31st Congress of the International Council of the Aeronautical Sciences

Belo Horizonte, Brazil; September 09-14, 2018

A HYBRID DIGITAL-PROPORTIONAL HYDRAULIC ACTUATION SYSTEM FOR AIRCRAFT FLIGHT CONTROL

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Keywords: *Efficient actuation, digital hydraulics, flight control system*

Abstract

In this paper the Digital Hydraulic Actuator, DHA, in combination with proportional Servo Hydraulic Actuators, SHA, is evaluated for aircraft flight control actuation. The DHA avoids the inherent throttling of traditional servo valves but lacks in control accuracy due to the discretized nature. The DHA has therefore a great potential to reduce the energy consumption of the flight control actuation system. Since the DHA utilizes on/off valves it can be made practically leak free, which further improves efficiency. By having several control surfaces on each wing allows for several actuators to share the control effort. In this way a DHA can be combined with a SHA, referred to as hybrid system, in order to reduce the energy consumption but keep the required control accuracy. The system is evaluated with simulation of an unstable delta-canard fighter aircraft. The results show that it is possible to fly with the system but further tuning is necessary.

1 Introduction

This paper investigates a new configuration of the hydraulic flight control actuation system by combining a Digital Hydraulic Actuator, DHA, with a traditional proportional servo system, with the purpose of reducing the energy consumption. The solution is referred to as a hybrid actuation system. In aircraft flight control 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 can easily handle high forces. The hydraulic cylinder offers very good linearity and the redundancy capability is very high. On the downside traditional hydraulic systems suffers from poor energy efficiency, mainly due to throttling and leakage.

An increased actuator efficiency would lead to several effects that decreases the aircraft weight. The required installed hydraulic power is reduced, which also has a positive effect on the component sizes. The required cooling is lower which contributes to a lower total weight.

The demand of actuation systems that better meets today's requirements has led to alternative solutions, such as the electrohydraulic and electromechanical actuators, [1]. These systems have an electric motor primary stage where the transformation to linear motion is done either through a hydraulic gear, that is a pump and cylinder, or through a mechanical gear. The main target with these solutions is to avoid the throttling of the traditional system by only applying the actuator demanded power. Another advantage is the decentralization and removal of the centralized hydraulic supply system. However, the system imposes a larger stress on the electrical system and several challenges must be adressed, such as thermal management, increased complexity, safety and increased actuator weight.

Extensive research within other domains has shown a great potential to reduce the energy consumption of hydraulic system by implementing new solutions. A solution that has emerged is the Digital Hydraulic system. It uses the idea to discretize the system output, such as flow or force, and to use discretized valued components, such as on/off valves. Several different solutions are under development and high inertia systems are in general beneficial to these solutions, [2], [3], [4] and [5].

The approach to the digital hydraulic technology adopted in this work is to combine a matrix of on/off valves with a multi-chamber cylinder, or tandem cylinder, and several pressure lines in order to generate and apply a discretized force. This is fundametally different to a traditional proportional servo hydraulic system where flow, and not force, is controlled. There are several interesting technological advantages such as:

- The technology overcomes the traditional throttling of servo hydraulic systems, that introduces great losses. Ideally, the on/off valves are either fully open or fully closed.
- The on/off valves can be made almost leak free, which otherwise is a big source to energy losses in the traditional system.
- Energy recovery is inherent.
- With force control, overloading the actuators is avoided

To the technological shortcomings following should be mentioned:

- The response time of the on/off valves needs to be very fast in order to realize smooth control.
- The technology relies on switching, which can have a negative impact on fatigue of components, generation of pressure spikes in the system, and though throttling losses are avoided, oil compressibility losses are very much apparent every time switching occurs.
- The discretized nature of the system will have a negative impact on control accuracy.

