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CONTROL OF AN ELECTRO-HYDROSTATIC ACTUATION SYSTEM FOR THE NOSE LANDING GEAR OF AN „ALL ELECTRIC AIRCRAFT"

GREISSNER, Carsten
Hamburg University of Technology
Institute for Aircraft Systems Engineering
Nesspriel 5, 21129 Hamburg, Germany
Phone: +49 (0)40 / 428 788-234
Fax: +49 (0)40 / 428 788-270
E-Mail: greissner@tuhh.de

CARL, Udo
Hamburg University of Technology
Institute for Aircraft Systems Engineering
Nesspriel 5, 21129 Hamburg, Germany
Phone: +49 (0)40 / 428 788-201
Fax: +49 (0)40 / 428 788-270
E-Mail: carl@tuhh.de

ABSTRACT

The EU research Project Power Optimised Aircraft (POA) investigates the approach to replace primary hydraulic supply by extended electric power systems towards a More or All Electric Aircraft [4].

This contribution presents an electrically powered actuation system for nose landing gears using an EHA (electro-hydrostatic actuator) approach. One motor pump unit supplies door and gear actuation as well as the steering system. Different control strategies for the individual actuators are introduced. The effects of different control strategies are shown by simulation results.

KEYWORDS

Electro-Hydrostatic Actuator (EHA); Nose Landing Gear; All Electric Aircraft; Power Optimised Aircraft (POA)

1 INTRODUCTION

Actuation systems for nose landing gears in today's commercial aircraft are typically powered by a central hydraulic system supplied by constant pressure controlled pumps. The velocity of landing gears and doors is controlled by orifices while the steering system operates in a closed position control using servo-valves.

One project goal is to develop an electrically powered actuation system for nose landing gears. This system has to supply landing gear and door actuation as well as steering. One possible approach is to use electro mechanical actuators, which convert electrical power directly into mechanical power. The drawback of this solution is a possible jam in the EMA, which would obstruct the gear from free fall, or cause a blocked steering system. As a second approach it is possible to employ a local constant pressure supply and the conventional landing gear hydraulic system. However, constant pressure systems imply the disadvantage of high losses; speed induced pump losses and pressure losses in orifices and servo valves.

This contribution presents an EHA (electro-hydrostatic actuator) approach combining the benefits of flow control (system pressure is proportional to external loads) to save power and the usage of conventional actuators to prevent jamming. One motor pump unit supplies door and gear actuation as well as the steering system [2].

2 CONCEPT DEFINITION

Figure 1 shows the hydraulic architecture of the actuation system based on the nose landing gear of a regional aircraft. The system is divided into five subsystems:

1. hydraulic power supply
2. hydraulic net
3. door actuation system
4. gear actuation system
5. steering system

A speed variable motor (brushless DC) and a fixed displacement pump (1) are used in order to power the system. This pump supplies a hydraulic net (2) that contains pressure relief valves to limit system pressure. Pilot-operated check valves and a reservoir balance the non-symmetric actuator flow due to the usage of differential cylinders.

The selector valves located in the door / gear actuation and steering systems are used to isolate or connect these subsystems with the hydraulic net. These complex valves are necessary due to the fact that the motor pump package can only supply subsystems one at a time.

A pilot-operated check valve secures the doors (2) in the open position (e.g. against wind loads) during gear extension / retraction. Orifices are used to align the movement of the doors even if the loads are unbalanced. During gear (4) extension the hydraulic system is driven by the gear. This hydraulic power is dissipated by an orifice-check valve combination.

The door (3) and gear (4) actuation subsystems are equipped with mechanical operated free fall valves to assure emergency extension.

