MAIN LANDING GEAR OPERATION POWERED BY MULTIFUNCTIONAL HIGH-LIFT PCUs

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Abstract

For conventional aircraft, the high-lift and main landing gear systems are hydraulic/electric consumers with high power demands. The paper shows how the supply systems of these can be combined to save system weight and cost for future more electric aircraft. This is made possible by multifunctional hybrid PCUs (MHPCUs), which can be used as electric motor pumps in addition to the conventional high-lift motor mode. A proposal for the architecture of this concrete center system as well as for the hydraulic drive train of the MHPCU is given. In the second part, the operating strategies and their control concepts are described. This is relevant for the main landing gear operation and the power transfer between the MHPCUs in the event of a failure. By means of system simulation, the operating strategies are tested and basic requirements are verified.

Keywords

Multifunctional Hybrid PCU (MHPCU); Hydraulic Power Generation; Main Landing Gear Operation, Decentralized Systems, Weight Reduction, Control Strategies, Simulation

1. INTRODUCTION

In conventional aircraft systems, most of the power to actuate the actuators is provided by central hydraulic architectures. These are usually supplied by engine-driven pumps (EDPs). According to latest research projects, the trend is towards increasing electrification of engines and overall system architecture. For this purpose, the EDP and also increasingly the hydraulic pipelines are to be eliminated. The actuators are then supplied by centralized or decentralized electrohydraulic systems or they are designed as electro-hydrostatic actuators (EHA) and electromechanical actuators (EMA). EHAs and EMAs, as well as decentralized or zonal electrohydraulic systems, have the advantage of reduced installation effort due to higher pre-integration. In addition, the pipe network is reduced and maintenance work is simplified. In the context of this paper, the focus is on the center zone of the aircraft where actuators with high loads are located and hydraulic actuation still seems very advantageous. This includes the main landing gear (MLG) system with left and right landing gear legs and doors as well as the high-lift system consisting of flaps and slats, each with a central drive unit, the power control unit (PCU). This set of consumers represents the system boundary for the following studies.

Different system concept proposals can be found in the literature for this zone. As part of the THERMAE II research project [1], the use of EHAs for the main landing gear actuation was investigated and demonstrated. For redundancy reasons, two electric motor pumps (EMPs)

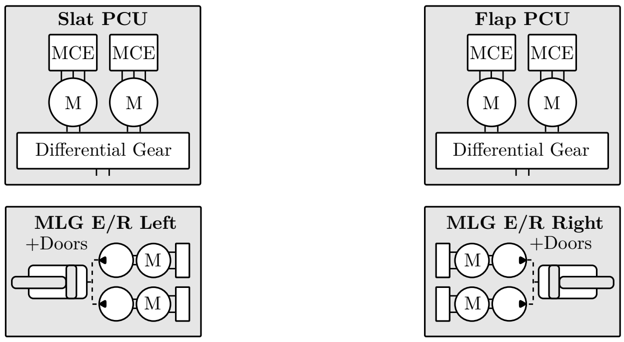

FIG 1. MLG EHA concept for center system

are integrated in each of the two extension/retraction actuators. While the studies only consider the main landing gear system, this architecture is particular advantageous when both PCUs are driven purely electrically, eliminating the need for a hydraulic system (figure 1). Accordingly, eight electric drives (motor + motor control electronics (MCE)) and four pumps are required for the actuation functions in the center, leading to relatively high system weight.

In the context that both high-lift and landing gear systems are only operated for a short time at the beginning and end of a flight, it seems reasonable to combine the electric drives located in close proximity for weight reasons. This approach is discussed in [2]. Here, a hydraulic power pack (HPP) with two redundant EMPs supplies the two landing gear actuators and optionally a hydraulic motor of the respective PCU (figure 2). The center

doi: 10.25967/550095

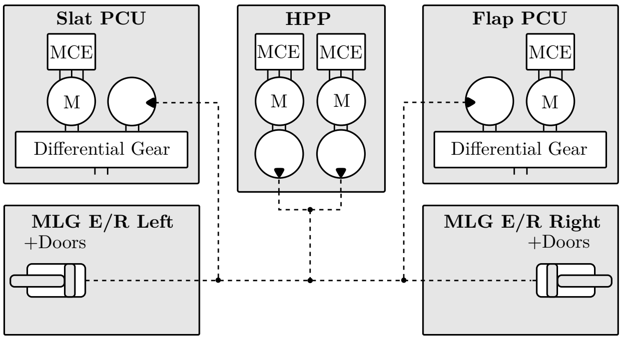

FIG 2. HPP concept for center system

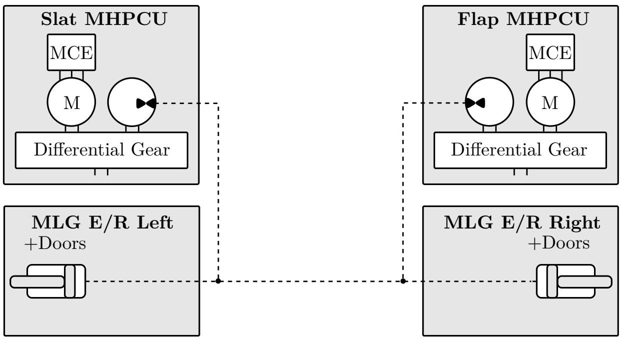

FIG 3. MHPCU concept for center system

system based on the HPP thus comprises four electric drives and four pumps. Compared to the EHA-based system, this appears to have achieved better utilization of the drives. Nevertheless, the HPP still has a high weight.