In a collaborative research between Saab AB, Linköping University and Federal University of Santa Catarina, the Digital Hydraulic Actuator, DHA, is investigated as an alternative solution to the traditional hydraulic actuation system for aircraft. The aim of the research is to understand the potential of the digital hydraulic system regarding advantages and disadvantages for aircraft flight control. Due to safety and redundancy requirements, a typical aircraft hydraulic system consists of several supply lines and tandem cylinders. The implementation of the DHA could therefore theoretically take full advantage of the system already in place. In previous research the design and performance of the digital actuator alone has been studied in [6] and [7]. A design architecture for aircraft application was also proposed. A digital hydraulic supply system compromised of fixed displacement pumps instead of the otherwise variable displacement pumps has also been investigated with the aim of reducing the energy consumption, [8] and [9]. A discussion about modern control principles for the DHA is given in [10].

It is highly likely that no single solution will fullfill all requirements of future actuation systems. Keeping a broad view of the problem increases the likelihood of finding a suitable solution. In this paper a new approach to the Digital Hydraulic system is presented, which was first studied in the Master thesis, [11], at Saab AB. The main purpose of this paper is to investigate the impact of some of the aforementioned technological advantages and shortcomings on a small delta-canard fighter aircraft, such as energy consumption and flight performance.

Since the motion of the aircraft is controlled with several control surfaces, it is possible to combine both a digital hydraulic system and a traditional servo system on different control surfaces to handle different portions of the control command. In an attempt to overcome the deficit in control accuracy and still benefit from the potential energy gain the DHA can be activated for large control commands, while during trim mode or for smaller commands, the DHA is locked and the control is handled by the proportional servo actuator only. The investigation is performed by simulations with a realistic modelling of the complete system. The performance of the DHA is compared to a traditional servo hydraulic actuator, SHA, and a discussion about the necessary technological development of the DHA regarding aircraft flight control actuation is outlined.

2 Delimitations

The work in this paper is focused on the performance of the Digital Hydraulic Actuator for flight control only. Therefore, no consideration is taken to the needs of the supply system but it is merely adapted to the specific needs of the DHA. Any safety requirements are also not considered at this point and are subjected to future studies. Although conventional flight control laws are implemented, no specific tuning is done in this work. This could potentially improve the performance of the system in a future version.

3 System description

This section describes the system and its control architecture under study.

3.1 Aircraft configuration

The aircraft configuration is based on the ADMIRE model described in [12], that in turn is based on the Generic Aerodata Model [13], and is depicted in figure 1. It is an unstable delta-canard configuration with data as in table 1. The model is restricted to Mach below 1.2 and height below 6000 m.

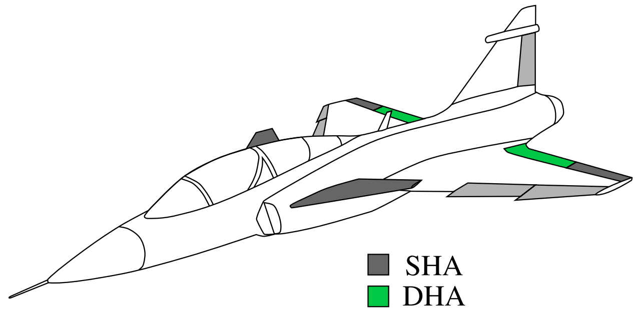

Fig. 1 Aircraft configuration for the intended study.

In this paper only the elevons and canards are under consideration and modelled, whereas the rudder and leading edge flaps are left for future implementation. The elevons are split in two halfs on each side. Two configurations are considered in this paper. One is the reference system which have all elevons and canard actuators of the servo hydraulic type with proportional control. The second configuration uses the digital hydraulic actuator for the inner elevon control surfaces, as shown in figure 1. In this way the work done for elevon actuation is split by the SHA and DHA actuators.

