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# DEVELOPMENT OF A HIGH EFFICIENT HYDRAULIC POWER PACK

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## Abstract

As a first-tier supplier, Liebherr-Aerospace faces the ever-growing challenge to provide the different airframers with competitive products within a highly competitive and agile business environment. Costs, time-to-market, product maturity, and ramp-up capabilities are driving factors for technology selection. Environmental aspects play a growing role and must also be taken into consideration by airframers and suppliers, since they are key criteria for success and customer satisfaction.

The electrification of aircraft contributes to the goal of greener air transportation. Several solutions must be developed on system-level to give airframers the required technologies for turning the “more electric aircraft” into reality.

Liebherr proposes a highly efficient solution for decentralized hydraulic power generation. It provides the airframes the flexibility to place the hydraulic power pack close to the consumers and eliminating long pipe sections between power generation and consumers. Two sizes of highly efficient power packs were designed; one for large power demand, typically applied for main landing gear retraction/extension, and one mid-sized pack for primary flight controls consumers placed in the aircraft tail (rudder and elevators). The system works solely on electric power, and thus is an important brick for the electrification of future aircraft.

This paper summarizes Liebherr-Aerospace’s R&T activities funded under the European Clean Sky 2 program for developing and maturing required next-generation hydraulic power pack technology bricks. The activities were combined within the SmartHePP project, which was launched in October 2017 and concluded in December 2021. It was a joint undertaking between Liebherr and partners from industry and academia. The technology bricks matured in SmartHePP now allows Liebherr to bring innovative solutions for de-centralized hydraulic power supply in next-generation aircraft to our customers facilitating more/all-electrical aircraft architectures for greener aviation.

**Keywords:** power pack; hydraulic power; motor pump, more electrical aircraft, all electrical aircraft, decentralized power, aircraft power systems, aircraft power supply

## 1. Introduction

The electrification of aircraft contributes to the goal of greener air transportation. Several solutions must be developed on system-level to give airframers the required technologies for turning the “more electric aircraft” into reality. Highly integrated electro-hydraulic power packages (HEPPs) with electric motor-driven pumps (EMPs) are a key enabler for electrification of future aircraft platforms.

The SAE AIR5005 [10] provides information on hydraulic systems fitted into many in-service commercial aircraft, including the number of independent hydraulic systems, and the number and type of the power sources. According to SAE ARP4752B [11], in configurations where the aircraft's hydraulic system supplies all the primary and secondary flight controls without manual backup, a minimum of three hydraulic systems is required to achieve the required level of redundancy and compliance with requirements of 14 CFR Part 25/CS 25.671 and 25.1309. The use of electro hydrostatic actuators (EHAs) or electro-mechanical actuators (EMAs) to supply primary and/or secondary flight controls opens the opportunity to reduce the number of independent hydraulic systems. This approach is reliant on having sufficient redundancy within the electrical power generation system such that the probability of failures of electrical and hydraulic systems that could result in the total loss of flight controls is less than 1 x 10-9/flight hour [11].

A main advantage of electrified aircraft systems is an optimized use of power generation enabled by an overall and flexible electric power management [1]. Additionally, an easier fault isolation and reconfiguration of power paths can be achieved in architectures with full electric distribution system [2]. Further, The electrification of aircraft systems tends to improve dispatch reliability of the aircraft as the number of hydraulic lines and connections and thus potential leakage sources are reduced.

In a traditional aircraft architecture, the flight controls, brakes, landing gear and thrust reverses systems are powered by hydraulic systems. In recent aircraft platforms, alternative solutions to hydraulic actuation are readily available for brakes and thrust reversers systems, using electrical and pneumatic actuation. For flight controls and landing gear systems, three main candidates for enabling the more electric aircraft initiative are the EMA, EHA and HEPP combined with hydraulic servocontrolled actuators (HSCA).

