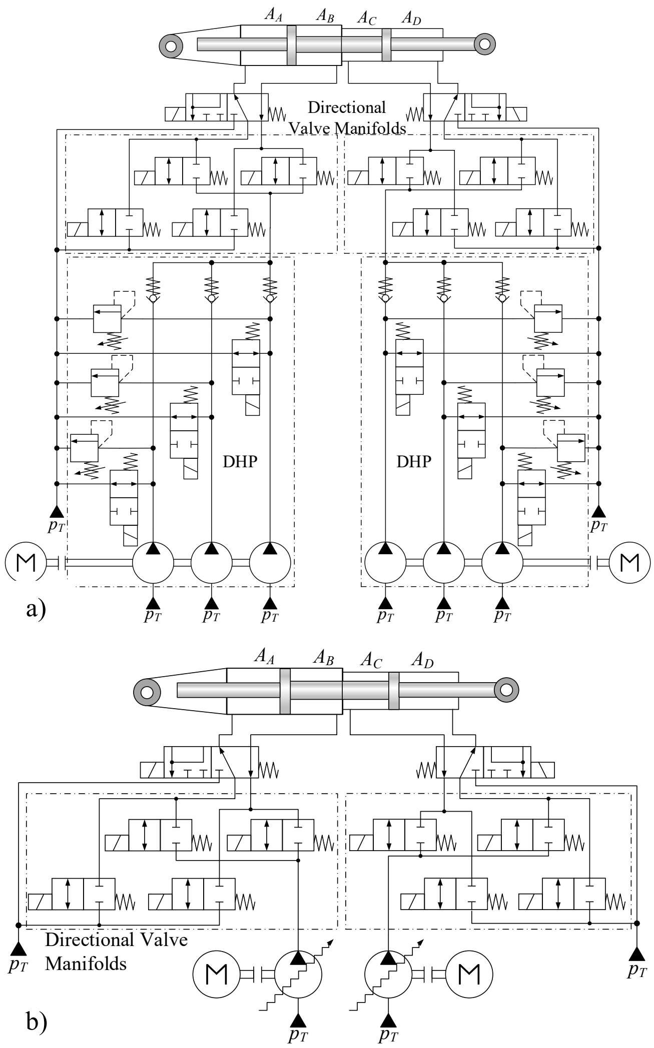

Figure 2: Redundant DEHA topology: a) full representation, b) DHPs simplified representation.

In conventional EHA systems, the pump always operates under loading conditions, even when maintaining the control surface stopped. Beyond the on/off valve advantages specified in section 2.1, when DEHA is applied, the pumps only are subject to outlet pressure when the cylinder is moving. In this way, the DEHA presented an energy efficiency 1.7 times better than the EHA, and 31 times better than the SHA while showing similar capabilities in position control [22]. When implemented to an aircraft model, DEHA achieved on average 23.1 times more energy efficiency than a conventional SHA counterpart [18].

The redundancy solution for the DEHA works much similarly to the one presented in the previous section. In this case, however, the reservoir line connected to the bypass valve is not a drawback as the application would be self-contained and, therefore, the components should be close to each other.

2.3 Variable Speed Digital Electro-Hydraulic Actuator

The last topology previously developed is the VSDEHA, as depicted in [11], [16] and [17]. It is much similar to the DEHA, hence the derivative name, but it introduced two major design advances.

The first is the use of proportional 2/2 valves installed in the directional valve manifold. When the system controls the actuator velocity while moving in the same direction of the load, it must just dissipate energy. In EHA as well as in the DEHA this is handled electrically, by activating the motor and running the pumps. Although controversial in a digital hydraulic field, Silva demonstrated that when throttle control is used while the system receives energy from the load, efficiency increases. Since the valves dissipate such energy, the system does not have to use its energy to counter act the load. [16] [17]

Another improvement present in this topology is the use of variable speed electric motors. This enables the system not only to combine the pump flow rates, but also to operate the pumps in their most efficient regions for a specific load. The control is selected by load maps for each system configuration. With these maps defined, the controller chooses the pump combination and the rotational frequency that should provide the lowest power consumption to achieve the desired actuator output. [11][16]

Much like the modifications made for the DEHA system, supply isolation and bypass valves are implemented to adhere to redundancy goals. The resulting circuit is shown in Figure 3.