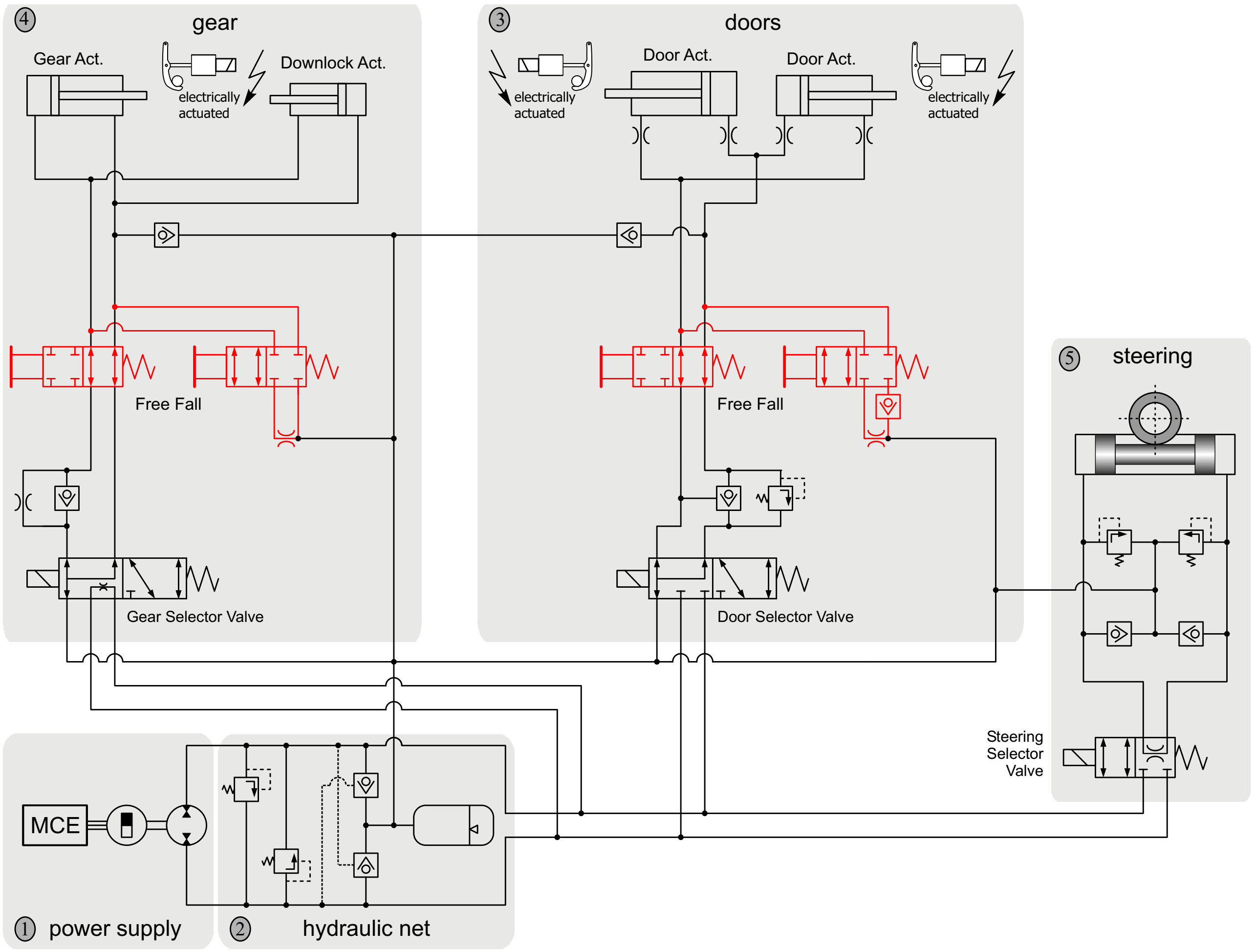

Figure 1: Electro-hydrostatic actuation system for nose landing gears

The steering system (5) is protected by anti cavitation valves and pressure relief valves. The steering actuator is a rack and pinion one. An orifice (shimmy damper) damps the movement of the wheels while the steering system is deactivated (free castor mode).