A hybrid PCU as in the system shown can theoretically also be used as an EMP [3]. For this purpose, the output of the differential gear is blocked so that the hydraulic motor can be driven by the electric motor to generate hydraulic power (pump mode). The question arises whether these multifunctional hybrid PCUs (MHPCUs) could be used to eliminate the HPP in order to save further system weight. The corresponding concept proposal is shown in figure 3. To extend and retract the landing gear, both MHPCUs are operated in pump mode. In the nominal case, the high-lift operation must then be performed by the electric motors only. Should one of the electric drives fail, power can be transferred via the hydraulic system by means of the other PCU. This active-passive operation thus differs from the conventional active-active operation traditionally used by Airbus. Initial analyses have shown that the center system based on the MHPCUs, which comprises only two electric and two hydraulic machines, could save up to 25% weight relative to the HPP-based supply system while having similar system reliability [4].

In the following, the question of whether the MHPCU-based center system is technically feasible and what a possible system architecture could look like is to be answered. Operating strategies are proposed and simulation-based tests are performed.

2. SYSTEM DESIGN

The new functionality of the PCU significantly influences the design of the center system. The motor/pump type of the hydraulic machine is a key design aspect. While conventional PCUs such as of the Airbus A320 are based on fixed displacement hydraulic machines (FDHM), the variable displacement hydraulic machine (VDHM) technology is used in newer, larger aircraft models such as the A350. In the following, both technologies are therefore evaluated and compared with regard to their use in the MHPCU-based center system.

2.1. FDHM vs. VDHM

The hydraulic machine of the MHPCU should meet some essential requirements for the motor mode that are state of the art. These include

- the isolation during non-operation phases,
- the bi-directional rotation for the extension and retraction of the high-lift devices,
- the absorption of hydraulic power caused by aiding loads during retraction, and
- closed loop motor speed control.

In addition, there is an essential requirement for pump mode: low pressure drop across both the low-pressure and high-pressure ports.

Figure 4 compares two concepts based on an FDHM and a VDHM that meet the requirements mentioned. In the FDHM, the direction of rotation in motor mode is reversed by a switching valve. The low-pressure side is equipped with a counterbalance valve, which generates a backpressure during high-lift mode with aiding loads. This prevents the motor from accelerating to uncontrollable speeds. It also ensures that a minimum pressure is built up at the high-pressure port, which ensures that the reservoir and thus the suction pressure are sufficiently pressurized. An additional pilot pressure line from the high-pressure port to the counterbalance valve prevents the pressure from exceeding values at maximum opposing loads that would require the hydraulic machine to be redesigned. A check valve parallel to the counterbalance valve enables free flow in pump mode. Speed control in motor mode can be realized by the respective pump.

The direction of rotation and speed of the concept based on a VDHM can be controlled via the swash plate which can be swiveled over center (four quadrants). Therefore, only an enable valve is required on the high-pressure side. In contrast to the previous concept, excess power can be transferred to the high-pressure side. Should the pressure exceeds the limit in this case, the pressure relief valve opens.

In principle, both concepts are suitable for use in an MHPCU. The individual advantages and disadvantages are listed in table 1. The advantages of the FDHM are mainly in the areas of complexity, mass, reliability and cost. The larger number of components for the

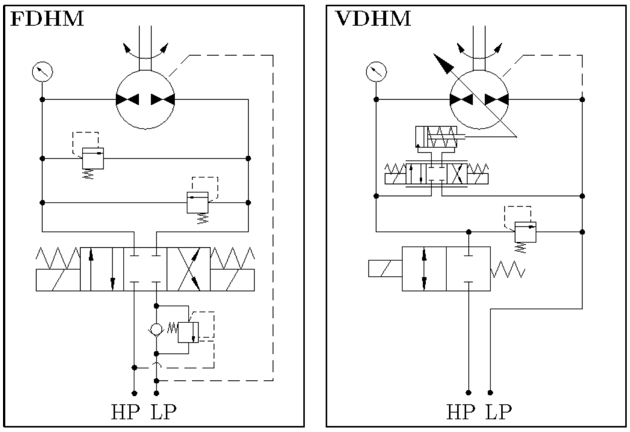

FIG 4. FDHM vs VDHM based hydraulic maschine

TAB 1. Comparison of FDHM and VDHM

Parameter	FDHM	VDHM
Complexity	+ No control elements	– Displacement control
Mass	+ Less Components	– More Components
Efficiency	– Higher losses	+ Lower losses
Performance	– Lower dynamic	+ Higher dynamic
Reliability	+ More robust	– More failure sources
Cost	+ Simple components	– Servo actuator
Features	– No simultaneous slat/flap operation for loss of one eletric motor	+ Simultaneous slat/flap operation despite loss of one electric motor

VDHM swash plate control mechanism results in increased weight and increases the number of potential failure sources. In addition, costs are expected to be higher due to the servo actuator and its related requirements. However, the VDHM does bring some advantages. For example, hydraulic losses are lower because no additional resistance is required for the aiding loads phase. Also, the flow path on the LP-side is free of valves, so there is less risk of cavitation in pump mode.

Another advantage of VDHM is the expected higher dynamics. While this is limited with the FDHM by the maximum torque and the relatively large inertias of the electric motor and the gearbox, control deviations can be compensated quickly with the aid of swash plate of the VDHM. The additional degree of freedom (speed control + swash plate control) opens up a feature that an FDHM-based concept does not allow. In case of loss of an electric motor, it is theoretically possible to continue to move slats and flaps simultaneously in a controlled manner. Since this is also possible in conventional systems, this could be a decisive criterion for the choice between FDHM and VDHM. However, it needs to be verified how simultaneous operation affects the total actuation time. If this takes longer than sequential operation, it would not be advantageous. This analysis is performed in the following.