The VSDEHA in [18] presented, on average, 26.4 times better energy efficiency compared to SHA when running in the aircraft model.

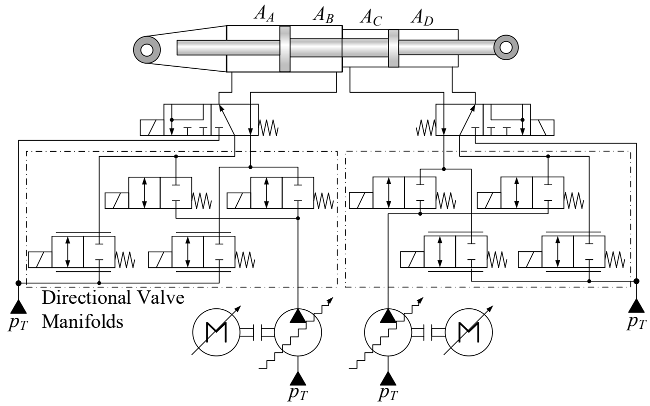

Figure 3: Redundant VSDEHA topology (with DHPs simplified representations).

2.4 DEHA/VSDEHA Topologies with Four-Way Valves

Lastly, a new topology is presented based on both the DEHA and the VSDEHA. Such configuration intents to fulfil all the functionality present in these systems while reducing the number of valves used. The topology is presented in Figure 4 and already adheres to the redundancy considerations previously discussed.

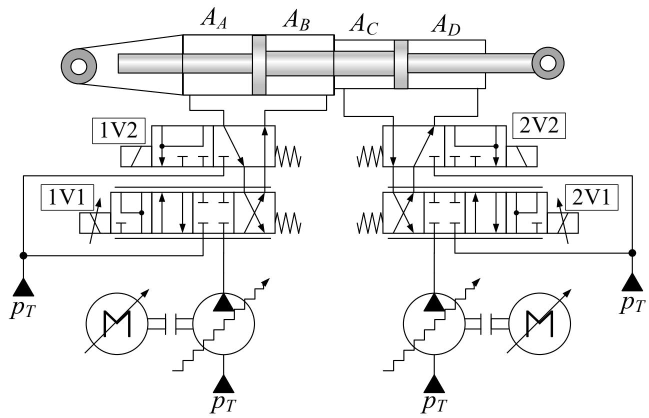

Figure 4: Novel topology with 4-way valves.

Valves 1V1 and 2V1 substitute the directional valve manifolds present in previous configurations. The combination of these two valves allows to achieve the same connections between cylinder chambers, pumps, and reservoir lines. They can also throttle the flow to dissipate the energy coming from the load, as done in [11] and [16], and stop the actuator in place without consuming energy in the closed position. Additionally, they can perform the hydraulic regeneration described in [22] when connecting both chambers, previously at different pressures, to the pumps. Each of these 4/4 proportional valves substitute four 2/2 on/off valves.

The configuration of the 1V1 and 2V1 valves makes it possible to achieve the functionality of the topologies discussed previously. However, valve construction principles differ, leading to distinct valve dynamics and leakage values. Therefore, future studies on system performance and energy consume are imperative to validate the circuit for implementation.

3 Size and weight estimation

When seeing the presented hydraulic diagrams, the visual complexity of the association of several components may suggest the same complexity and size in the physical arrangement. Fortunately, this is most often not the case. Such diagrams depict functions that are actually performed by small elements.

In this scenario, the proposed topologies are to be parametrized and components specified to better estimate their size and weight. Aircraft components tend to be specific for each application and highly integrated within systems, which escalates the difficulty of predicting its dimensions beforehand. Industrial components, conversely, have largely available variety and well-defined dimensions. Thus, a correlation in dimension is to be defined between the two component types. This should allow estimates to be made using industry components, which will subsequently be fitted to provide an approximation of the expected dimensions in an aircraft system.

3.1 Industrial-aerospace correlation

One of the modern aircraft with documents open for the public is the F-35, presented in [26] and [27]. The information presented is much similar to the system description provided by Moog in [28] and [29]. A general EHA for aerospace applications by Moog shows great resemblance with the aforementioned actuators and has available information in [30].