3 SYSTEM MODEL

The nose landing gear actuation system can be described by the following set of non-linear equations for the brushless DC motor [5] and the hydraulic system [1].
An equivalent 2-phase rotor fixed coordinate system [3] is used to analyse the permanent magnet synchronous motor (brushless DC). The stator and space fixed 3-phase variables are transformed into a rotating $d-q-$frame.
The $d-$ and $q-$axis current equations are given by:

$$(1) \quad \frac{d\,i_d}{dt} = \frac{1}{L_d}u_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}\omega_{el}\,i_q \,,$$

$$(2) \quad \frac{d\,i_q}{dt} = \frac{1}{L_q}u_q - \frac{R}{L_q}i_q - \frac{L_d}{L_q}\omega_{el}\,i_d - \frac{2}{3}k_t\,\omega_{mech} \,.$$

The motor torque can be calculated with:

$$(3) \quad M_{mi} = k_t \cdot i_q + \frac{3}{2}Z_p\,(i_d \cdot i_q)\cdot(L_d - L_q)\,.$$

For the linearisation of the motor the $d-$axis can be neglected because a vector flux control with $i_{d,ref} = 0 \approx i_d$ is applied. Thus the brushless DC motor can be described by the following set of equations:

$$(4) \quad \frac{d\,i_q}{dt} = \frac{1}{L}u_q - \frac{R}{L}i_q - \frac{2}{3}k_t\,\omega_{mech} \,,$$

$$(5) \quad M_{mi} = k_t \cdot i_q \,.$$

The equation of motion for the whole system results in:

$$(6) \quad J_{total}\frac{d}{dt}\omega_{mech} = M_{mi} - M_{hyd} - M_{fric}\,.$$

Assuming pressure depending linear leakage the flow delivery of the pump can be described as:

$$(7) \quad Q_p = Q_{p,th} - c_{leak}\cdot p$$

with the theoretical flow given by:

$$(8) \quad Q_{p,th} = \frac{V}{2\pi}\cdot\omega_{mech}\,.$$

System pressure can be calculated from:

$$(9) \quad \dot{p} = \frac{1}{C_h}(Q_p - Q_{load})$$

with the hydraulic capacity C_h.
Using system pressure the equation of motion of the cylinder is represented by:

$$(10) \quad \ddot{x} = \frac{1}{m} A_p \cdot p - F_{load} - F_{fric}$$

with a speed depending friction F_{fric}.

4 ACTUATOR CONTROL

In todays aircraft the landing gear actuation system both gear and door actuators are powered by the central constant pressure system. Actuator speed is controlled by the use of orifices. On the one hand the maximum speed is limited to adjust operation time and on the other hand the impact velocity is reduced near end of stroke using damping orifices (snubbing devices).
Applying the EHA principle for landing gears the system is no longer supplied by constant pressure. In fact system pressure depends on external loads. That is why actuator speed has to be controlled by hydraulic flow, which is affected by motor speed. The approach used in conventional flight control EHA is a closed position control loop. The disadvantage of such a strategy is the need of position sensors in every actuator. Nevertheless this strategy is introduced as a reference.
Another possibility is to command a constant actuator speed thus a constant motor speed. The actuator speed will be reduced automatically every time the piston enters the snubbing area. Because of the orifices the pressure will rise and a subsidiary pressure control loop has to limit system pressure to nominal pressure.

4.1 Performance Requirements

In opposite to flight control actuators for gear and door actuators there are only two relevant positions. The doors can be commanded into their

- closed position ($x_{cmd} = 0$ mm) or
- opened position ($x_{cmd} = x_{max} = 250$ mm),

and the gear can be commanded into

- retracted position ($x_{cmd} = x_{max} = 197$ mm) or
- extended position ($x_{cmd} = 0$ mm).

Dynamic requirements result from a reduction of velocity at end of stroke to approximately 50 % and limited actuation times:

doors : $T_{min} = 2$ sec and $T_{max} = 2.5$ sec ,
gear : $T_{min} = 8$ sec and $T_{max} = 10$ sec .