As stated by Trochelman et al. [8], both EMA and EHA concepts still come along with major challenges and specific drawbacks. EHAs are already in use to power primary flight controls in platforms like Airbus A350 and A380, but they are operated in stand-by mode and only become active in the event of a failure in the frontline conventional hydraulic system [4]. That being said, the de-centralization of the hydraulic power generation can be seen as an intermediate step between the traditional and future all-electric aircraft architectures. The strategy of installing tailored highly efficient power pack (HEPP) close to the consumers becomes attractive due to the combination of proven and mature method of hydraulic actuation with the flexibility of the more-electric aircraft approach. On top of that, the HEPP allows flexibility to planning the aircraft assembly once long hydraulic lines along the fuselage are eliminated. Another significant benefit of HEPP concept is the simplification of the engine system by eliminating the interface with engine driven pumps (EDP) and associated hydraulic shut-off valves present in traditional hydraulic systems.

## 2. Initial trades and assessment of key system parameters for concept selection and sizing

When considering decentralized hydraulic power generation, selection of consumers to be supplied by each HEPP has an important impact on the power pack size and its integrated functions.

A baseline aircraft architecture was defined in collaboration with Airbus in SmartHePP project. Where one large power pack (HEPP-1) is sized to power the main landing gear (MLG) retraction/extension, aircraft braking, and the high-lift systems, and a second smaller power pack (HEPP-2) is sized to power the primary flight controls (rudder and elevators) in the empennage, c.f Figure 1.

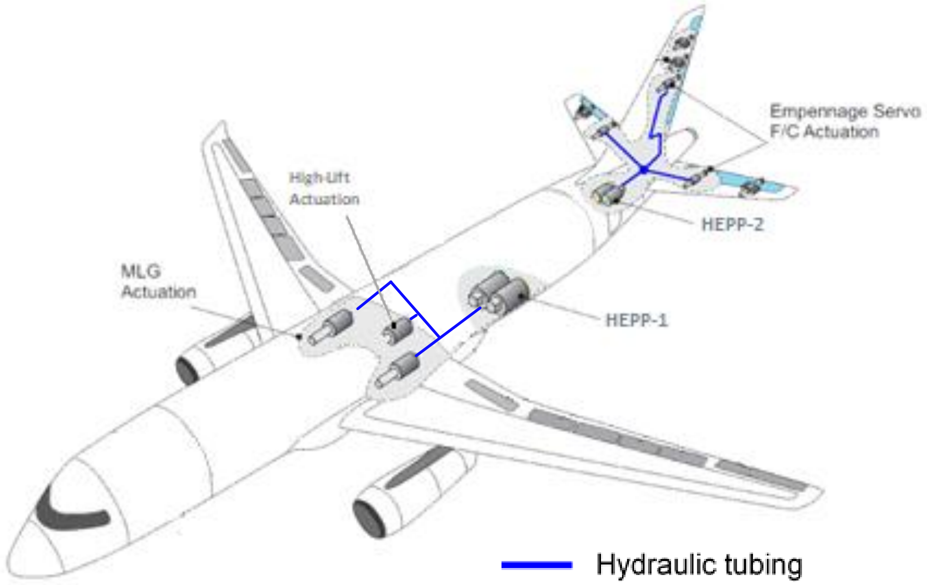


Figure 1 – Decentralized hydraulic power generation

The subsequent sections describe the consumer's characteristics and respective HEPP architecture.

## 2.1 HEPP-1

HEPP-1 is a power pack designed to supply the MLG retraction/extension, aircraft braking, and high-lift systems. All three systems have similar characteristics of short operating time and high flow demand. A summary of the operational requirements is listed in Table 1. Another key requirement when defining the HEPP architecture is the system safety objectives. For securing the aircraft safety objectives, the required probability of total loss of HEPP-1 hydraulic power supply shall be lower than 1E-5 per flight hour.