Therefore, the EHA model Type V CEHA in [30] is considered as the aerospace industry specific reference for this paper. As shown in [30], the system consists of a dual electric motor and axial piston pump associated with a tandem linear actuator. It should also contain a small reservoir, anti-cavitation check valves, relief valves and bypass valves for each separated circuit, as described in [28].

To achieve a proper correlation between aeronautical and industrial systems, 210 bar (3000 psi) typical high pressure, 406 mm/s (16 in/s) of rated velocity, 151 kN (34000 lbf) of stall force, and a total stroke of 431 mm (16.9 in) (extension + retraction) were assumed. This resulted in a 190 kg (420 lbs) EHA system with a length of 1.4 m (56.5 in) in the neutral position or 1.21 m (47.5 in) fully retracted. [28][30]

The force and velocity values, are assumed to be the maximum ones and occurring simultaneously. Considering two symmetrical cylinders in tandem and a reservoir pressure of 7.5 bar, the actuator areas and pump flow rate result on 0.0037 m² and 90 L/min, respectively.

Commercial components with parameters as close as possible to those must then be selected. A wide and accessible catalogue of components is preferable in this step, so components can be picked as close as possible to the desired values to compose the analogy and, later on, to allow for a greater range of systems to be conceived without changing the manufacturer. The analogy, therefore, will be caried with Parker components, a manufacturer that, in addition to industrial components, has an established aerospace division.

Axial piston pumps are common in aviation for their higher volumetric efficiency. In that category, the chosen manufacturer presents pumps with displacements of 45 cm^3/rev, which would supply 81 L/min at 1800 rev/min (industry standard), and of 60 cm^3/rev, which supply 108 L/min. Since EHA pumps are expected to rotate at higher rotational frequencies, the lower displacement approximation was assumed while choosing a model that allows for higher rotational frequency. The P1045 pump was chosen, which weighs 23 kg with dimensions of 188 mm (axial direction) x 193 mm x 200 mm when mounted [32]. These and the dimensions of following components are organized in Table 1 for convenience. The columns M, L, W, H, and Qt correspond to mass (in kilograms), length, width, height (all in millimeters), and quantity, respectively. The bottom row, named ASM, represents the assembled system. The next tables will adhere to the same pattern.

To run such pumps, an electric motor is needed. To maintain similarity with the application, a low inertia brushless motor was selected, since the angular speed and direction must be quickly changed in EHA [28]. Considering the conditions of operation and the displacement of the selected pump, the motor usual torque should go up to 145 Nm. Therefore, the MPP2708 model was selected. Stall torque in this model is about 150 Nm and the rated speed goes up to 1962 rev/min. The component weighs 94.3 kg, is 344 mm long when mounted (excluding shaft head), and has 267 mm of width and 336 mm of height. [33]

Table 1: Selected components – reference system

Part	Series	M	L	W	H	Qt
Pump	P1045	23	188	193	200	2
Motor	MPP2708	94.3	344	267	336	2
1 rod cylinder	MA3	82	944	Ø170	Ø170	1
2 rod cylinder	MA3	109	1301	Ø170	Ø170	1
Rod eye	AP6 ISO8132	7.6	208	-	-	1
Bypass valve	D3W	4.8	-	-	-	2
Proport. valve	SE15	1	-	-	-	2
Check valve	SPZBE NG16	0.25	-	-	-	4
Relief valve	EVSA NG06	0.3	-	-	-	4
ASM		447	2022	~704	<336	-

Data from [32],[33],[34],[35],[36],[38] and [39].

Tandem cylinders are not readily available in catalogues. For that reason, the component will be approximated as the association of two cylinders, both of same diameter, but one single rod and the other double rod. For the application pressure, the cylinder MA3 series was selected. The closest diameter dimensions available that beat the goal force (151 kN) are a 100 mm bore with a 70 mm rod, which should provide 81 kN per cylinder. The single rod cylinder will be considered of fixed eye cap, which would attach the assemble to the fuselage, and should weigh 82 kg while being 944 mm long when retracted. The double rod one should be of flange mount, weighs 109 kg and has a length of 1301 mm. Both lengths exclude threads in rod ends. The two cylinders have 431 mm of stroke and an external diameter of 170 mm (excluding ports and flanges). The double rodded component should be increased by a rod eye that holds 200 kN of nominal force, adding 7.6 kg and 208 mm to the length, which would be attached to the control surface. [34]

The bypass and the proportional directional valves must attend each circuit flow rate at the working pressures, both determined previously for the reference system. A SE15 series servovalve, weighting 1 kg [35], and a D3W series directional control valve, at 4.8 kg [36] were selected for the functions, respectively. The check and relief valves must handle system pressure, but only work with minimal flow rates, comparable to pump leakage. The smallest check valve and relief valve in the catalogue would easily handle such low flow rates. For mounting optimization, the SPZBE and EVSA series were selected, which should weigh close to 0.3 kg each valve [36].