4.2 Closed Position Control Loop

Continuous position sensors for each actuator are used to control the actuators in a closed position control loop with an inner speed control (figure 2).
In the case of an increasing leakage the subsidiary speed controller will adjust motor speed and thus pump flow. Thus, the dynamic of the system is independent of load and internal leakage.
Actuator speed is limited to an upper value in order to comply with the requirements in chapter 4.1.
The position controller commands a position-depending actuator speed. Thus, the impact velocity of gear and doors is reduced to a minimum, because the commanded actuator speed approaches zero at the end of stroke.

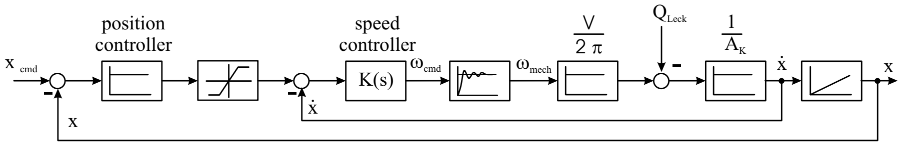

Figure 2: Closed position control loop

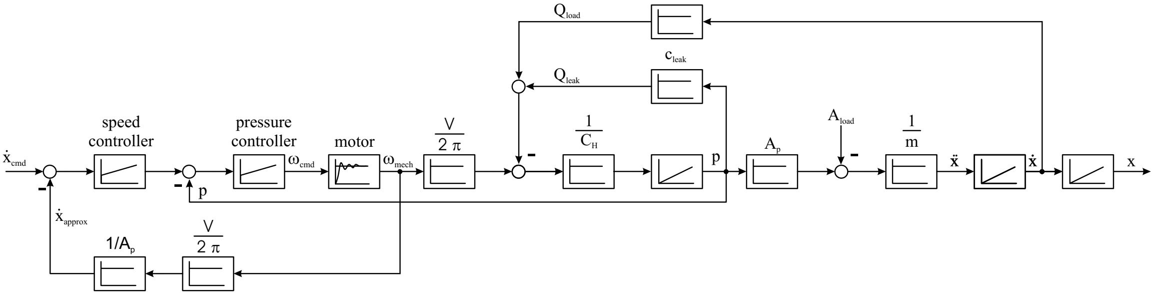

Figure 3: Open position control loop including a subsidiary pressure control

The significant reduction of actuator speed in the snubbing area is necessary to limit system pressure. Without a reduction in speed (constant flow delivery of the pump) system pressure will rise to an abnormal value, because the end stop dampers are designed to reduce actuator speed to 50% of nominal velocity at nominal pressure.

4.3 Open Position Control Loop Including Subsidiary Pressure Control

One goal in aerospace actuation systems is the reduction of sensors. A concept applying an open loop position control is introduced in order to save position sensors for every actuator.
To ensure a smooth impact of the actuator a speed reduction at the end of the stroke is required. To decelerate the actuator a position indication is needed to reduce motor speed and thus actuator velocity. Another possibility is the usage of existing end stop dampers. To apply this pressure induced speed reduction a subsidiary pressure control loop is necessary (figure 3). When the piston enters the snubbing area strong orifices are engaged. Due to constant pump flow system pressure will rise and the pressure controller will limit the pressure. Thus, actuator speed is reduced to a predefined value.
Applying this concept it is not necessary to control actuator position or speed due to moderate time requirements. Thus, an approximation of actuator speed is sufficient:

$$\dot{x}_{approx} = \frac{V}{2\pi A_p}\,\omega_{mech}\ . \tag{11}$$

Hence, position sensors for every actuator can be omitted and only two pressure transducers at the pump are needed. The disadvantage is that no leakage compensation is possible, but this has only a minor impact on the actuation time.