3.2 Servo hydraulic actuator

The servo hydraulic system is a general solution and well explained by the literature, see e.g. [14]. It is a duplex hydraulic system represented by two equal servo valves fed with the same signal and a symmetrical tandem cylinder, illustrated in figure 2. The two valves are fed from two different hydraulic systems at 280 bar. The controller

Parameter	Value	Unit
Wing area	45	m^2
Wing span	10	m
Wing mean chord	5.2	m
Mass	9100	kg
Ix	21000	kgm^2
Iy	81000	kgm^2
Iz	101000	kgm^2
Ixz	2500	kgm^2

Table 1 Aircraft configuration data from [12].

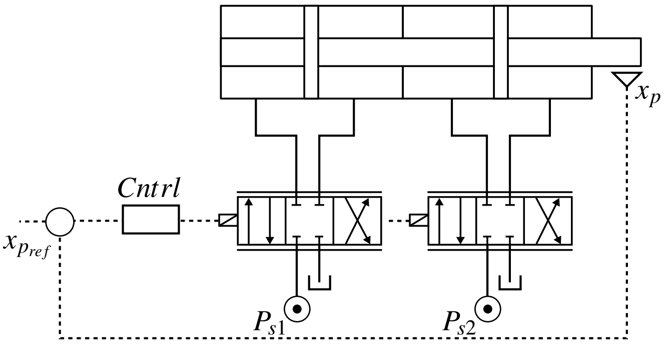

Fig. 2 The servo hydraulic actuator.

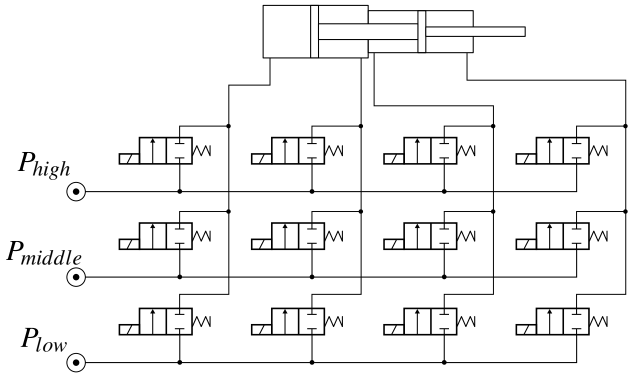

Fig. 3 The digital hydraulic actuator.

closes the position servo loop through a low pass filter and a gain. It is designed to give a closed loop response similar to the transfer function in equation 1, where s denotes the Laplace operator. Only normal operation is considered.

$$G_{SHA}(s) = \frac{1}{(1+0.05s)(1+0.01s)} \qquad (1)$$

3.3 Digital hydraulic actuator

The digital hydraulic actuator takes advantage of both the multiple pressure lines and tandem cylinder available. The design, however, differs from the original system. The tandem cylinder is designed with four unique pressure areas. The pressure lines need also to be at three unique levels, since this will generate a higher resolution of the force spectrum. By applying three pressure levels with four different cylinder pressure areas, $3^4 = 81$ unique forces are available. As shown in [6], it is possible to find a set of pressure areas and pressure levels that will accomodate the needs of the actuator regarding symmetri and physical size.

The servo valve is replaced with an array of 12 on/off valves referred to as DFCU, Digital Flow Control Unit. These valves connects the pressure lines to the different cylinder chambers by different combinations of activated on/off valves and thereby controls the output force. The system is illustrated in figure 3.

The actuator utilizes the two available pumps and the pressurized return system. One pump remains at the original 280 bar while the other is set at 72.22 bar, with a return pressure at 7.5 bar. With the cylinder sizing $A = \{30.09, 26.36, 24.87, 25.11\} \cdot 10^{-4}$ m^2, the force spectrum in figure 4 is generated.