In the proposed topologies, the valves have little influence for their size, as is the manifold in which they are mounted that defines the occupied space. The manifold, however, is specific for each designed system and hardly estimated with precision. For this reason, valve dimensions will be excluded from the size estimation. They will be, however, included in the weight estimation and must, of course, be accounted for in any proposed assembly.

With the components to be considered defined, a correlation is drawn between them and the reference system. Firstly, the mass of all components was combined. It is important to emphasize that the arrangement is composed by two systems side by side. Although the cylinders are already considered in the correct amount, the pump, motor, bypass and proportional valves must be doubled. Also, the check and relief valves must be quadrupled, since they appear twice in each circuit (once for each actuator chamber).

A total mass of 447 kg was obtained for the catalogue selected components. The reference aerospace EHA presents a 57.5% lower mass. Such difference represents the contribution of various sources. Reduction in weigh would result, for instance, from case grouping and different material selection. Small reservoirs and oil mass would affect also the total mass.

Regarding to actuator dimensions, the components must be assembled to better represent the reference model. The length, greatest dimension and the only one explicitly provided by [30], is obtained by the tandem association of cylinders. Arranging the industrial cylinders accordingly, a 2.02 m retracted length was found. The corresponding dimension on the aerospace system is 40% shorter. Here, the main players may be cap reduction and integration to the body, wall reduction and better material choice.

The other dimensions cannot be analysed with specificity as there is no reference value. In addition, it is observed in [30] that the EHA assembly width comes from the association of the cylinder external diameter and twice the biggest width between pump and motor (a pair is positioned on each side of the cylinder). Considering this, it is inferred that an approximation of system width would be 700 mm. As component walls can be reduced and combined, the aviation version should be of a slightly smaller value. Carrying the same observation for height, total value is approximated as motor height (336 mm) or smaller.

3.2 Analyses of the proposed topologies

Based on the correlations presented above, mass and dimensions of the topologies aforementioned in this paper are now estimated. The digital hydraulic actuators can be applied for different control surfaces but in the present study an aileron control (in the same way as in Section 3.1) is assumed.

The requirements, however, are taken from the aileron actuator of F-18 Systems Research Aircraft, which is operated by an EHA, as presented in [37] and [18]. The system to be designed should, therefore, meet a 114 mm stroke, a 195 mm/s velocity and a 59 kN force. The high and low supply pressures will be the same as before, 210 bar and 7.5 bar, respectively.

3.2.1 DHA

As presented in Section 3.1, system sizing begins with cylinder definition based on the needed force. The circuit shown in Figure 1 features a tandem assembly unlike the previously presented, this actuator is asymmetrical, which results in different diameters of the selected components. The single rod cylinder considered has a bore diameter of 63 mm, a rod diameter of 45 mm, a 512 mm length and 120 mm of external diameter, resulting in 25.4 kg. The double rod one was sized to have an 80 mm bore diameter and two different rods, with 50 mm and 56 mm diameters. This results in a cylinder 765 mm long, already considering the mounting accessories, with 145 mm of external diameter, and summing 54 kg [34]. When associated, the actuator would have the capacity for at least 74 kN. These and the following values are presented in Table 2. The last row of this and the following tables shows the dimensions found after applying the above-mentioned correlation to aerospace components.

Although the different cylinder chamber areas require different flow rates, the valve sizing was based only on the largest flow rate, equal to 36 L/min. Therefore, the on/off valves selected were GS04 81 series with 0.17 kg each and the bypass valves were D1MW series with 1.5 kg each [36].

