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CONCEPTUAL STUDY OF THE DIGITAL HYDRAULIC ACTUATOR WITH PROPORTIONAL CONTROL FOR FLIGHT CONTROL ACTUATION SYSTEMS

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Abstract

With increasing demand of energy efficient future airborne platforms new solutions for the flight control actuation system is necessary. Digital Hydraulics is an upcoming technology in the mobile hydraulics sector as an energy efficient solution. The technology utilizes a multi-chamber cylinder and on/off valves to control flow. This paper demonstrates how Digital Hydraulics with the multi-chamber cylinder can be combined with proportional control in flight control actuation systems in order to realize a multi-mode control system. The system has the potential to significantly reduce the required pump flow, and thereby a down-sizing of the supply system is possible. Several configurations which give different mode variants are compared and it is shown that a two pressure level system with five modes can reduce the flow and power take-out significantly compared to the traditional system. The solution offers the possibility to actively select modes during flight to minimize power take-out.

Keywords: Flight control system, multi-mode control, digital hydraulics

1. Introduction

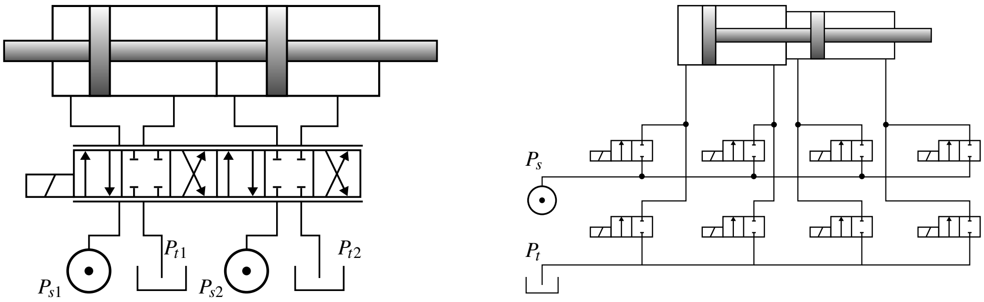
With increasing demand of energy efficient future airborne platforms new solutions for the flight control actuation system is necessary. Digital Hydraulics is an upcoming technology in the mobile hydraulics sector as an energy efficient solution, [1]. The traditional way of controlling the flight control surfaces is by means of hydraulic power through a proportional servo system. This is a mature technology with several advantages such as high power density and high forces can easily be managed. The hydraulic cylinder offers very good linear control and the redundancy capability is very high. On the downside traditional hydraulic system suffers from poor energy efficiency, mainly due to throttling and leakage. The nature of hydraulic systems means that the cylinder needs to be sized for maximum load, where the required speed is usually low. This results in a very high pump flow for low load cases where the speed instead is high.

In a collaborative research between Saab AB and Linköping University in Sweden, and Federal University of Santa Catarina and CERTI in Brazil, Digital Hydraulics is investigated in various forms including both the supply system and actuators, [2] [3] [4] [5] [6]. Both the concept and control strategies has been developed over the years. Digital Hydraulic discretizes the system output, such as flow or force, and to utilizes discretised valued components, such as on/off valves, typically of seat valve type. The Digital Hydraulic Actuator, DHA, utilizes a tandem cylinder with several pressure lines at different levels but replaces the servo valve with an array of on/off valves referred to as DFCU, Digital Flow Control Unit. Since the cylinder can be designed with different area sizes and the control valves connects the cylinder chambers to different pressure levels, the actuator behaves like a secondary controlled system where force is the primary control output, instead of the speed as is typical. Ideally only the necessary force to move the load is applied while the control valves are either fully open or closed, throttling is minimized while leakage is negligible. The challenge is the reduced control