Simultaneous Slat/Flap Operation

Figure 5 shows how simultaneous operation of slats and flaps is possible in case of failure of the flap MHPCU electric motor. The speed ratio of the input and output of the slat MHPCU is calculated using the equation

$$n_{\text{TM,Slat}} = \frac{1}{2 \cdot i_{\text{G}}} \cdot (n_{\text{EM,Slat}} + n_{\text{HM,Slat}}) \tag{1}$$

with i_{G} the gear ratio prior to the differential gear [5]. The corresponding torque at the output is calculated as

$$M_{\text{TM,Slat}} = i_{\text{G}} \cdot (M_{\text{EM,Slat}} + M_{\text{HM,Slat}}), \tag{2}$$

where in general $M_{\text{EM,Slat}} = M_{\text{HM,Slat}}$ assuming ideal gear box without losses. The torque/speed ratios of the flap MHPCU behave analogously. Via the two VDHMs, mechanical power of the slat MHPCU is converted to hydraulic power and converted back to mechanical power in the flap MHPCU. This hydraulic transmission can be described in simplified terms and by neglecting losses with the transmission ratio i_{H}. Consequently, the speeds and torques at the hydraulic machines are as follows

$$n_{\text{HM,Slat}} = -i_{\text{H}} \cdot n_{\text{HM,Flap}}, \tag{3}$$

$$M_{\text{HM,Slat}} = \frac{1}{i_{\text{H}}} \cdot M_{\text{HM,Flap}}. \tag{4}$$

Simultaneous operation of slats and flaps in the considered failure case is characterized by equalization of the speeds (except for the speed reduction when approaching the target position). With the help of the equation

$$n_{\text{TM}} = n_{\text{TM,Slat}} = n_{\text{TM,Flap}} \tag{5}$$

and equations 1 to 4 the following relationship between output speed (transmission shaft) and input speed of electric motor of slat MHPCU can be found

$$n_{\text{TM}} = n_{\text{EM,Slat}} \cdot \frac{1}{2 \cdot i_{\text{G}}} \cdot \frac{1}{1 + \frac{M_{\text{TM,Flap}}}{M_{\text{TM,Slat}}}}. \tag{6}$$

As expected, the desired transmission speed is proportional to the speed of the electric motor. However, a decisive factor is the load ratio $\frac{M_{\text{TM,Flap}}}{M_{\text{TM,Slat}}}$. If the load torque of the flaps is greater than that of the slats, the maximum possible speed of both outputs drops below half of what can be achieved by sequential operation. The result would be a longer actuation time than driving flaps and slats sequentially. This uncertainty is not acceptable for the safety-critical high-lift system. Thus, this expected

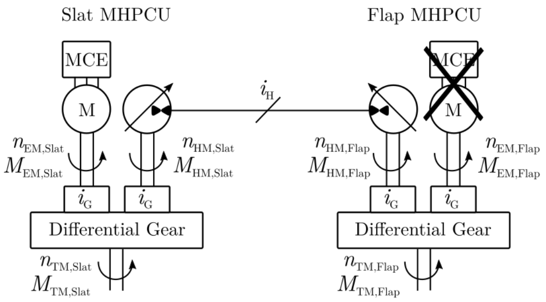

FIG 5. Simultaneous slat/flap operation via VDHM power transfer for loss of flap electric motor

feature of the VDHM-based concept is not a decisive advantage over the FDHM-based concept.
Against this background, a solution based on FDHM appears more advantageous. The lower dynamics play a less significant role in a zonal system without parallel consumers than in conventional central constant-pressure systems. The fact that the high-lift and landing gear systems are only actuated for a short time during a flight mission means that the higher hydraulic losses are not significant.

2.2. Overall System

Figure 6 shows a proposal for the design of the center system based on FDHM. The (simplified) architecture of the consumers is based on a typical short/medium range aircraft. This includes the landing gear actuation system with the door actuators as well as the retraction actuators. They are each activated by a selector valve (DSV and GSV). The differential cylinders generate large delta volumes that have to be stored in an appropriate reservoir. A bootstrap reservoir is recommended for this purpose, since a certain tank pressure can be ensured without having to provide external compressed air supply. Important for the implementation of the multifunctional system is the connection of the return filter into the reservoir. A check-valve arrangement prevents the filter from being passed through in both directions via the low-pressure line of the MHPCUs.

The MHPCU is composed of a permament magnet synchronous motor and the FDHM, which are coupled to a speed-summing differential gear. Both machines can each be passivated via a power-off brake (POB). Typically, the brake of the hydraulic drive is hydraulically actuated. However, since the MHPCU-based center system does not have an external hydraulic supply, it could not be released in pump mode. Therefore, an electrically operated ePOB is recommended for both drive sides.