5 SIMULATION

For controller design the model described in chapter 3 was used. For this chapter a more complex model including e.g. valves, low pressure reservoir and end stop damping (snubbing devices) was used to show landing gear non-linear dynamic behaviour. Simulation results for each of the introduced control strategies are discussed in the following passages.
On the one hand the actuators are operated in a closed position control loop. The reference signal is a stepwise change in the commanded position. Actuator speed results from the position controller.
On the other hand the actuator is operated in an open position control and a subsidiary pressure control loop is applied. The reference signal is actuator speed whereas the actual velocity for system control is calculated from motor speed (equation (11)).

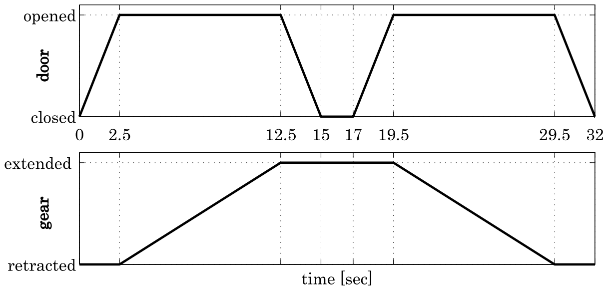

Figure 4: Sequencing of the nose landing gear

Figure 4 illustrates the sequence of steps to extend and retract the nose landing gear. At the beginning the doors are closed and the gear is retracted. At first the doors are opened and secured by a pilot-operated check valve (see figure 1). After gear extension the doors are closed. Two seconds later (at 17 sec) the sequence recurs to retract the gear.

5.1 Closed Position Control Loop

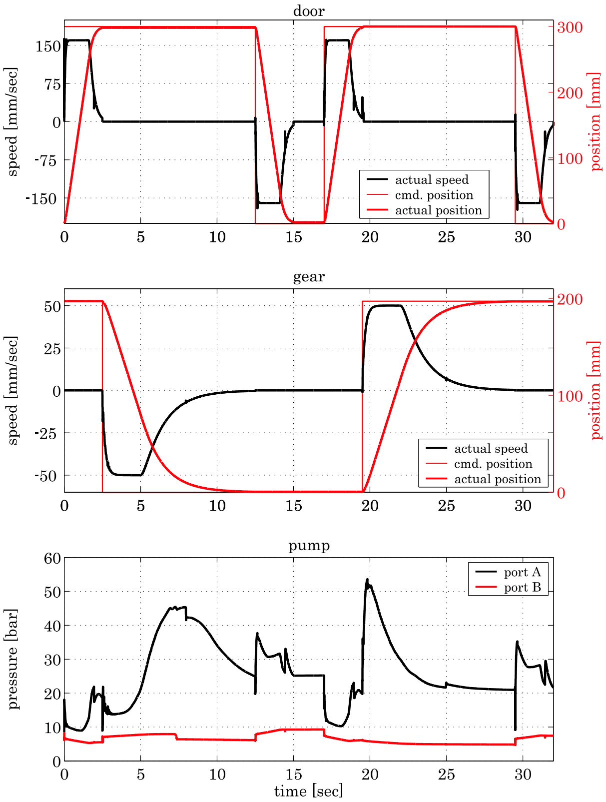

Figure 5: Closed position control loop

In figure 5 simulation results are shown. At first the doors are opened. After an initial acceleration phase the doors move with constant velocity. Near end of stroke (approx. 2.3 sec) actuator speed is reduced by the position controller. The peak in velocity occurs due to the engagement of the snubbing device. In the next step the gear extended. After a period of constant speed the actuator velocity is reduced depending on actual door position.

In order to close the doors (12.5 sec) it is necessary to initially unlock the pilot-operated check valve. This results in a pressure peak at the pump outlet (12.5 sec). At 17 sec gear retraction starts with door opening.

5.2 Open Position Control Loop including Subsidiary Pressure Control

To open the doors a constant velocity is commanded. The speed controller adjusts system pressure to achieve the set point. Figure 6 shows a constant deviation between commanded and actual actuator speed. The difference results from system leakage that is not considered to control the velocity because actuator speed is calculated from motor speed (eqn. (11)). When the system enters snubbing device actuator speed is substantially reduced. Because of the increasing deviation between commanded and actual speed system pressure rises to nominal pressure (200 bar between pump ports) with a maximum overshoot to 224 bar.