accuracy since control now relies on constant switching of the valves and not proportional control. This leads to a jerky behaviour, thus the technology is best suited to high inertial systems, and the switching itself causes pressure spikes.
A simulation study integrating the DHA in the actuation system studied the effect of the discrete control, [6], where the inner elevon was equipped with a DHA and the outer elevon with a Servo Hydraulic Actuator, SHA. Although the aircraft in itself is a high inertial system, its still challenging to achieve the desired control accuracy. A DHA also requires constant switching of the on/off valves which affects e.g. reliability and can generate pressure spikes in the system. An interesting approach would instead be to utilize the advantages of both Digital Hydraulics and proportional control at the actuator level. The main idea presented in this paper is a multi-mode control strategy. The Digital Hydraulic section with the multi-chamber cylinder realizes different control modes that each can generate a certain maximum cylinder force. The proportional hydraulics section is used to control the actuator speed.
Mode controlled actuation system for flight control has already been realized for the Northrop/Mc Donnel Douglas YF-23A, [7]. This solution incorporated two modes where a spool valve was actuated to select which cylinder areas would be active. This reduced the pump flow with 50 to 60 %. A few examples of combined digital and proportional control also exist for mobile hydraulic systems. In [8] a set of proportional valves are used instead of the typical on/off valves. If the desired force is not available, throttling can be used to increase the resolution. Another solution is presented by [9] where three chambers are controlled with on/off valves and the fourth with a proportional valve. Accuracy is good but switching leads to force spikes. The STEAM project, [10], combines on/off valves with the proportional 4/3-valve. The on/off valves connects different pressure levels to the 4/3-valve in order to reduce the throttling losses.
This paper presents a conceptual simulation study by comparing different solutions for multi-mode control of the primary aircraft flight control system, taking advantage of the logic mode control from the on/off valves with the multi-chamber cylinder and proportional control from the servo valve. The multi-chamber cylinder is similar to the tandem cylinder used by many fighter aircraft due to redundancy requirements. The initial work was first presented in the Master thesis [11]. Three main solutions were investigated for different configurations using pressure control. Two-, three-, and four pressure lines were compared with different control strategies. Here, the work is extended by studying position control with the focus on down-sizing. The different configurations are compared by static modelling and simulation where each configuration is designed based on the control surface performance requirements. The models are also combined with a 6-DOF aircraft model to verify the benefits also during flight.

2. Conceptual architectures and system design

The traditional primary actuator is a servo hydraulic system schematically shown i figure 1. Due to redundancy requirements a common solution is a dual independent hydraulic system. Two actuators can be used on the same control surface, or as in the figure 1, a tandem cylinder can be used, which is typical for fighter aircraft and helicopters. The reference uses a symmetrical cylinder designed to give a maximum force of ±130 kN with supply pressures P_{s1} and P_{s2} at 280 bar, tank pressures P_{t1} and P_{t2} at 7.5 bar and cylinder area A at 2.4$\cdot 10^{-3} m^2$. The servo valve is designed to give a flow of about 25 l/min at no load pressure, corresponding to a control surface rate of 25°/s.
The DHA is shown in the same figure, here with two pressure levels, assuming the pressurized tank accommodates for one level. The DHA can be supplied with several pressure levels, although two or three are practically feasible. One of the key components of the DHA is the tandem cylinder, commonly referred to as a multi-chamber cylinder, where every cylinder area is of different size. This cylinder can be considered as having a discrete variable area that increases system flexibility and control modes. The on/off valves connect the pressure lines to respective cylinder chamber and the output is a discrete force. With two pressure levels and four cylinder chambers, 16 forces are available. With three pressure levels the number of available forces is 81.

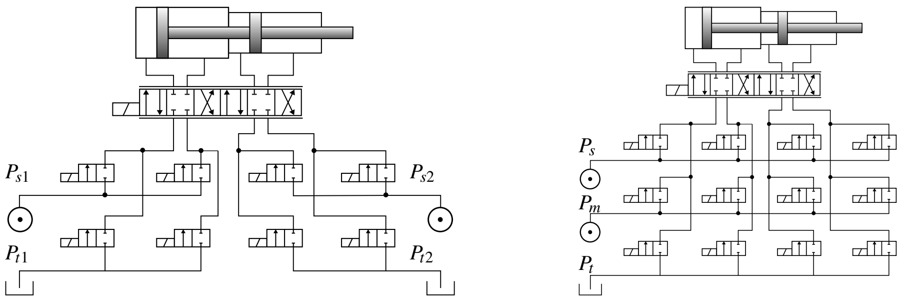


(a) Reference system.

(b) Digital Hydraulic Actuator.