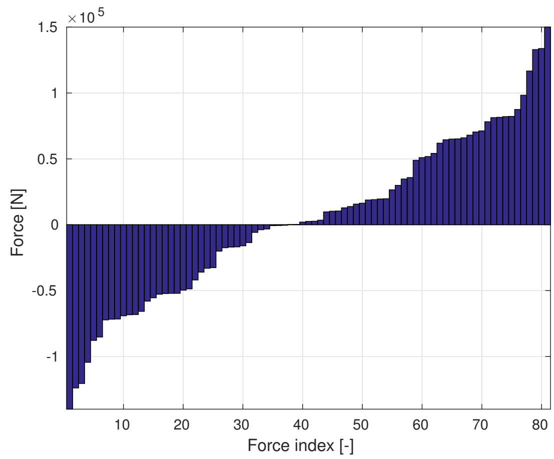

Fig. 4 Available force spectrum for the DHA with given design.

3.4 Control

3.4.1 Flight control layout

The flight control system consists of two control loops. The inner most controller is the actuator control loop. The outer most loop is responsible for stability and handling qualities. A detailed explanation is given in [12]. It consists of a longitudinal and a lateral part. The longitudinal part is a pitch rate controller for Mach number below 0.58, and a load factor controller above Mach number 0.62, with a mixed function in between. The lateral controller is responsible for roll and sideslip angle control. The three control channels are then distributed to each control surface. A time lag of 20 ms is introduced to resemble the signal delay of the actual flight control computer.

3.4.2 Digital hydraulic actuator control

The actuator control takes the outer loop signal as reference value, which corresponds to a desired cylinder position. However, as mentioned, the DHA differs from the SHA in that it controls force and not flow. The controller will therefore has to consider this and the input to the actuator is the desired force. The typical approach to controlling the DHA is a feedback controller with PID gains and possbily a forward path. Some examples are seen in [5] and [7]. Fast switching will improve smoothness in the position tracking. This will also require very fast valves. On the other hand, exact position tracking is very difficult. Due to the discretized nature of the actuator, exact matching of the desired force and the actual force are hardly ever achieved. This will lead to excessive switching which have several downsides. There is a risk that the motion becomes jerky and compression losses occurs for every switch. A penalty function can be introduced to minimize the switching. This will, however, lead to a loss in control accuracy. There is a clear compromise in how to set up the system.

The approach in this paper is to keep the fundamental property of the DHA, which is to control the force. Figure 5 shows a schematic of the DHA control structure. Here it is assumed that the required force for a given control surface deflection is known, i.e. a perfect force estimation, and the job of the controller is to convert the desired deflection coming from the outer loop into a force. The force estimator is therefore the control surface load model from [13], but with the commanded control surface deflection is input. A selection scheme then chooses the combination of on/off valves that gives the closest actual force possible. This approach can be seen as a pure feedforward. A filter is added to the control signal to smoothen the output. In this way the selection scheme will have to apply all available forces between the previous value and the new value, and a too large force step is avoided. This approach is also feasible considering that the outer flight control loop handles the positioning of the aircraft. How the system behaves if there exists an error in the estimated force is left for future work. A penalty function as explained in [11] is implemented to avoid unnecessary switching. The function compares the current and requested force from the actuator, but only applies the new force if the difference exceeds the penalty value. Here it is set to 2000 N.

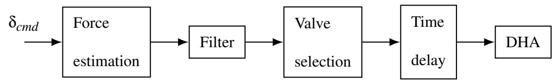

Fig. 5 Control scheme of the DHA.

Another concern is the limited bandwith of the on/off valves. For each time a switching occurs two valves to the same cylinder chamber will be open during a short period of time leading to a hydraulic short circuit between two pressure sources. This results in increased losses. To overcome this a time delay is introduced that closes all valves before a new combination of valves are opened. This will of course reduce control accuracy and the time delay is tuned to find a good compromise between energy consumption and control accuracy.

The fact that exact matching of the required force for a certain control surface deflection and the available force is unlikely to match, control accuracy is penalized at steady-state. In order to avoid switching between two adjacent force levels, a locking function is implemented. If the cylinder speed and the difference between the reference cylinder position and actual position are below a certain threshold, all valves are closed. Besides from avoiding an oscillatory behavior, leakage is also minimized. The speed threshold is set to 0.005 m/s and the position threshold to 1 mm.