The gearbox output of the respective MHPCU drives a transmission shaft that is routed into both halves of the wing to provide mechanical power to the high-lift system actuators. Conventional wing tip brakes (WTB) lock the entire transmission shaft once a failure is identified that results in asymmetric retraction or extension. This pre-

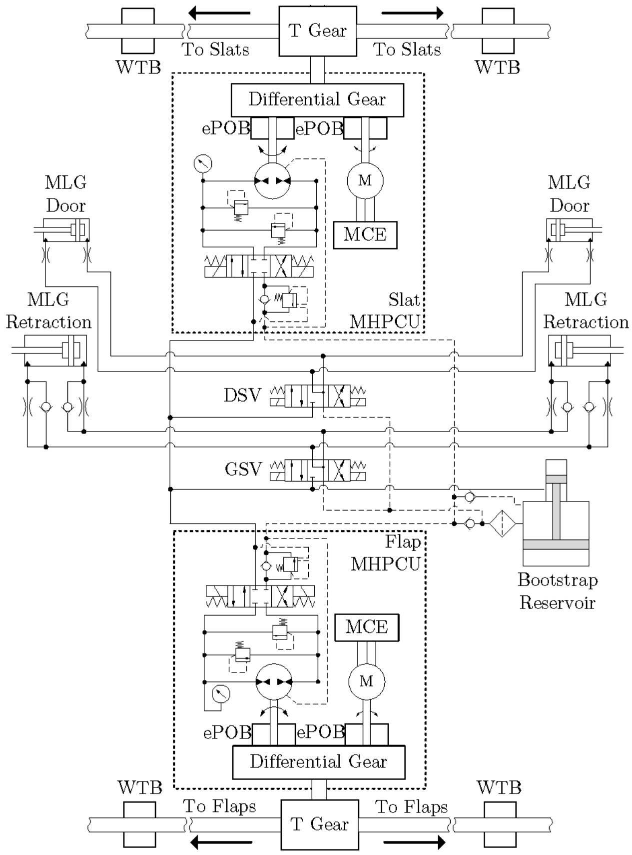

FIG 6. MHPCU center system schematic

vents rolling moments that can no longer be compensated by the primary flight control system. The WTBs could also be used to block the gearbox output for the new pump mode of the MHPCU while holding the slats and flaps in position. The direction of pump operation should be chosen in a way that the air loads oppose the pump torque to reduce the load on the WTBs. Alternatively, the MHPCU have to be equipped with an additional brake at the output shaft.

2.3. MHPCU Sizing

The MHPCU system is based on the HPP-based center system discussed in the literature [2] , which has already been pre-designed in system design studies. Therefore, only a redesign of the system components that have to be modified for a realization of the MHPCU system is performed. This essentially applies to the electric motor of the MHPCU. It is assumed that the gear ratios, and thus also the size of the hydraulic motor remain unchanged compared to the reference system. The design assumptions (based on typical narrow-body aircraft) are listed in table 2.

Design Speed

Since the MHPCU is to be operated in active-passive mode instead of active-active mode, the electric motor must drive the flaps/slats on its own in the nominal case. This requires an increased speed for the high-lift mode

TAB 2. Design parameter assumptions

Description	Symbol	Value
Supply pressure	p_V	200 bar
Transmission shaft speed	n_TM	400 rpm
Gear ratio (one-motor operation)	i_G	16
Efficiencies (generalized)	η_xx	0.9
Hydraulic machine size	V_HM	5.3 $\frac{\mathsf{cm}^3}{\mathsf{rev}}$
MLG flow demand	Q_HFW	70 lpm

of

$$n_{\mathsf{EM,HL,erf}} = n_{\mathsf{TM,nom}} \cdot i_\mathsf{G} \approx 6400\,\mathrm{rpm}. \tag{7}$$

For the landing gear mode, the required speed results from the given flow demand:

$$n_{\mathsf{EM,MLG,erf}} = \frac{1}{2} \cdot \frac{Q_\mathsf{HFW}}{\eta_\mathsf{vol} \cdot V_\mathsf{HM}} \approx 7300\,\mathrm{rpm}. \tag{8}$$

According to [5], the maximum speed of the PCU drives of a typical narrow-body aircraft such as the Airbus A320 is about 4300 rpm. Accordingly, the speed of the electric motor of the MHPCU must be increased by about 70 % to 7300 rpm to achieve the same actuation times. Since such PCU speed levels are common (compare A310/A330: 6000 rpm to 7000 rpm [6]), implementation seems technically possible.

Design Torque

The required torque of the electric motor in high-lift operation of a conventional PCU corresponds to that of the hydraulic motor. For the MHPCU this means

$$M_{\mathsf{EM,HL,erf}} = \frac{V_\mathsf{HM} \cdot \Delta p_\mathsf{V} \cdot \eta_\mathsf{hm}}{2 \cdot \pi} \approx 15.4\,\mathrm{Nm}. \tag{9}$$

Due to the power and efficiency inversion during landing gear operation of the MHPCU, the required torque of the electric motor increases to

$$M_{\mathsf{EM,HFW,erf}} = \frac{V_\mathsf{HM} \cdot \Delta p_\mathsf{V}}{2 \cdot \pi \cdot \eta_\mathsf{hm} \cdot \eta_\mathsf{G}} \approx 21.1\,\mathrm{Nm}. \tag{10}$$

Accordingly, the design torque of the electric drive must be increased by about 37 % compared to the reference system. In view of the fact that the increased torque only occurs in the pump mode, where the high-lift system is passivated, and that the pump loads act against the air loads, a redesign of the mechanical components of gearbox and transmission might not be necessary. However, further analyses are needed for a final evaluation.

3. OPERATION STRATEGY

Depending on the mode and degradation level, different operating strategies are necessary. The following sections describe a concept for landing gear operation and for the (degraded) high-lift mode after the loss of one electric motor.