Figure 1 – (a) shows the reference system in a simplified schematic. (b) shows the DHA with two pressure lines as originally studied.

2.1 Concept definition and configurations

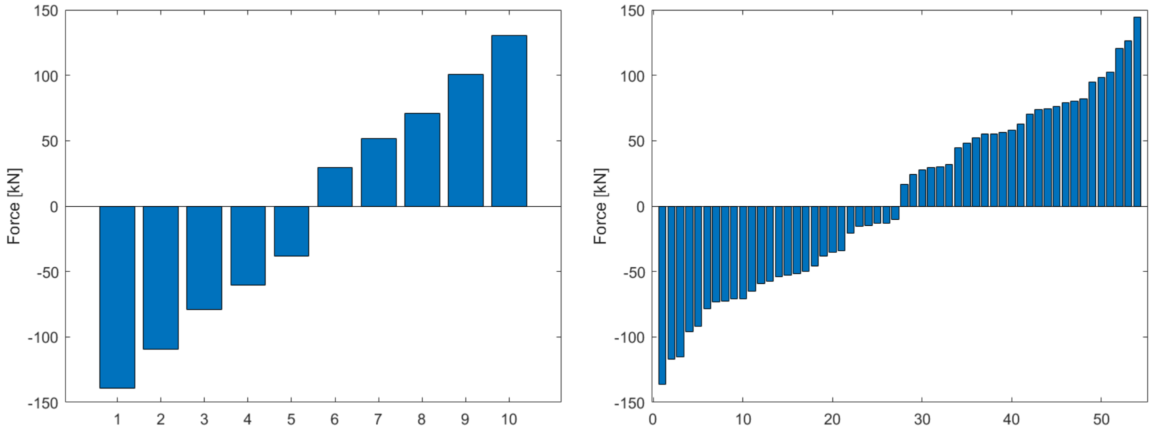


(a) On/off valves combined with 4/3 servo valves and two pressure lines.

(b) On/off valves combined with 4/3 servo valves and three pressure lines.

Figure 2 – Concepts where the DHA is combined with servo valves.

The concept, shown in figure 2, combines the reference system with the original DHA. The outcome is a system that is inherently position controlled. The purpose of the discrete valves is to select control mode where only the necessary force to control the load is applied. Since the load should always be controllable, modes that give the same pressure level on the meter-in and meter-out side for both hydraulic systems are excluded. The modes are also selected such that port P_s has a higher or equal value to port P_t. This will keep the servo valve with the same condition as the reference system and simplify control. Available control modes for the examples in figure 2 is defined by the force spectrum in figure 3.



(a) Available modes with two pressure levels. (b) Available modes with three pressure levels.

Figure 3 – Force spectrum for systems with two and three pressure levels. Each force is to be considered as a control mode.

This study will compare both two and three pressure levels as shown in figure 2. The original DHA, whether it uses two or three pressure levels, is allowed to combine each pressure source with each cylinder chamber. Due to redundancy requirements in aircraft systems the hydraulic systems need to be separated. This is easily done for the system with two pressure levels, since two pumps are already in place. With three pressure levels, two additional pumps, four in total, are needed. An alternative would be to only utilize the two hydraulic systems and reconfigure the system with the on/off valves in case of a fault. This approach requires, however, an extensive systems safety analysis to verify its feasibility, which is not part of this study.
From the baseline in figure 2, several configuration can defined. Following configurations are investigated:

1. Three pressure levels and asymmetric cylinder,
   A=[3.0,2.6,2.3,2.4]$\cdot 10^{-3} m^2$, P=[280,200,7.5] bar, 54 modes, F= -136:145 kN
2. Two pressure levels and asymmetric cylinder,
   A=[3.7,2.9,1.1,2.2]$\cdot 10^{-3} m^2$, P=[280,7.5] bar, 5 modes, F=-130:130 kN
3. Two pressure levels and asymmetric cylinder,
   A=[3.3,3.3,1.5,1.5]$\cdot 10^{-3} m^2$, P=[280,7.5] bar, 3 modes, F=-130:130 kN
4. Two pressure levels and symmetric cylinder (reference cylinder),
   A=[2.4,2.4,2.4,2.4]$\cdot 10^{-3} m^2$, P=[280,7.5] bar, 2 modes, F=-130:130kN