4 Simulation model

A full system model is provided in order to study the DHA in its intended application. As mentioned the ADMIRE model described in [12] is used in this work in order to provide a platform on which to evaluate the effect of the DHA on the flying qualities and analyze the performance, advantages and drawbacks, and necessary future development steps. The aircraft model is provided in Matlab/Simulink while the actuation system is modelled in Hopsan, [15]. All Hopsan code is generated to Matlab/Simulink S-functions for the full system simulations.

4.1 Flight control actuation system model

4.1.1 Reference system model

The reference actuation system is a traditional servo hydraulic system. Each of the inner and outer elevons and canard actuators are designed to meet 150 kN of both pushing and retractive force at a maximum speed of 0.0873 m/s, corresponding to a control surface rate of 50°/s. The symmetrical area of all four chambers is set to $27.53 \cdot 10^{-4}$ m^2 with a mass of 300 kg and viscous friction of 10000 Ns/m. For simplicity the cylinder volumes are fixed at a size of 0.5 L. The duplex servo valve is represented by two 4/3 directional valves with a resonance frequency of 250 Hz and damping ratio 1. The valve has a purely turbulent flow-pressure relation and the symmetrical maximum opening area of the valve is set to $2.2 \cdot 10^{-6}$ m^2, the flow discharge coefficent is set to 0.6 and the oil density to 850 kg/m^2. Both valves are fed with the same signal to ensure identical opening. A leakage between the supply and return lines is modelled as a laminar flow of 1 L at 280 bar for each hydraulic system and for each servo valve.

As mentioned, the supply system is not considered in particular in this work. A constant speed, pressure controlled variable pump is set to hold 280 bar for each hydraulic system. The pumps are dimensioned to provide the necessary flow to the actuators at a response time of 10 Hz. No losses of the supply system is included.

4.1.2 Digital hydraulic actuation model

The same tandem cylinder model with volumes as the reference system is used for the DHA model with the area of each cylinder chamber as described section 3.3. The design is based on trying to achieve a maximum force as close as possible to the SHA. Each on/off valve is modelled as a 2/2 valve with a second order resonance at 300 Hz and a damping coefficent of 1, a turbulent flow-pressure relation with same oil properties as the SHA model and a maximum area opening of $6.3 \cdot 10^{-5}$ m^2. No leakage is included for the DHA since the on/off valves are practically leak free. The control filter has a breakfrequency of 200 rad/s.

In classical proportional systems, the valve is a large contributor to system damping, see e.g. [16]. This effect is removed when using on/off valves with the intention to avoid throttling. The maximum area opening is therefore chosen to be rather small to contribute to some damping, but not too small in order to avoid throttling losses. This is of course a compromise, since an undamped system will oscillate and consume more energy.

4.1.3 Hybrid digital-proportional actuation system

The new hybrid digital-proportional actuation system is composed of the digital actuators in replacement for the inner elevons servo hydraulic actuators. The outer elevons and canards are still of the proportional type. The supply system is now altered to fit the flow and pressure requirements of the new system. Since one of the hydraulic systems is adjusted to fit the middle pressure level of the DHA system, all SHA need to be supplied be the same supply system and the pump displacements are therefore corrected to the different need. Future work will have to investigate new solutions for the supply system that will better accomodate safety, efficiency and the set up for the DHA.

4.2 Full system model

The ADMIRE model is a 6 degrees of freedom model of an unstable delta-canard aircraft. Input to the model is longitudinal and lateral stick deflection, rudder pedal deflection and throttle stick setting. In this work the speed is set to a constant value and maintained by the longitudinal controller. The ADMIRE model also provides a model of the flight control actuators as a rate limiter and a first order filter with time constant 0.05 s. The rate limiter is kept to prevent the actuators from running to fast and gives a maximum rate of 50 °/s. The first order lag is replaced with the Hopsan generated model of both the reference system and the digital-proportional system. For simplicity a fixed hinge leverage of 0.1 m is placed between the actuator and control surfaces. The in-place outer loop controller responsible for flying and handling qualities is not altered in this work. This is to understand any necessary development steps of the flight controller.

