Full Paper
Aerospace Technology Congress
11-12 October 2016, Solna, Stockholm

New perspectives on digital hydraulics for aerospace applications

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Abstract
This paper discusses the use of the digital hydraulics instead of the conventional circuits in aircraft application. The main focus is on energy efficiency on the hydraulic system, which results, in the end, on aircraft weight, either from the fuel consumed on running the pumps or from the heat sink necessary due the heat produced by energy losses.
It is presented proposals for increasing the energy efficiency on different stages, or functional units, of the fluid power conversion and ways to control each one of these units, which deals with switching regimes, time delay, saturation, quantization and non-linear characteristics. Most of the control used on digital hydraulics are derived from classical control, for instance, an outer PID controller with an inner on/off valve selection logic. It is explored the use of switched control theory and modern control approach, for instance $\mathcal{H}_\infty$.
It is presented results based on simulation and recent achievements obtained. A brief discussion is presented on the digital hydraulic reliability, in which, as long the digital hydraulic is done by an array of on/off valves, its redundancy is intrinsic.

Keywords: aircraft hydraulic actuation, digital fluid power, energy efficiency, switched systems.

INTRODUCTION

Since the beginning of aviation, weight has been always the main concern on design and operation of aircrafts. Light materials is the direct approach to cope with this problem. Indirect approaches are focusing on energy efficiency, which leads to the reduction on the fuel supply resulting on the spiral effect on the weight reduction.
Digital fluid power is a technology focusing the use of low-cost on/off valves instead of servo valves in order to reduce the power losses due the throttling, avoid internal leakage and recover the mechanical power. It can be done a correspondence between a power electronics and hydraulic, where a rheostat relates to the conventional proportional valve and the digital hydraulic are related to solutions based on thyristors.
From the safety perspective, the digital approach has some intrinsic advantages, which comes to the fact of using an array of parallel valves and multi-chamber cylinder, meaning that the system is already redundant.

Efficiency and hydraulic functional units

Spite of the nowadays trend on reducing the energy losses, hydraulic systems are still known to have low energy efficiency. The hydraulic power is the product of flow and pressure difference ($H_s=Q\cdot\Delta p$), which can be positive, when the pressure is increased or negative, when there is pressure drop due the energy wasted in a restriction or used in a hydraulic device. From energy conservativeness perspective, the amount of power converted into hydraulic power in form of pressure and flow, if not stored, should be either used on its designed purpose, either wasted. In this way, the possibilities are matching constant pressure plus variable displacement actuator, variable pressure plus fixed displacement actuators, and variable pressure plus variable displacement actuators (Linjama and Huhtala, 2010).

Here, it is adopted the functional units classification for hydraulic systems: i. Storage and conditioning; ii. Primary conversion, where the energy is converted into the hydraulic system; iii. Limitation and control; and iv. Secondary conversion, where the energy in the hydraulic system is converted back to its designed purpose (Belan, et al., 2015). On the limitation and control unit, the main source of losses are due the throttling, resulting basically heating which is transferred to the fluid. When using proportional valves for control proposes, the regulation of the pressure or flow is done by throttling the fluid, resulting in a low energy efficiency.

Digital hydraulics is a promising alternative to the throttling for reducing the power transferred to the secondary conversion. The term "digital" is from the fact that the power is transferred in discrete steps, using controlled on/off valves, instead of a continuously selected by a proportional valve.

Using digital hydraulics for control proposes, there are basically two main branches, one is using several parallel conventional on/off valves replacing a conventional proportional valve (Belan, et al., 2015, Dell'Amico el al., 2013). The other strategy makes use of hydraulic inductance phenomena with a fast continuous switching valve (De Negri, et al., 2014).

One way to measure the energy loss, is the time integral of the power loss over the complete work cycle. In hydraulic valves, there is no power loss when the valve has no resistance to flow, resulting zero pressure drop or when the valve completely blocks the fluid, resulting in zero flow. As long the valve commutation is not instantaneous, there is a region between complete opening and complete close, where the valve itself consumes a big amount of power. In the Fig. 1 it is shown a result of a simulation made on Hopsan (Braun, R., 2016) of simple circuit consisted of a pressure source, an on/off valve and a restriction. The upper plot shows the pressure drop and the flow and the bottom plot the power loss in the valve. After the valve opening at 0.1s, it can be seen that the power loss has pick just after the valve opening, but it remain small before and after the opening. For this reason, the efficiency in digital hydraulics is increased when the valve has a short commutation time, and when there are few switches in a time interval. For digital valves, it is expected with switching time between 1 and 10ms.