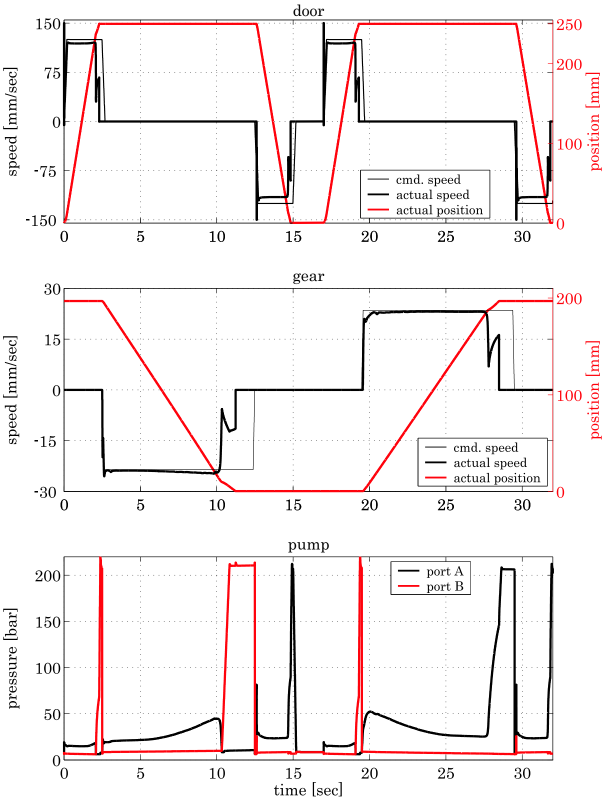

Figure 6: Pressure control loop

During gear extension external loads assist the movement of the gear. That is why port A is pressurized to decelerate gear extension. If the gear actuator enters the snubbing area speed is reduced to a lower value. To adjust actual to commanded speed the pressure level at port B changes to nominal pressure (200 bar difference) with a maximum pressure of 215 bar. To close the doors a pressure peak appears to unlock the pilot-operated check valves. At 17 sec the sequence starts again to retract the gear against opposing loads.

6 CONCLUSION

This paper presents a strategy to control landing gear actuators without position sensors. To decelerate the actuator near end of stroke the built-in end stop dampers are used. Simulation results show that such a strategy can be applied without high pressure peaks. To validate the presented concept a demonstrator is build up at the moment.
Further investigations aim to reveal wether it is possible to calculate system pressure from motor current without using additional sensors.

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NOTATIONS

variables and parameters		
A_p	piston area	m^2
c_{leak}	leakage coefficient	$\frac{\mathrm{m}^3}{\mathrm{sec}}\frac{\mathrm{m}^2}{\mathrm{N}}$
C_h	hydraulic capacity	$\frac{\mathrm{m}^5}{\mathrm{N}}$
i	current	A
J_{total}	total inertia	$\mathrm{kg}\cdot\mathrm{m}^2$
k_t	torque constant	$\frac{\mathrm{Nm}}{\mathrm{A}}$
L	inductance	H
m	reduced piston mass	kg
M	torque	Nm
p	pressure	$\frac{\mathrm{N}}{\mathrm{m}^2}$
R	resistance	Ω
u	voltage	V
V	pump displacement	m^3
Z_p	number of pair of poles	–
ω	angular speed	$\frac{\mathrm{rad}}{\mathrm{sec}}$

indices	
$()_d$	d-axis
$()_q$	q-axis
$()_{el}$	electrical
$()_{fric}$	friction
$()_{hyd}$	hydraulic
$()_{load}$	load
$()_{mech}$	mechanical
$()_{mi}$	air gap
$()_p$	pump
$()_{th}$	theoretical

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