5 Simulation setup and results

5.1 DHA performance

A step response and sine tracking reveals the performance of the DHA compared to the SHA. Figure 6 shows a 6 mm step response of the SHA and DHA. The servos work against a spring with stiffness $5 \cdot 10^6$ N/m to resemble the external load. The locking function of the DHA control is clearly visible.

Figure 7 shows the response for a sine input at 1 Hz and an amplitude of 6 mm. The same spring load applies. Though the step response shows a smooth behavior of the DHA, the sine tracking reveals the discrete nature of the actuator. In this case, the energy consumption of the DHA compared to the SHA is about 54 %, i.e. 4 kJ for the DHA compared to 7.4 kJ for the SHA.

Figure 8 shows the sine response of the DHA when the load is much lower, in this case a spring with stiffness $5 \cdot 10^5$ N/m. It is compared to the ideal response, i.e. as the transfer function G_{SHA}. No penalty function is used here in order to increase the accuracy.

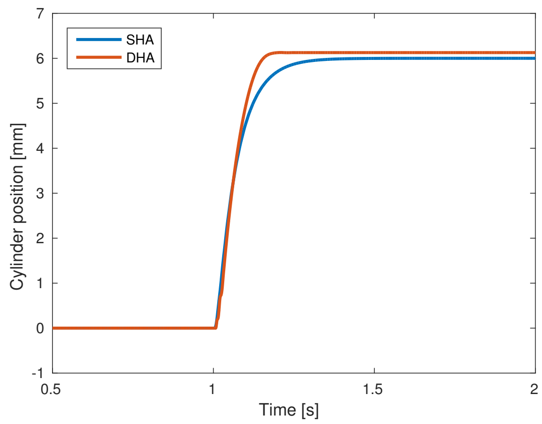

Fig. 6 Step responses of the SHA and DHA.

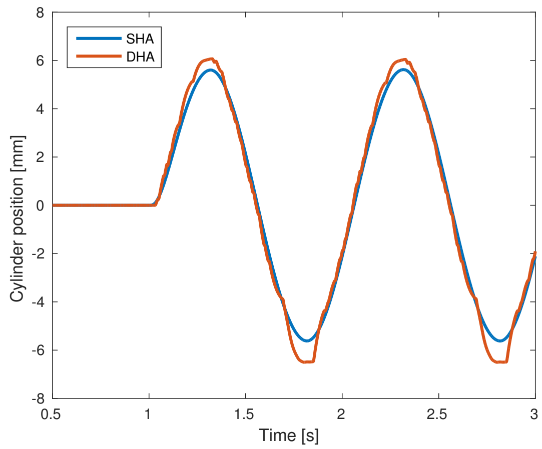

Fig. 7 Sine responses of the SHA and DHA.

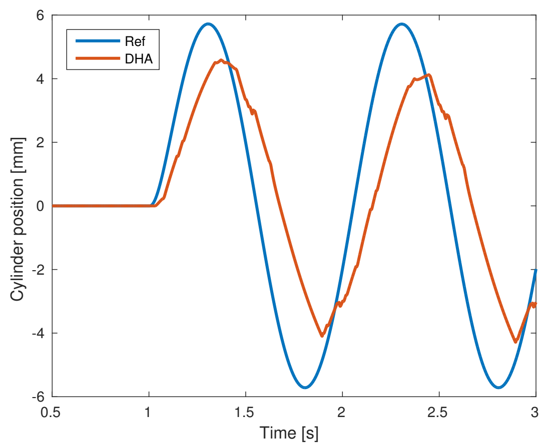

Fig. 8 Sine responses of the DHA compared to the ideal response with a low load.