Table 1 – HEPP-1 consumers operation

| Consumer | Operation | Cycles per flight | Duration [s] | System pressure [bar] | Flow |
|---|---|---|---|---|---|
| MLG | on-demand | 2 | 11 | 207 | High |
| High-lift | on-demand | 5 | 30 | 207 | Medium |

The proposed HEPP-1 architecture is depicted in Figure 2. It integrates the power generation by electro-motor pump units (EMPs) and hydraulic system equipment as well as electronic power and control/monitoring in an integrated package, c.f Figure 3. For fluid storage a bootstrap reservoir with capacity of approximately 10 liters is necessary to accommodate fluid volume changes due to operation of unbalanced MLG actuators (unequal working areas on both side of the piston head). All common hydraulic system components like filters, valves and sensors are mounted into the reservoir-integrated manifold. Two redundant EMPs ensure the safety objectives and high operational availability [8]. Electric power is supplied by two independent high voltage direct current (HVDC) networks. Power is modulated by motor control electronics (MCEs). The MCEs comprise the power drive electronics and dual channel (control/monitoring architecture) control computers. The control computers host the motor pump control. Two redundant pressure sensors feedback the control signal. Moreover, the computers take over system monitoring functions. The interfaces between the HEPP-1 and aircraft are the electric connector of the MCEs, a connector for the bus communication system (for instance AFDX), and the hydraulic ports, primarily high pressure and return.