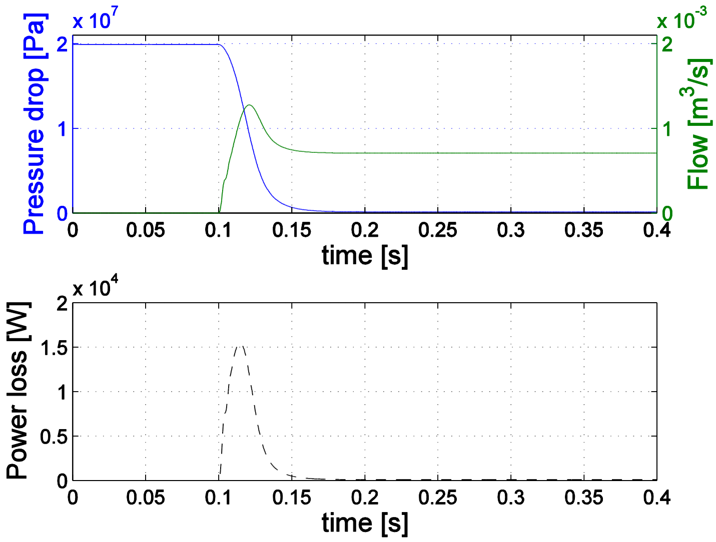

Figure 1. Power loss during a valve opening

Control and safety

Safety is a very important aspect on any engineering task, especially in aircrafts. Safety concerns is distributed in many different researching areas with results in each of them. In the control community, this area has been called *self-repairing control*, later *fault tolerant control* (FTC) and later giving rise on the important area called *robust control*, which is considered a passive FTC. Active FTC, or simple FTC

uses fault detection and identification (FDI) systems to reconfiguration of the control when the system is in fault mode. FTC is essentially an open problem (Alwi, et al., 2010). The robust control approach can be used in order to ensure that the system is stable under failure until the fault is detected and the system has been reconfigured.
Redundancy is a common practice for increasing reliability and it has been largely used in aircraft application. In digital hydraulic with parallel valves, the redundancy is intrinsic. When, for example, a valve is damaged, the amount of discrete steps is reduced, but the device is still functional in a "degraded" mode.

Energy aspects of aircraft's control surfaces

In regular flight conditions, the reaction force on the aircraft's control surfaces acts like a spring, increasing the force as its angle is increased. On the Fig. 2, as the angle of the control surface increases, the power is transferred from the pump to the control surface. In other hand, when the control surfaces moves back to its neutral position, the power is transferred from the control surface to the hydraulic system.

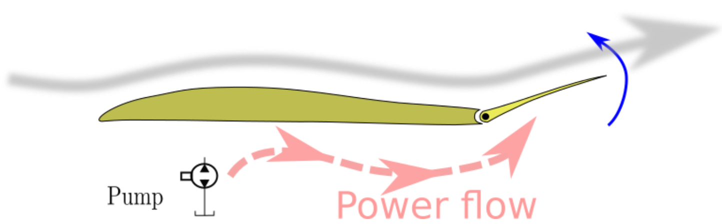

Figure 2. Power from the pump to the control surface

The usual approach uses a proportional valves, so, when the control surface angle is increased, the pump gives more power them necessary and the valve throttling is responsible for spend the extra unnecessary power delivered by the pump. When the control surface moves back to the neutral position, the power is transferred from the control surface back to the hydraulic system. With proportional valves, this power is wasted on the valve.

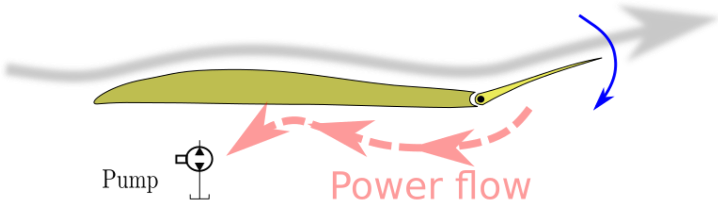

Figure 3. Power from the control surface to the pump

In the most of applications, when the power is transferred back to the hydraulic system cannot be recovered. In other hand, with digital hydraulics, there is possibility of transferring power from different supply lines and the cylinder of the control surface acts as a pump. If there are no other devices using power from the fluid, the pump has to have the possibility to recover or waste this power. The integral of the power loss is the amount of energy wasted in the form of heating.