5.2 Flying qualities with DHA

The effect of the DHA on flight performance is studied during a turn at high Mach nunmber 1.2 at 5900 m for maximum actuator loading, shown in figures 9 for aircraft performance and 10 for left inner and outer elevons deflections. At 3 s the pilot performs a roll manuever and at 5 s the pilot performs a pitch manuever by controlling the stick deflection accordingly.

The energy consumption for the actuation system is shown in figure 11, with a comparison between the SHA and DHA. To better understand the effect from the control principle of the actuator technology, the same manuever is also performed with leakage removed from the SHA model. With leakage the hybrid system uses about 74 % of the energy compared to the reference system. With no leakage included, the hybrid system uses about 81 % of the energy.

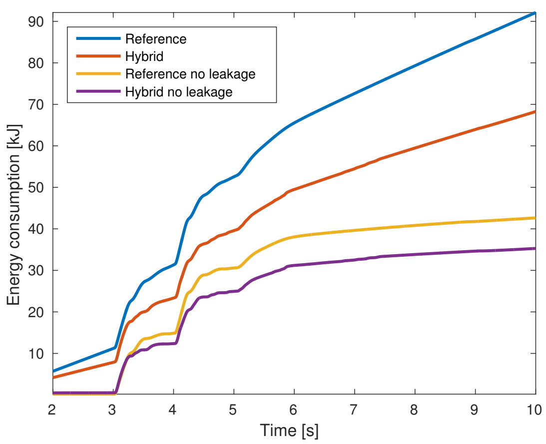

Fig. 11 Energy consumptions of proportional and hybrid actuation systems, with and without leakage included.

6 Discussion

The performance of the DHA is dependent on the working conditions. This is shown in figures 6, 7 and 8. While the step input generates a smooth response, the sine input shows that the response is only smooth if the required force is available. For the low load case the response is poor because the DHA is working in the lower part of the force spectrum and the resolution is poor. A feedback loop would increase the switching to better follow the reference input, but this will also increase the losses. A better allocation of the control demand between the SHA and DHA dependent on the flight envelope might improve things. Alternatively the resolution can be increased by altering the supply pressure levels. Both of these approaches require further studies.

A feeback loop is, however, probably necessary to handle disturbances, model uncertainties and overrunning the actuator. This is left for future work, but it is possible that the outer flight control loop will handle disturbances as well.

A well damped behavior is of great importance. This is partially solved by allowing for some throttling of the fluid. The throttling might also cause cavitation in the cylinder chamber for the low pressure side. This can be avoided with e.g. check valves, but a future version will have to look at a more sophisticated solution, e.g. actively control the damping.

Looking at figure 9 it appears that the hybrid system generates a somewhat more damped response compared to the reference system. The effect of the discrete nature of the DHA is, however, visible with a less of smooth response. Figure 10 shows a slight difference between the inner elevon deflection of the reference and hybrid systems. Here, the discrete control of the DHA is seen. The outer elevon deflection is very similar for both systems, indicating little need to compensate for the DHA response. But the SHA response is also limited and a higher response could perhaps smoothen the flight response better.

Overall, a significant amount of energy was saved by only replacing two out of six proportional actuators for digital ones. A great portion of this also comes from reduced leakage.

7 Conclusions

This paper proposes a hybrid flight control actuation system by combining traditional proportional servo control with the digital hydraulic actuator. Simulation results show that the aircraft does not significantly suffer from a loss in per-