The first configuration uses three different pressure lines with four different cylinder chamber areas. This gives 54 modes. The sizing is not optimized but the areas are selected to give an evenly spread force spectrum. This results in a slightly oversized cylinder. The second configuration uses four different cylinder chamber areas but with two pressure sources, high pressure from the pumps and a pressurized tank, as in the reference system. This gives 5 modes with the same specification as the reference cylinder. The third configuration has a symmetrical cylinder for each half, rendering three modes. The last configuration uses a completely symmetrical cylinder, the same as reference, giving two modes.
The valve sizing will depend on configuration. In general the valve needs to be sized to give the required cylinder speed. This is straight forward for the reference system, where the valve is sized for the no load case and stalls at maximum load. For a multi-mode configuration, stall could occur for every mode, not only the maximum load. This can also be handled by controlling the switching of modes in order to assure the valve does not stall.

3. System modelling and control strategies

System modelling

All modelling is done using the Matlab Simscape package. Only the static models are implemented. This simplifies the analysis where effects of mode switching is not considered. The models include the following elements: static cylinder speed and static chamber pressure, the pressure-flow relation with transition from laminar to turbulent flow, leakage paths for each metering port, constant supply and return pressure. The servo valve and on/off valves are modelled in a similar way with the difference that the servo valve is of 4/3 type and the on/off valves of 2/2 type. The leakage is modelled using the standard orifice equation where the opening is described by equation 1 depending on the flow path. This gives a maximum leakage of about 0.5 l/min at max pressure difference when the valve is at centered position and a total of about 1 l/min for the entire valve. A constant pressure source is implemented since the focus is on the comparison of the actuator concepts alone and the assumption is that the supply system is capable of delivering the necessary flow.

$$
\begin{aligned}
A_{q_l} &= 0.002\frac{10^{-10}}{10^{-5}-0.7x_v}, \qquad -10^{-3} \leq x_v \leq 0 \\
A_{q_l} &= 0.002\frac{10^{-10}}{10^{-5}+0.7x_v}, \qquad 0 \leq x_v \leq 10^{-3}
\end{aligned} \tag{1}
$$

Position control

The closed loop position control of the actuator is based on the feedback of the measured position. The controller structure is defined by $G_f(s)$ in eq 2, where s is the Laplace transform variable.

$$
G_f(s) = \frac{K_p}{\tau s + 1} \tag{2}
$$

The gain K_p and filter coefficient τ are selected such that the closed loop response becomes as defined by $G_c(s)$ in equation 3 under no load condition.

$$
G_c(s) = \frac{1}{(0.05s+1)(0.005s+1)} \tag{3}
$$

This control loop is equal for both the reference system and the multi-mode concept and is defined for the no load case. This means that for the reference system the gain will go down as the load pressure increases. For the multi-mode concept, however, the loop gain varies with mode selection and a gain scheduling is used in order to control the response over the working range. This is done by compensating the controller gain with the square root of the total servo valve pressure drop. Since the servo valve is designed to deliver maximum flow at a lower pressure drop than the reference system, the performance needs to be controlled so that a relevant comparison can be made.

Mode switching strategy

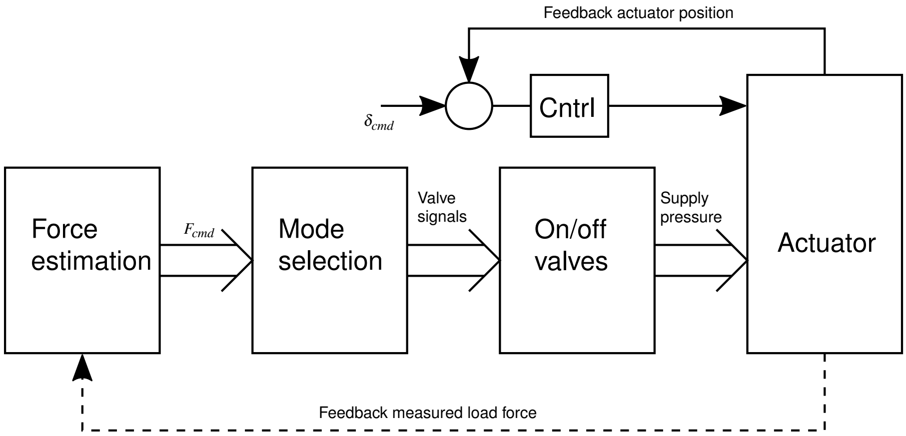


Figure 4 – Control structure.