The accumulators present in the circuit only are used when the bypass valve is activated and would only handle the volume difference between connected chambers. For simplicity, both accumulators were set to the largest volume difference (0.06 L). Therefore, the smallest model of the EHV series was selected. It supports 0.17 L, weights 2.5 kg, is 268 mm long and has an external diameter of 58 mm.

Table 2: Components selected – DHA

Part	Series	M	L	W	H	Qt
1 rod cylinder	MA3	25.4	512	Ø120	Ø120	1
2 rod cylinder	MA3	53.9	623	Ø145	Ø145	1
Rod eye	AP6 ISO8132	2.1	142	-	-	1
Bypass valve	D1MW	1.5	-	-	-	2
On/off valve	GS04 81	0.17	-	-	-	12
Accu-mulator	EHV	2.5	268	Ø 58	Ø 58	2
ASM	-	89.4	1163	~203	~145	-
Aero	-	38	698	-	-	-

Data from [32],[33],[34],[35],[36],[38] and [39].

When computing all the component masses, a total of 89.4 kg was found. Also, as in the reference case, it becomes clear that the greatest dimension in this system is defined by the tandem cylinder. Considering the same arranging process seen in Section 3.1, a length of 1163 mm was achieved (when retracted). Applying the parametric correlation presented in Section 3.1, a 38 kg and 698 mm long system was estimated. Furthermore, if well placed, the valves should have little influence on the system main dimensions. The width may be estimated for the association of cylinder and accumulator external diameters, converging to 203 mm, and the height would remain similar to the cylinders, at 145 mm. Figure 5 shows a side-by-side view of feasible assemblies of the DHA system in both industrial and aerospace versions. It becomes clear how collapsing component housing and tubing into each other makes the system far smaller.

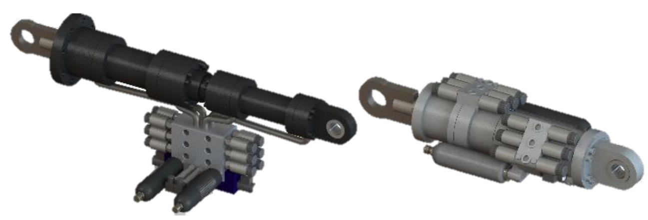

Figure 5: Industrial vs. aerospace system – side-by-side view.

3.2.2 DEHA and VSDEHA

The system presented in Figure 2 shares the same cylinder and bypass valve conception as the DHA. Therefore, the flow rate required is, as previously stated, 36 L/min. If pump sizes could be chosen freely, the methodologies presented in [15] and [17] would be useful to determine them. Since, within the scope of this paper, the choice of components was restricted to a catalogue, an easier way would be to find three pumps of different sizes that could be directly coupled into each other and that together would provide the desired maximum flow rate at the defined rotational frequency. The smallest axial piston pump in the catalogue that can be assembled in line, however, is of the P1018 series, which supplies 32 L/min at 1800 rev/min. When associated, three of such pumps would be able to supply a flow rate more than 2.5 times greater than the need. In the absence of smaller pumps, this one was used to size the set of three pumps comprising the digital pump. It should be noted, though, that this representation is largely oversized. Each pump would weigh 15 kg and measure 199 mm (axial direction) x 170 mm x 184 mm in the thru-drive configuration [32]. The dimensions for this system are presented in Table 3.

Table 3: Components selected – DEHA and VSDEHA

Part	Series	M	L	W	H	Qt
Pump	P1018	15	199	170	184	6
Motor	MPP2706	75.8	293	267	336	2
1 rod cylinder	MA3	25.4	512	Ø120	Ø120	1
2 rod cylinder	MA3	53.9	623	Ø145	Ø145	1
Rod eye	AP6 ISO8132	2.1	142	-	-	1
Bypass valve	D1MW	1.5	-	-	-	2
On/off valve	GS04 81	0.17	-	-	-	12
Check valve	SPZBE	0.25	-	-	-	6
Relief valve	EVSA	0.3	-	-	-	6
ASM	-	330	1163	~679	<336	-
Aero	-	140	698	-	-	-

Data from [32],[33],[34],[35],[36],[38] and [39].