PRIMARY CONVERSION

The primary conversion is briefly the set of devices and methods used to convert an external source of power into fluid power. The primary conversion, for instance of regular military aircraft, is compound by two variable displacement pump split into two hydraulic circuits: hydraulic circuit 1 (HC 1) and hydraulic circuit 2 (HC 2). Beyond the variable displacement pump, the HC 1 has more two pumps: one fixed displacement pump driven by an Auxiliary Power Unit (APU) and other fixed displacement pump driven by thermal batteries.
The fixed displacement pump driven by APU is used to starting the engine, for cooling, pneumatic supply and also for moving the control surfaces on the ground before the engine starts. The APU can be used in the case of failure of HC 1 and HC 2. The pump driven by thermal batteries is an emergency hydraulic pump and just allow safety operations, avoiding collision and do not allow the aircraft's landing. Both the fixed displacement units are just for backup and driven only in case of failure in the hydraulic system.
When the military aircraft is in a steady state flight e.g. in cruise speed, there is low flow in the

hydraulic system. This flow is due to internal leakages or small control activities from servo valves and it is often called “internal leakages flow”. To supply the internal leakage, the variable displacement pumps works with low displacement, which consists in a range of very low efficiency. There is a low useful power (just for the internal leakages) and high volumetric losses (high pressure in the pump outlet) and high hydro-mechanical losses (high friction).
A proposal for the primary conversion system consist in use one of these backup pumps to operate together with the variable displacement pumps in order to supply the internal leakage of the aircraft hydraulic system. It is possible to work in a region of high efficiency of a small fixed displacement pump while the variable displacement pump work in idle model. According the previous theoretical research, it possible to save around 20% energy with few modifications in the hydraulic circuit.

SECONDARY CONVERSION

The secondary conversion is briefly the set of devices and methods used to convert the fluid power back to mechanical power, for its designed purpose, mostly for linear or angular displacement. For its simplicity and applicability, the most common device for secondary conversion is the linear cylinder. Continuously changing the piston area of a cylinder is technically difficult, for this reason, a finite set of areas is the standard solution.
In digital hydraulics, the usual devices are the multi-chamber cylinder and the tandem cylinder. These kind of cylinders can be seen as different cylinders mounted on the same axis, or in the case of tandem cylinder, two cylinder attached back to back.

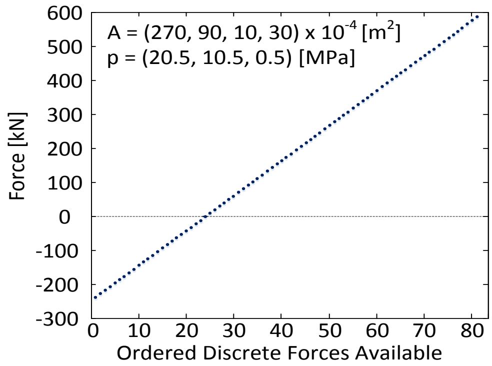

Figure 4. Linear force distribution (Belan, et al., 2015)

With a set of piston areas and supply pressures, the number of possible forces is given by N^M, where N is the number of pressures and M is the number of areas. There are many different ways to define the different areas in the piston.
Designing a combination of areas and pressures is an intricate task, which depends not only on the range of the desired forces, but also on the standard sealing sizes, external diameter of the cylinder and the distribution of the desired forces. The distribution of force steps obtained can be optimized for a specific task, for instance, having more fine steps around the usual working point and a coarse steps on other regions, in order to obtain a bigger range on forces. On the Fig. 4 it is shown a linear force distribution using the “27:9:1:3” area rate and pressures equally spaced. On the Fig. 5 it is shown a force distribution closer to Fibonacci, where near zero, the force steps are smaller and bigger near the end of the range (Belan, et al., 2015).

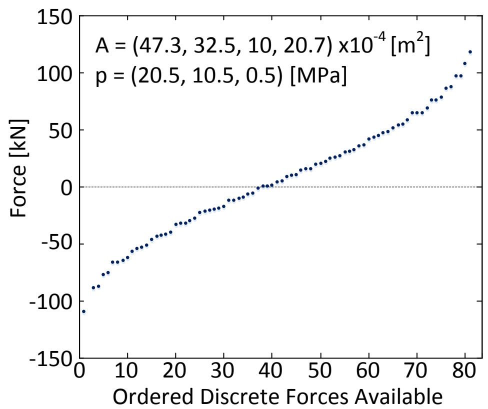

Figure 5. Area rate closer to Fibonacci (Belan, et al., 2015)

Another approach is using conventional cylinder together with fast switching valves, in order to obtain different forces using similar methods found on power electronics. More detail on this point will be discusses in the next section.