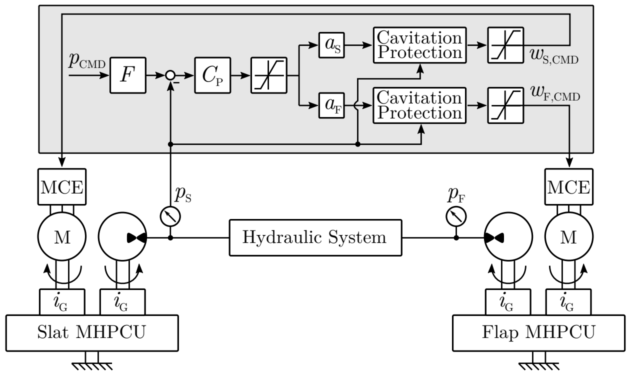

FIG 7. MHPCU pressure controller

3.1. Main Landing Gear Operation

The considered center system assumes a conventional landing gear actuation architecture. This is typically supplied with constant pressure of 3000 psi (207 bar). Therefore, the MHPCU system shall be able to provide constant pressure for the landing gear mode. There are considerable publications on this topic for the HPP-based center system, which, like the MHPCU system, also relies on two redundant variable-speed pumps [7], [8], [9]. The focus in this paper is therefore on the special characteristics of the MHCPU system. These include, in particular, the increased inertia due to the gearbox and the question of the need for a hydraulic accumulator. In addition, special attention is paid to the suction pressure of the hydraulic machine, as the MHPCU is exposed to an increased risk of cavitation.

A suitable control structure for dual pump operation according to [9] is shown in figure 7. A central controller C_P receives the pressure signal from one of the two MHPCUs. This prevents possible instabilities or non-uniform power distributions ($\alpha_\mathsf{F} = \alpha_\mathsf{S} = 0.5$). The controller is of type PI whose gains were determined using loop shaping techniques.

In addition, a cavitation protection is implemented in the control structure. Unlike the EMPs of an HPP, the hydraulic machine does not have an additional impeller or boost pump due to the bidirectionality. Also, the slat and flap MHPCU are located separately, so longer suction lines to the common reservoir must be installed. Both increase the risk of damaging cavitation. The protection limits the positive acceleration of the electric motor depending on the system pressure (figure 8). This prevents high accelerations from causing critical pressure drops due to the inertia of the fluid, especially during startup, where system and suction pressure are low.

In general, requirements for pressure control can be found in SAE AS 595 [10]. However, studies on the HPP-based center system have already shown that especially the response time requirement is difficult to meet by means of variable-speed pressure control [7].

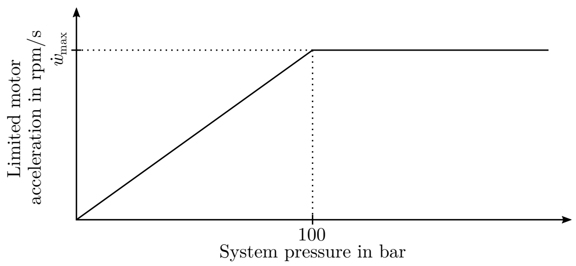

FIG 8. Cavitation protection

TAB 3. Considered requirements for MLG operation

Description	Symbol	Value
Max. transient pressure	p_{max}	257.5 bar
Max. nominal ret. time	$t_{ret,max}$	10 s
Max. nominal ext. time	$t_{ext,max}$	13 s

With the MHPCU system it is even more challenging due to the additional gear inertia. However, this requirement was initially defined for centralized systems with multiple parallel consumers such as flight control actuators. It is questionable whether a single landing gear system has to meet these high requirements at all, especially for the response time. In the following, therefore, only the requirement from SAE AS 595 for the maximum transient pressure in the target system is tracked. In addition to that, the assessment of actuation times of the landing gear [11] is carried out. Both requirements are listed in table 3.

The requirements are verified by means of non-linear simulation. For this purpose, a dynamic model has been developed in the AMESim simulation environment. The model represents the system layout according to figure 6. Parameters and external loads are based on a typical narrow-body aircraft such as the Airbus A320. Figure 9 shows a representative retraction and extension cycle of the main landing gear. From the actuator positions, a smooth operation can be observed. The retraction and extension times (door opening, gear up/down, door closing) with a total of 10 s and 13 s, respectively, are within the requirements. The graph of the system pressure shows many overshoots and transient pressure drops. This is due to the fact that no hydraulic accumulator was used, so that the system has a high degree of stiffness. However, since all pressure peaks are below the allowed limit, an accumulator seems to be not necessary with respect to these requirements. It could have an impact on the life cycle though. During the retraction process, it can also be seen that the target pressure of 206 bar cannot be maintained. This is because the required flow rate used for speed sizing was derived from the retraction time without considering the restictors of the MLG system. An increase in the pump flow rate would result in the 200 bar being controlled. However, since the actuation times are maintained, this is not essential.