The mode switching strategy analogy for the configurations is to minimize switching as much as possible and only apply it when it is beneficial in terms of energy efficiency. The reason for this is difficulty in keeping a smooth control when switching is frequent and the compressibility losses that occur. Since the models are all static, synchronization during switching and dynamic behaviour of the on/off valves are not considered. This means that switching control can be kept rather simple in order to investigate the energy savings potential for the concept. The switching algorithm searches for the closest force available from the force spectrum to the commanded force. 1 kN force is added to the command and certain combinations are removed to ensure controllability, as described previously. The best possible energy saving is achieved if the output force follows the required force to move the load. The measured load is therefore used as a feedback to the switching algorithm. The complete control schedule is seen in figure 4. The force estimation block only passes the information to the Mode selection block in this work, but can be used to estimate the required force on other signals than the load feedback.

Complete mission simulation

For the flight mission simulation the Admire simulation model is used to implement the actuator system. The Admire model is an open tool implemented in Matlab Simulink for simulation of a delta-canard fighter configuration aircraft, containing a six DOF flight mechanics model, flight control system for stabilization, propulsion model and aerodata model. See [13] for a description of the model and data. Primary control surfaces are canards, inner and outer elevons, and rudder.
Since the study is focused on the actuator concept's potential to save energy, it is sufficient to implement the actuator models for a few control surfaces only. Only the canards are investigated in this paper, but the concept can be extended to include all control surfaces.

4. Analysis of power requirements

In this analysis the required pump flow and power is investigated for each configuration. The required flow and power is based on the required control surface moment and rate for the canards. The corresponding cylinder force and speed is shown in figure 5.

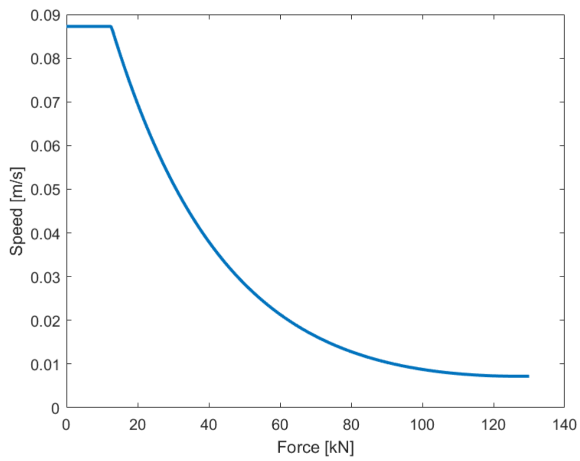
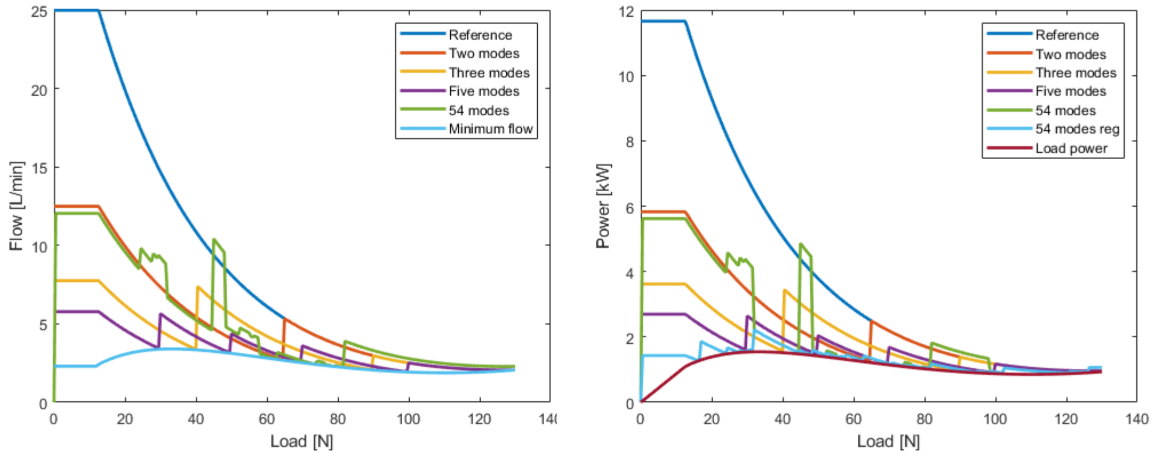