LIMITATION AND CONTROL

As the name suggests, limitation and control is a division of the hydraulic system responsible for controlling and limiting the pressure of the fluid. The term control, here, refers also to the act of distributing the fluid power to different lines in order to perform a specific task. There are basically two approaches for controlling in digital hydraulics. One of them has straightforward connection to power electronics, for instance, the buck-bust[1] converters. This solution uses conventional cylinder, connected to hydraulic capacitance (hydraulic accumulator) and hydraulic inductance, which is essentially a long tube. The regulation is often based on pulse-width modulation (PWM) or pulse-density modulation (PDM). For more information on this method, please refer to De Negri (De Negri, et al., 2014).

The main interest on this paper is the use of an array of simple on/off valves connected to a multi-chamber cylinder, as seen on the Fig. 6. For more details on the design and the analysis of this concept, please refer to Belan, et al. (2015).

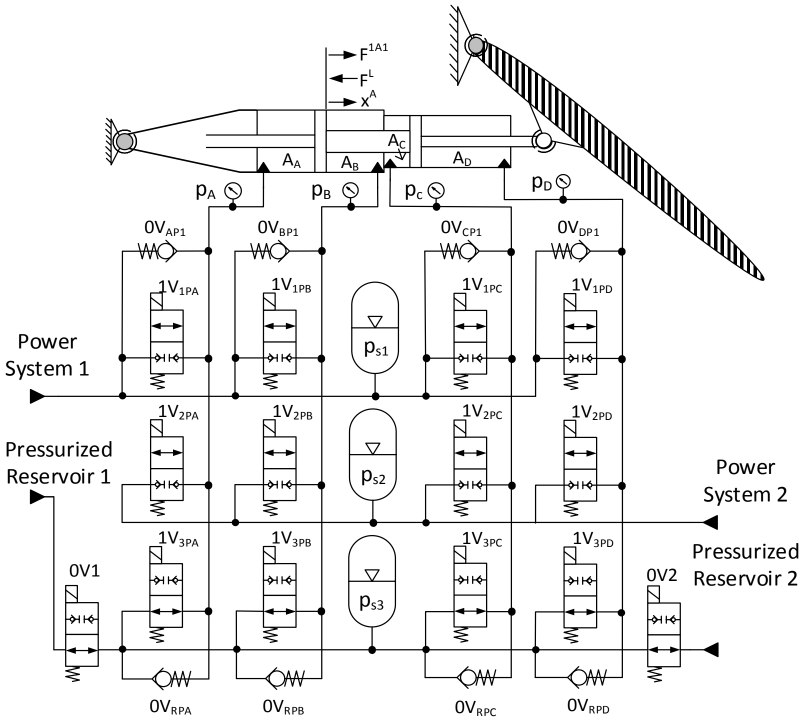

Figure 6. Digital hydraulic concept (Belan, et al., 2016)

A control strategy on digital hydraulics

Usually, the main challenges on controlling hydraulic systems are due the valve nonlinearities, for instance the pressure drop on the fluid threatening, deadbands, time delays and hysteresis. In other hand, when dealing with digital hydraulic, pressure drop is not a big concern. Deadbands and hysteresis, commonly found in proportional valves are also not a problem on controlling digital hydraulic systems. The main problem is, for instance, the time delays, which is part of the valve dynamics and it is necessary in order to avoid hydraulic “short circuit” when commuting the pressures on the cylinder chamber. Another important characteristic is the quantization which comes from the fact that the set of possible forces is a discrete set.

The control strategy includes two approximations of the hydraulic system, which implies some conservativeness on the solution, these points will be discussed in the sequel. The first approximation is neglecting the valve throttling, which is justified by the fact that it is used conventional on/off valves of simple construction, designed particularly to be energy efficient, offering as little restriction as possible. The time delay offers also a better approximation of the valve nonlinearities, because the response of this kind of non-linearities, comparing to the linear system, exhibit a slower rising time and a finite settle time. Please refer to (Jelali & Kroll, 2012) for more information. The time delay on the modeling also includes the time differences on the valve commutation, necessary to avoid short-circuit between tow pressure lines. Note that, in the Fig. (6), if more than one valve is open in the same column, the pressure lines are directly connected (short-circuit).