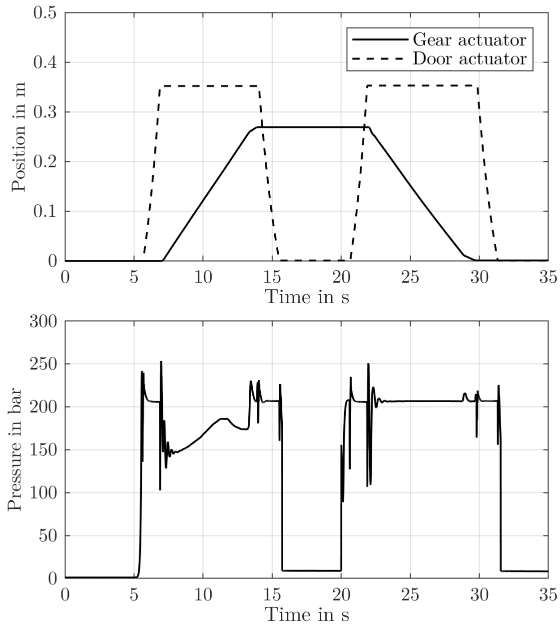

FIG 9. Main landing gear operation

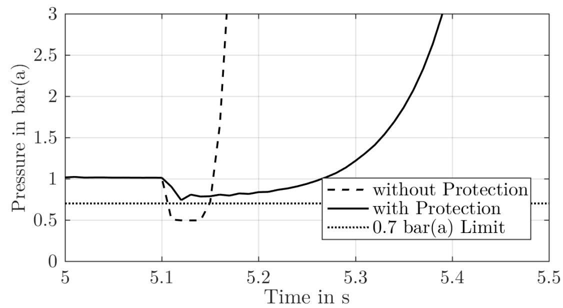

FIG 10. Flap MHPCU suction pressure

In figure 10 the effect of the cavitation protection is visible. The suction pressure of the flap MHPCU at the time of pump start-up is shown. Without limiting the acceleration of the electric motor at low system pressures, the hydraulic inductance leads to a critical pressure drop. The protection lets the pressure not fall below the minimum allowed pressure of 0.7 bar [12].

3.2. Degraded High-Lift Operation

While PCU motors of older aircraft families such as those of the Airbus A320 or A330 are typically resistance-controlled, the A380/A350 ones are speed-controlled by means of VDHMs. Speed-controlled, load-independent extension and retraction is thus state-of-the-art and shall be the basis for the MHPCU system. In nominal mode, speed control is performed by the respective electric motor while the hydraulic machine is passivated. The A380/A350 Slat PCUs are already operated in this mode when the hydraulic drive is lost. Therefore the focus at this point is only on degraded operation (loss of one electric drive) of the MHPCU system. In this case, power is transferred to the degraded MHPCU

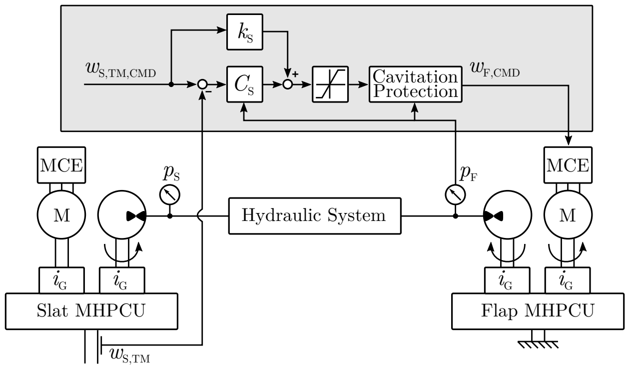

FIG 11. MHPCU speed controller

via the hydraulic system by means of the intact MHPCU.

A proposal for a corresponding control structure in the degraded mode is given in figure 11. This consists of a feedforward gain k_S and a controller C_S. The feedforward gain takes into account the mechanical gear ratio i_G between the electric motor of the intact MHPCU and the hydraulic machine of the degraded MHPCU. The control deviation caused mainly by internal leakage of the hydraulic machines is compensated by the controller. Here, a cavitation protection is to prevent critical suction pressure drops, too.

The control gains are determined by classical loop shaping methods according to reference tracking with the help of the sisotool of Matlab. For this purpose, first a frequency response between plant input and plant output has been performed using the non-linear simulation model in order to characterize the plant P_S (figure 12). Up to the frequency bandwidth of about 62 rad/s, the magnitude is between -25 dB and -28 dB. This is primarily due to the gear ratio i_G and additionally to the volumetric losses of the hydraulic machines. The bandwidth is mainly affected by the hydraulic capacity of the system. Since the MHPCU system does not require an accumulator, the capacity is very low and thus relatively high dynamics can be achieved.

The Bode diagram also shows the open loop transfer function $L_S = C_S \cdot P_S$ resulting from loop shaping and the closed loop transfer function $T_S = \frac{L_S}{1+L_S}$. The controller applied is a single integrator with a resulting crossover frequency of about 1 Hz (6.28 rad/s). Particular importance was given to high stability margins (gain margin 20 dB, phase margin 80°). The combination of a single integrator with high stability margins leads to a very cautious controller with the aim of obtaining a smooth controlled speed. This is at the cost of the bandwidth of the control, which is why the perfomance needs to be tested.

The performance of speed reference tracking is verified by a typical speed command profile (figure 13). Basically, this is divided into an acceleration phase, a phase with constant maximum speed, and gradual deceleration when approaching the target position. It is shown that