Figure 5 – Cylinder power requirements.

For each configuration the pump flow and input power is calculated based on the cylinder sizes and cylinder speed. This is done by multiplying the speed with each cylinder piston area and summarize the pump flow. For the cases the pump is connected to the same chamber the flow will recirculate and the net pump flow is reduced. The pump power is calculated by multiplying the total flow with the pump pressure. The situation is more complicated for the 54 mode configuration. It is assumed that the supply system consists of different pumps generating the high and middle pressure. This means that the flow is not recirculated. This results in a higher flow and hence a higher power. On the other hand, if it is assumed that the return flow can be regenerated, the total power will decrease. This is not evaluated further. Instead the result indicate the potential energy saving from this configuration.

The results are shown in figure 6. The minimum required flow and load power are also shown for comparison. Each configuration significantly reduces both pump flow and power. Due to the many control modes, configuration 1 with 54 modes manages to reach very high efficiency if the power is regenerated. If not, the flow and power are reduced but the benefit is quite low. Configuration 2 with five modes offers an advantage compared to configuration 3 with three modes. The additional modes can be utilized during flight to optimize the power input. Configuration 4 reduces the required pump flow with half.



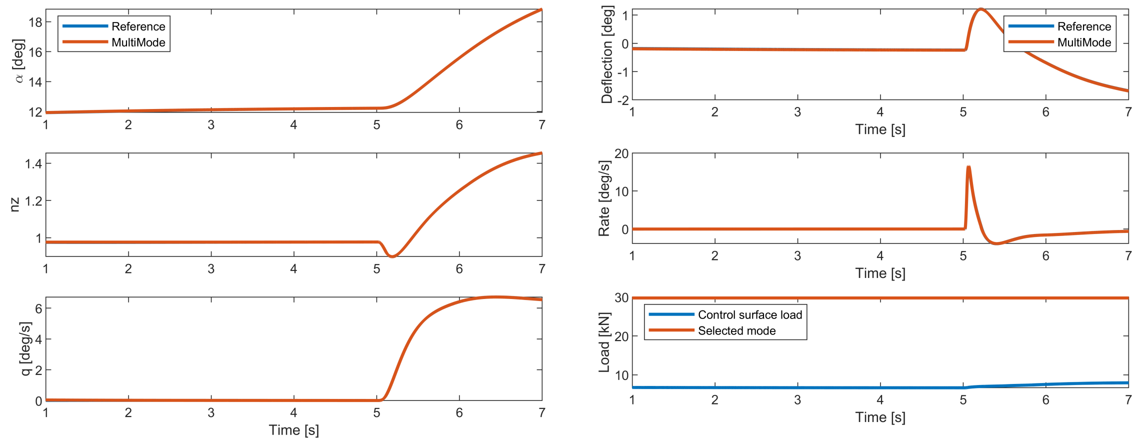
(a) Required pump flow for each configuration. (b) Required input power for each configuration.

Figure 6 – Flow and power analysis of each configuration.

Configuration 2 is selected for further investigation. The complexity for configuration 2 to 4 is very similar, although the asymmetry pose some requirements on the valve. The complexity of configuration 1 is difficult to motivate considering the supply system requirements and safety aspects.