The result of neglecting the valve throttling is shown as a linear system in (1), where *x(t)* is the displacement, *m* is the total mass of the system, *k* is the spring constant, *b* is the dumping constant, A_A, A_B, A_C and A_D are the cylinder areas, p_A, p_B, p_C and p_D are the pressure for each cylinder chamber, chosen from available pressures, including the pressure of the reservoir and *d* is the time delay.

$$m\frac{d^2x(t)}{dt^2} = -kx(t) - b\frac{dx(t)}{dt} + A_Ap_A(t-d) - A_Bp_B(t-d) + A_Cp_C(t-d) - A_Dp_D(t-d) \qquad (1)$$

1 Also known as step-down and step-up converters.

In order to control the position *x(t)* or the velocity $dx(t)/dt$ the control input, defined as *u(·)* is the force generated by the pressure differences.
The second approximation is due the quantization of the available forces. The quantization function, which maps the continuous domain to the discrete domain is represented by *q(·)*. The actuation error due the quantization is defined by (2).

$$w(t-d) = q(u(t-d)) - u(t-d) \tag{2}$$

The quantization function can be choose in many different ways. The usual quantization function is choosing the closest value from the input. Some possibilities is to add hysteresis or using the information form the input while within each quantization step. Without considering any saturation, it can be seen that the quantization error *w(·)* is limited. The conservativeness of this approach is due the fact that *w(·)* is an unknown disturbance with unbounded frequency, which is not true, from the fact that the commutation frequency of the valve is not infinite and it is known.
The model used for designing the control gain is given by the state space representation shown on (3).

$$\frac{d\mathbf{x}(t)}{dt} = A\mathbf{x}(t) + Bu(t-d) + Bw(t-d), \tag{3}$$

where $A = \begin{bmatrix} 0 & 1 \\ \frac{-k}{m} & \frac{-b}{m} \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix}$ and $\mathbf{x}(t) = \begin{bmatrix} x(t) \\ \frac{dx(t)}{dt} \end{bmatrix}$ is the vector of state variables.

From (3), the project of the controller is based on space state representation of order 2, with transport delay on the control actuation and a disturbance input. The actuation is firstly quantized to one of the available forces and then decoded as a set of valves to be switched on and off.
There are many methods to design a control gain for the system (3). Both quantized and time-delayed control system is an active researching field, even for the linear case. The recent results have reduced the conservativeness and have include the possibility of have variable time delays, please refer to (Fridman & Dambrine, 2009; Brockett & Liberzon, 2000; Fridman, 2014; Ariba & Gouaisbaut, 2007; Liberzon, 2006).

NUMERIC EXAMPLE

From the model presented on (3), it was added an extra state variable as the integral of the position, in order to reduce the steady state error. The project of the controller gain is based on (Fridman & Dambrine, 2009) for the case of quantized control input. The simulation has been done using the same model of Belan, et al. (2015) made on Hopsan (Braun, R., 2016), which offers a rich modeling, including, for example the valves dynamics,