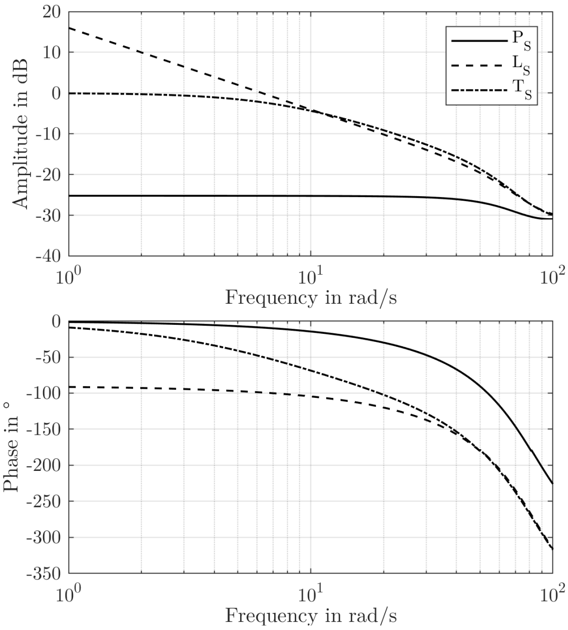

FIG 12. Bode diagram of open and closed loop transfer functions

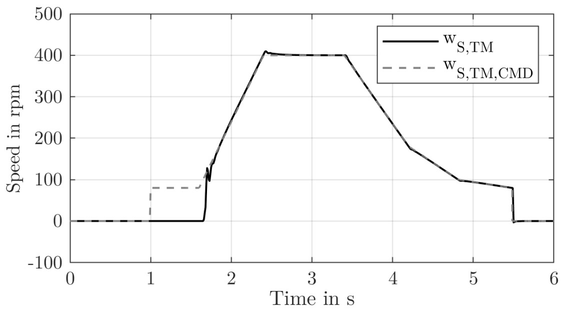

FIG 13. Speed reference tracking performance

with the cautious controller, very good reference tracking can be achieved without large overshoots. Particular attention is paid to the start-up phase between 1 s and 1.7 s. Direct start-up from standstill is not possible here, since a minimum pressure must first be built up in the hydraulic system to open the counterbalance valve und to overcome loads acting on the hydraulic motor of the degraded MHPCU. The following startup sequence has proven successful for this purpose:

1) activate flap MHPCU EMP mode,
2) enable slat MHPCU selector valve,
3) pressurize system in open-loop low speed control (integrator disabled),
4) release slat MHPCU POB at minimum pressure of 100 bar,
5) enable closed loop controller.

Due to the initial pressure build-up, the operating time increases slightly compared to conventional operation. It must be checked whether the specified requirements (table 4) are still met.

TAB 4. Considered requirements for High-Lift operation

Description	Symbol	Value
Max. transient pressure	p_{max}	257.5 bar
Max. nominal op. time	$t_{\text{nom,max}}$	24 s [13]
Max. degraded op. time	$t_{\text{deg,max}}$	48 s

The simulation model of the system is also used here to verify the requirements. A typical profile is simulated according to the following sequence:

1) extend flaps/slats on ground without loads,
2) retract flaps/slat after takeoff with maximum aiding loads,
3) extend flaps/slats before landing with maximum opposing loads.

Here, the loss of the slat MHPCU electric motor is simulated to test the mode of power transfer between the MHPCUs. Figure 14 shows the simulation results. As in the nominal case, the flaps are operated directly by the associated electric motor. The degraded operation is characterized by the fact that the movement of the flaps and slats is sequential. Once the flaps have reached the desired position, power is transferred to the degraded MHPCU. The position and velocity profile of both transmission shafts is very similar. The total travel time (flaps + slats) of nearly 44 s for each phase is within the requirement.

Due to the control concept presented, the flow rate characteristic of the flap MHPCU corresponds to the velocity profile of the slats. Thanks to the counterbalance valve, the system pressure is kept relatively constant despite the different load situations of the three operating sequences. This ensures sufficient tank pressure and prevents uncontrolled acceleration under aiding loads. Pressure surges do not occur in high-lift operation, so this requirement is also met.

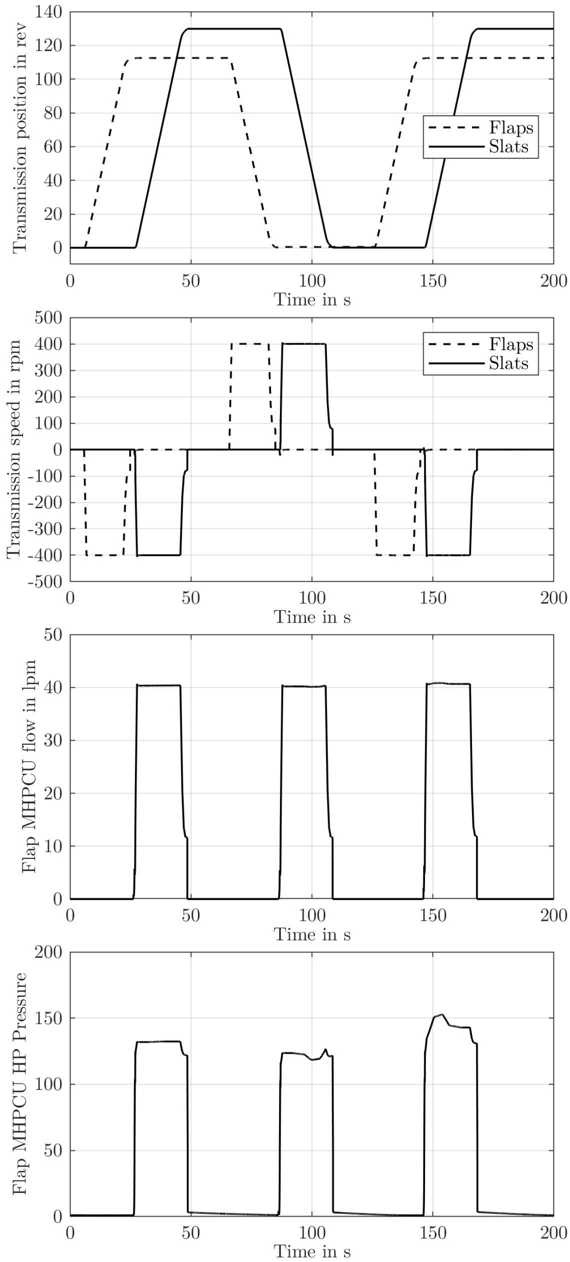

FIG 14. High-lift operation

4. CONCLUSIONS AND OUTLOOK

In this paper a new concept for power supply of main landing gear and high-lift system was proposed. Instead of using EHAs or an HPP the main landing gear is operated by multifunctional hybrid PCUs. In the first section, the design of this MHPCU center system was addressed. The focus was on the characteristics of the bidirectional system as well as the question regarding the type of hydraulic machine. It has been found that the advantages of an FDHM- over a VDHM-based MHPCU outweigh the disadvantages for this specific system.