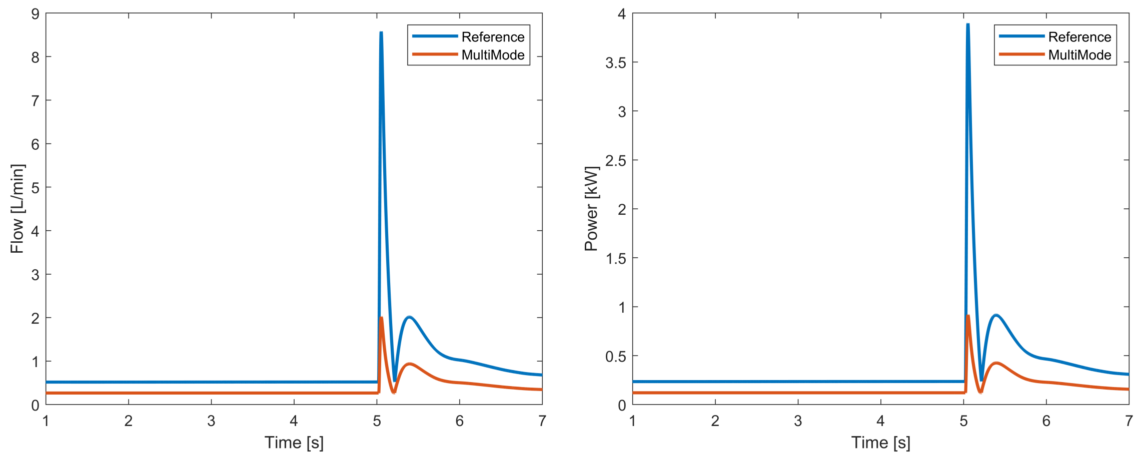
5. Flow and power consumption during flight manoeuvres

The concept is analyzed by simulating two different manoeuvers where the pilot demands a pitch up. The first manoeuvre takes place at 1000 m at Mach 0.2 and the second manoeuvre at Mach 1.1. The simulation results are shown in figure 7 to 10, which shows: the aircraft behaviour as α angle, load factor and pitch rate; the control surface deflection, rate and load; the pump flow and input power. The selected mode, shown as available control force, is also plotted. The first case generates low loads but the control surface rate is high. The concept manages to reduce the maximum input power by around 76%. For the second manoeuvre the load is high while the rate is low. The maximum input power is reduced by 30%. What is also seen is that during level flight the input power is halved. The reason is that for certain modes the two chambers of the same side are connected to the same pressure line, eliminating leakage.



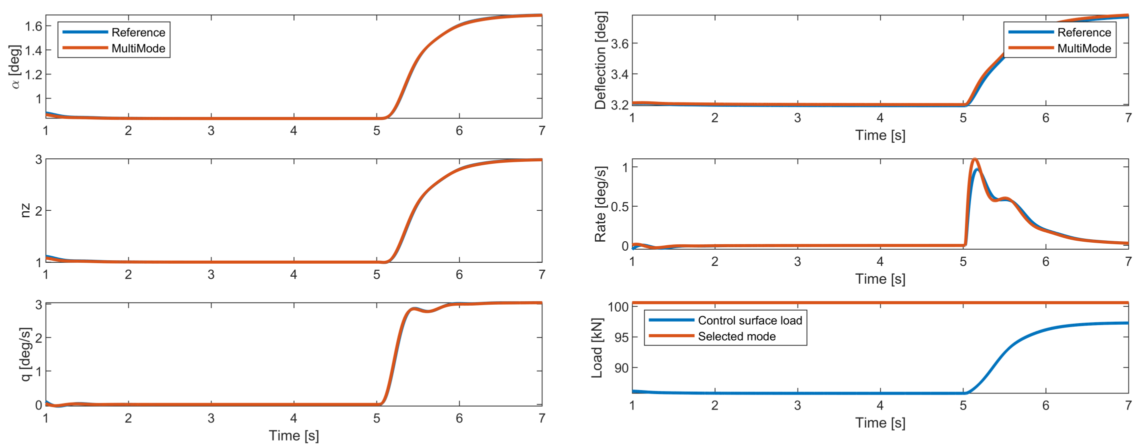
(a) Aircraft behaviour. (b) Control surface deflection, rate and load.

Figure 7 – Analysis of reference system and configuration 2.