The electric motor driving the pumps must handle the torque from three pumps at once. Considering the selected pumps, it corresponds to 174 Nm. The actual torque in case of using the required smaller pumps would be 65 Nm. Considering the later, a still oversized motor from the MPP2706 series was selected. Such component weighs 75.8 kg and has a length of 293 mm, a width of 267 mm and a height of 336 mm. [33]

The on/off valves ought to be of the GS04 81 series. The relief and check valves, although they operate at a much higher flow rate than in the systems analysed above (as they can be subject to the full pump flow rates), work as well as the EVSA and SPZBE series used in the reference model. [36]

When summing the masses for the DEHA concept, a total of 330 kg emerges. The greatest dimension remained the length and is caused by the cylinder set, totalizing the same 1163 mm. This would only change if the pumps and motor assembly became longer than the cylinders. Using the parametric correlation estimated before, the mass of the system would be of 140 kg and the length of 698 mm if developed for aircraft specifically. The VSDEHA concept uses largely the same components, with exception of four of the on/off valves that become proportional. Applying such modification changed the values in less than a kilogram. Therefore, the same results were considered.

The width of these designs, as done in the reference system, can be approximated by the sum of the cylinder diameter and two motor widths, resulting in 679 mm. Similarly, the total height should be that of the motor (336 mm) or smaller.

3.2.3 DEHA/VSDEHA with Four-Way Valves

The newly proposed topology in this paper (Figure 4) shares many of its components with the DEHA and VSDEHA concepts. The main dimensions of the systems are, as seen previously, defined primarily by these shared components. The difference should, then, be in the weight, as 8 of the valves in the previous circuits become only 2.

The included proportional valves would be ideally of the same series as the bypass and, therefore, should handle 36 L/min. The D1FP series was selected, with 3.6 kg per valve and very low leakage in the overlap version [36]. The physical properties of these valves and other considered components are presented in Table 4.

System major dimensions would not suffer any changes, as the valves can be located between other components. System mass, conversely, would be increased to 335 kg for including bigger valves. When applying the proposed parameter correlation, this increase would be only of 3 kg (to 143 kg). It is important to consider in this scenario, that the assemble housing design and manufacturing could become far more convenient.

3.3 Final remarks

The estimated system dimensions are shown in Table 5, although specific for the requirements presented in Section 3.2. This information can ease the analysis of the application of digital hydraulics for flight control actuation, as systems with similar capabilities can be compared in terms of dimensions.

Additionally, the technique presented in Section 3 could be implemented by designer in general aware of system dimensions to easily and more precisely estimate digital hydraulic dimensions for specific applications.

Table 4: Components selected – DEHA/VSDEHA with 4-way valves

Part	Series	M	L	W	H	Qt
Pump	P1018	15	199	170	184	6
Motor	MPP2706	75.8	293	267	336	2
1 rod cylinder	MA3	25.4	512	Ø120	Ø120	1
2 rod cylinder	MA3	53.9	623	Ø145	Ø145	1
Rod eye	AP6 ISO8132	2.1	142	-	-	1
Bypass valve	D1MW	1.5	-	-	-	2
On/off valve	GS04 81	0.17	-	-	-	6
Proport. valve	D1FP	3.6	-	-	-	2
Check valve	SPZBE	0.25	-	-	-	6
Relief valve	EVSA	0.3	-	-	-	6
ASM	-	335	1163	~679	<336	-
Aero	-	143	698	-	-	-

Information from [32],[33],[34],[35],[36],[38] and [39].

Table 5: Estimated physical parameters for digital hydraulics in an aircraft application.

Topology	M	L	W	H
DHA	38	698	~203	~145
DEHA	140	698	~679	<336
VSDEHA	140	698	~679	<336
With 4-way Valves	143	698	~679	<336

4 Conclusion

As seen in the presented paper, digital hydraulic systems can be easily adapted to adhere to reliability requirements and standard safety solutions of the aviation industry. This better assured safety associated with the much higher energy efficiency of digital hydraulics may make them exceptionally competitive for flight control actuation for the next generations.

Additionally, it was shown that, although the hydraulic diagrams of the presented systems may seem more complex, the geometry and dimensions of the actual physical systems should remain similar to the ones in use by the aerospace industry.

Finally, as evidenced by the new topology presented, various system components can be implemented using either on/off valves or several-position valves, with minimal impact on functionality. This approach facilitates an iterative transition towards digital hydraulics, offering flexibility and gradual adoption across different system segments.

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