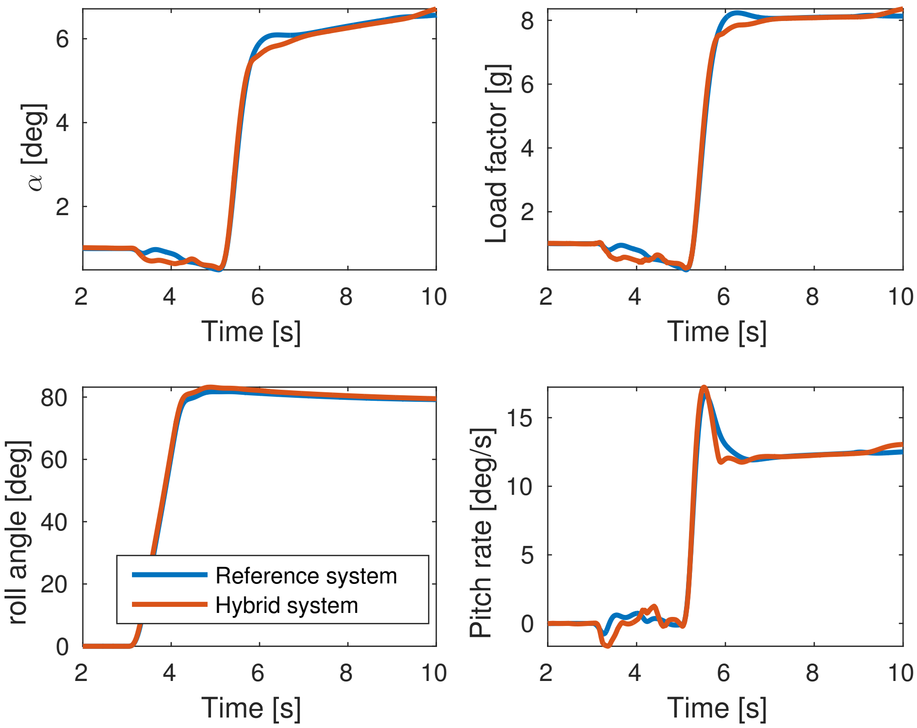

Fig. 9 Flight responses of reference and hybrid systems.

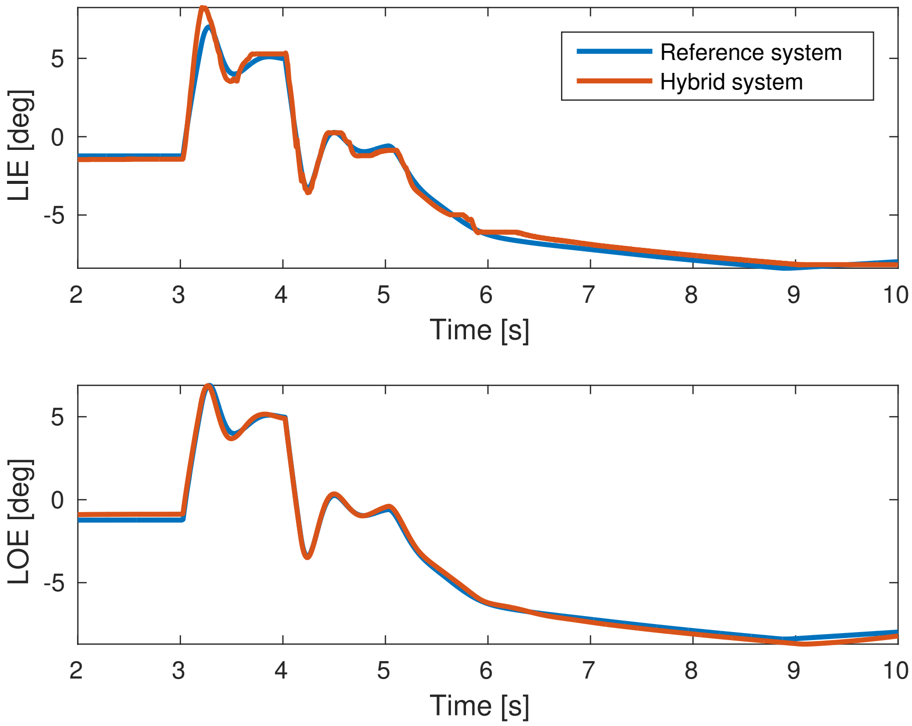

Fig. 10 Control surface deflections of the left inner and outer elevon, LIE and LOE.

formance while energy is saved. Further tuning of the system is necessary.

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