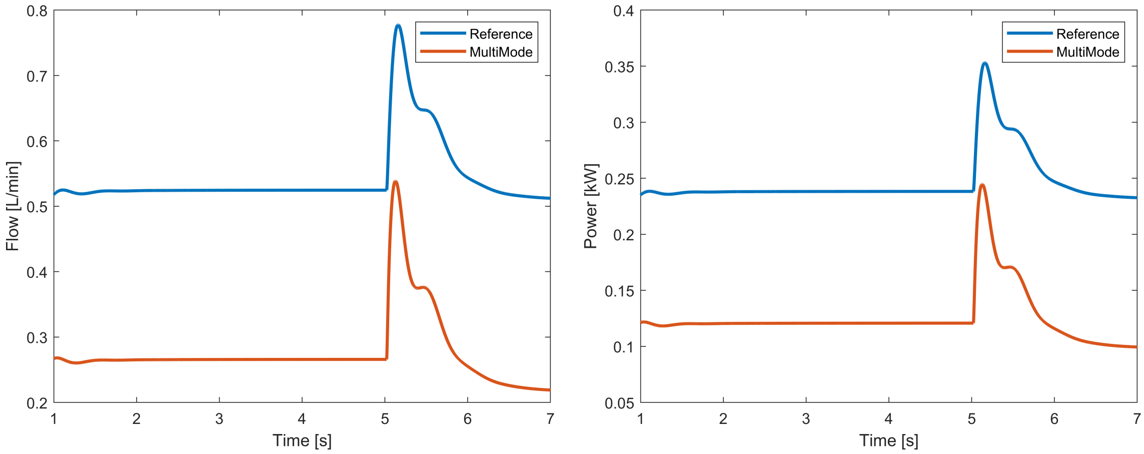
(a) Pump flow. (b) Input power.

Figure 8 – Analysis of reference system and configuration 2 for manoeuvre 1.



(a) Aircraft behaviour. (b) Control surface deflection, rate and load.

Figure 9 – Analysis of reference system and configuration 2.



(a) Pump flow.

(b) Input power.

Figure 10 – Analysis of reference system and configuration 2 for manoeuvre 2.

5.1 Discussion

The gain in efficiency should be compared to the increased complexity, weight and cost of the system. This is not entirely straight forward. Although the system add weight through an increased number of components, an increased efficiency on the other hand reduce the input power and cooling needs. An important aspect is safety. More components reduces reliability but the flexibility of the system could allow to reconfigure in case of a fault. All these aspects are not addressed in this work. Instead the important aspect has been to demonstrate by which means Digital Hydraulics and the multi-chamber cylinder can be utilized for multi-mode control to reduce the energy consumption, and the possibilities it brings to increase efficiency.

There are two aspects to consider. The internal leakage will always be present. If the control surfaces only do little work during a mission flight, the leakage will the biggest contributor to the energy losses. The concepts will half the leakage for a large range of the flight envelope. The other is the required pump flow and input power. Also here the results show a significant reduction which means not only a more efficient system, but a down-sizing of the supply system is possible. This can results in significant weight savings, which is the biggest benefit of the system. Additional control modes are enabled by selecting a completely asymmetric cylinder without increasing complexity. The additional modes can be used to optimize the consumed power by the actuation system. This is shown for manoeuvre 2. Even though a very high control force is required, a lower mode is possible which results in power savings. The actual gains will in the end depend on the specific case and flight mission.

When comparing the different configurations, the benefit of selecting three pressure levels over two is quite low compared to the increased complexity. With two pressure levels the architecture of the reference system can easily be used where the block of on/off valves are an add-on to the system. If a tandem cylinder is already in place, the design could be tailored to the specific needs and requirements. The challenge with the concept will be mode switching and to avoid cavitation. This is left for future work. The five mode system could draw benefits of actively control the modes, if mode switching could be handled efficiently.

6. Conclusions

This paper has shown how Digital Hydraulics with the multi-chamber cylinder can be combined with proportional control to enable a multi-mode control actuation system. This includes the combination of on/off valves, servo valves and the multi-chamber cylinder. For this type of system, two pressure levels are sufficient to significantly increase the energy efficiency compared to a traditional system. In this way the increased complexity is kept at a minimum. Significant supply system down-sizing is possible and the use of an asymmetric cylinder can tweak the system to enable several modes which further increases efficiency.

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8. Copyright Statement

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