In the second part, strategies for landing gear operation and high-lift operation were presented. For the first one, a constant pressure control based on [9] was implemented. Due to the principle-related increased risk of cavitation of the MHPCUs, a corresponding protection function was added. Through simulation, it was shown that the system can be operated without an accumulator. This had a beneficial effect on the high-lift mode. Here, a control concept for the power transfer from an intact MHPCU to a degraded unit was presented and designed using loop shaping. It was shown by simulation that speed control can also be implemented well using FDHMs. A counterbalance valve integrated into the MHPCU prevents uncontrolled movement in the case of aiding loads and ensures sufficient tank pressure.

So far, the concept analyses for the MHPCU center system have been carried out virtually. In the next steps, these are to be extended by initial hardware tests. For this purpose, an MHPCU demonstrator is being built at the TUHH Institute of Aircraft Systems Engineering on the basis of an original PCU (figure 15). The conven-

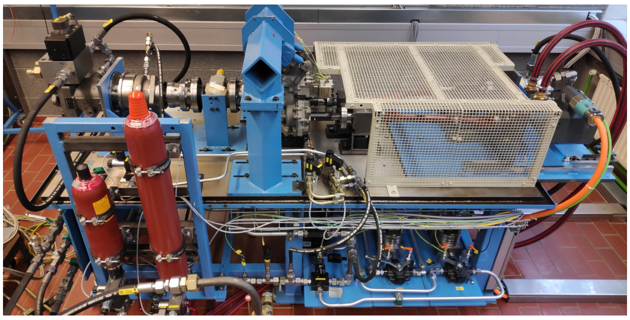

FIG 15. MHPCU concept demonstrator

tional drives are replaced by industrial components (electric motor and pump). The focus of further investigations is the new EMP mode of the MHPCU. In addition to early performance validation, the test bench also offers the possibility to perform hybrid tests. In this context, the MHPCU demonstrator can be integrated into any virtual system to test control concepts at system level.

Acknowledgement

The authors would like to thank the department of High-Lift and Hydraulic Systems of Airbus for their support and cooperation within pre-studies to this topic.

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References

[1] Nick Elliot, Stephen Linforth, and Callum Moore. Thermae ii (main landing gear & door eh actuation system) integration and testing. In *Recent Advances in Aerospace Actuation Systems and Components, March 16-18, 2016, Toulouse, France*, 2016.

[2] Nils Trochelmann, Frank Thielecke, Robert. M. Behr, and Martin Hamm. Electro-hydraulic system architectures for mea – comparison of central and zonal power packages. In *Recent Advances in Aerospace Actuation Systems and Components, May 30 - June 1, 2018, Toulouse, France*, 2018.

[3] Andreas Fleddermann and Mark Heintjes. Method for Generating Hydraulic Power in an Aircraft, use of a Hybrid Power Control Unit and Drive System. Patent EP 2690007B1, Airbus Operations GmbH, 2016.

[4] Lennard Nordmann, Frank Thielecke, Peter Luecken, and Martin Hamm. Concept studies on a multifunctional unit for hydraulic supply and high lift actuation in aircraft. In *ASME/BATH 2019 Symposium on Fluid Power and Motion Control (FPMC2019)*, 2019.

[5] Gerhard Geerling. *Entwicklung und Untersuchung neuer Konzepte elektrohydraulischer Antriebe von Flugzeug-Landeklappensystemen*. PhD thesis, TUHH, 2002. VDI Fortschritt-Berichte Reihe 12 Nr. 538 Duesseldorf: VDI ISBN: 3-18-353812-1.

[6] SAE International (Publ.). *Aerospace Information Report AIR5005A - Commercial Aircraft Hydraulic Systems*, 2015.

[7] Nils Trochelmann, Phillip Bischof, Frank Thielecke, Dirk Metzler, and Stefan Bassett. A robust pressure controller for a variable speed ac motor pump – application to aircraft hydraulic power packages. In *Bath/ASME 2018 Symposium on Fluid Power and Motion Control (FPMC)*, 2018.

[8] Nils Trochelmann, Frank Thielecke, Dirk Metzler, Marcelo Duval, and Ingrid Kirchmann. Thermal-dynamic investigation of advanced system control strategies for decentralized electro-hydraulic power generation in more electric aircraft. In *Aerospace Europe Conference (AEC), Feb. 25 - 27, 2020, Bordeaux, France*, 2020.

[9] Nils Trochelmann and Frank Thielecke. Control Strategies for a Dual AC Motor Pump System in Aircraft Hydraulic Power Packages. In *The 17th Scandinavian International Conference on Fluid Power, SICFP'21, May 31- June 2, 2021, Linköping, Sweden*, 2021.

[10] SAE International (Publ.). *Aerospace Standard 595 - Pressure compensated variable displacement aircraft pumps - Revision D*, 2010.

[11] Dennis Doberstein. *Modellbasierter Entwurf und experimentelle Validierung von elektro-mechanischen Betaetigungsfunktionen fuer ein Bugfahrwerksystem*. Dissertation, Technische Universitaet Hamburg, February 2016. Schriftenreihe Flugzeug-Systemtechnik.

[12] Lennard Nordmann, Frank Thielecke, Peter Luecken, and Martin Hamm. Virtual testing of aircraft hydraulic systems. In *Recent Advances in Aerospace Actuation Systems and Components, May 30 - June 1, 2018, Toulouse, France*, 2018.

[13] Malte Pfennig. *Methodik zum wissensbasierten Entwurf der Antriebssysteme von Hochauftriebssystemen*. PhD thesis, TUHH, 2012.