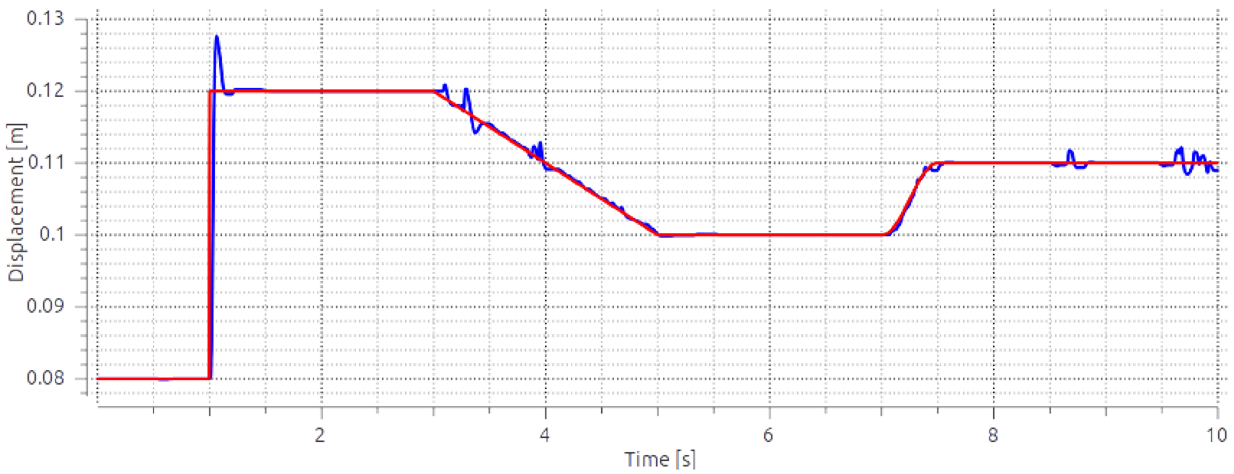

Figure 8. Position control

cylinder modeling and external disturbances. On this model it is considered force disturbances and viscous, static and kinematic fictions. The result can be seen on the Fig. 7, where in red is the set point and in blue is the measured position.
On the Fig. 8, it is shown the control output *u(t)* in blue in the available force actuation in red. In order to reduce the amount of switching, it was used hysteresis in conjunction with the valve switching logic. Without the hysteresis, when the quantization is simply chosen the closest value, it might appear infinite switching in the border between two close force steps. The hysteresis increases the error on the trajectory tracking and increases the conservativeness on the solution, but the reduction on the amount of successive switching is substantially reduced.

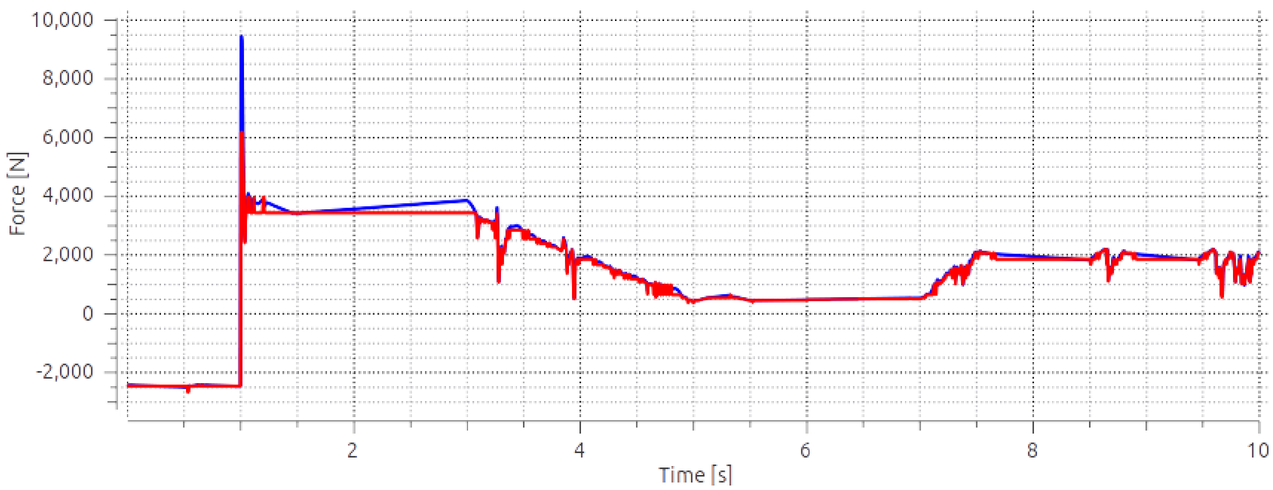

Figure 8. Control actuation

ADVANTAGES OF DIGITAL HYDRAULICS AND PERSPECTIVES

This approach has many advantages for aircraft applications, for instance, significant increase on energy efficiency which can be as large as 80%, as shown in Belan, et al. (2016). It also offers the possibility of recovering the energy from one pressure line to another, when the power is transferred from the actuator back to the hydraulic system. One important aspect is that this approach is intrinsically redundant, offering the possibility to remedy many different failures, for instance, pressure loss in one of the pressure lines, failure in one of the valve solenoid, problems in one of the cylinder chambers, among others. The simplicity and robustness of the construction is another important aspect to be considered.
One important point in development is the switching speed of the valves. Faster valves has advantage for both control problems and reducing the energy consumption. From the control perspective, large delays forecloses the gains in higher frequencies.

CONCLUSION

It has been presented some aspects of the digital hydraulics which are important for aircraft applications, including a control design, showing the feasibility of the approach. Energy saving and recovering are two of the main points of the proposal. Spite of the complexity of the digital hydraulic system, which includes non-linearities and switching, the low cost of the processors enables both control, diagnostic, reconfiguration and adaptation. Numeric example has been presented to validate the design of the control.

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