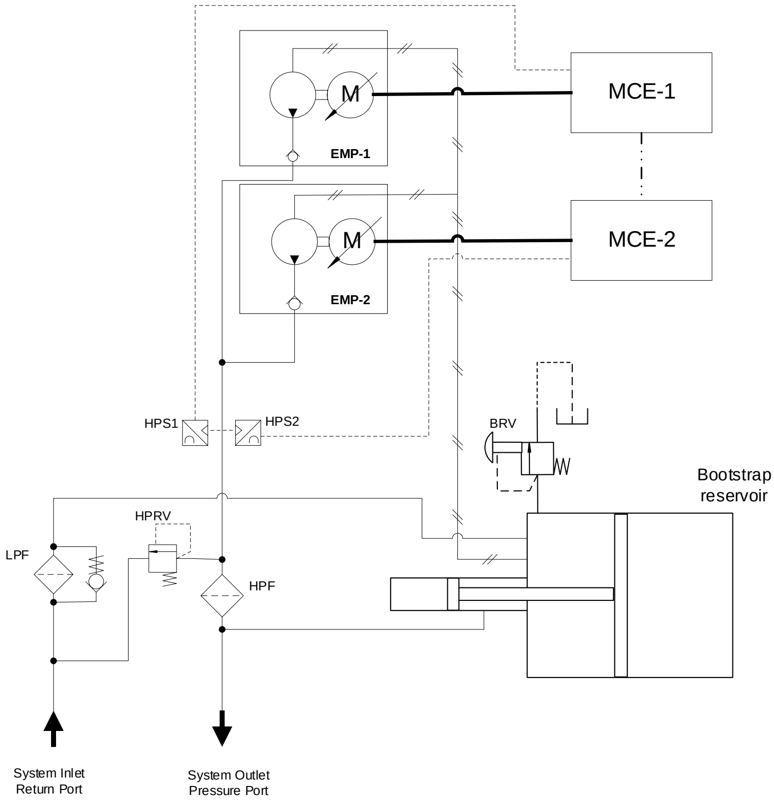


Figure 2 – HEPP-1 Architecture

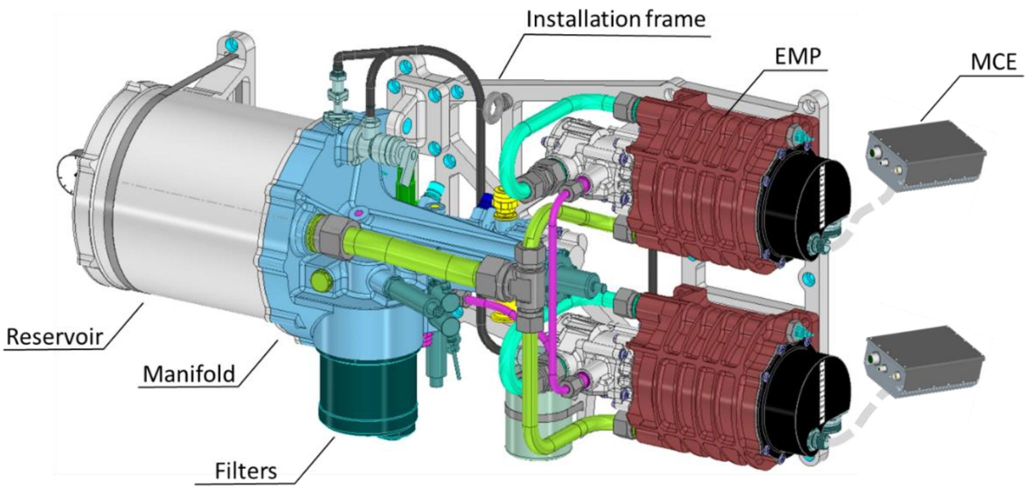


Figure 3 – HEPP-1 DMU

## 2.2 HEPP-2

HEPP-2 is a power pack designed to supply the consumers located in the empennage – rudder and elevator servocontrol actuators. Both systems have similar characteristics of continuous operation and low flow demand. A summary of the operation requirements is available in Table 2. For securing the aircraft safety objectives, the probability of total loss of HEPP-2 hydraulic power shall be lower than 1E-5 per flight hour.

Table 2 – HEPP-2 consumers operation

| **Consumer** | **Operation** | **System pressure [bar]** | **Flow** |
|---|---|---|---|
| Rudder & elevators | Continuous | 207 | Low / Medium |

The proposed HEPP-2 architecture is depicted in Figure 4. Due to reduced flow requirements and inexistence of unbalanced actuators, the HEPP-2 components are significantly smaller than HEPP-1 and therefore, permitting a higher level of integration, i.e. filter manifold taking structural function, as shown in Figure 5. The main differences from HEPP-2 to HEPP-1 is the presence of a high-pressure accumulator and the pre-charged metal bellow reservoir. The high-pressure accumulator improves the hydraulic output quality by supporting the response to rapid flow demand increase and filtering pressure ripples. The selection of the pre-charged metal bellow reservoir technology becomes viable due to the reduced fluid volume capacity required to overcome volume changes due to in-service leakage and pressure and temperature effects.

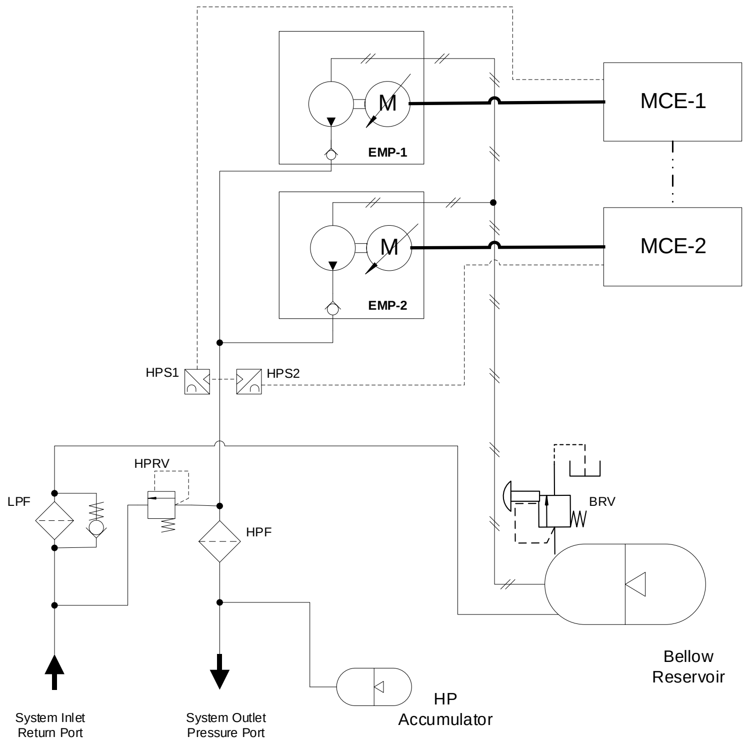


Figure 4 – HEPP-2 Architecture

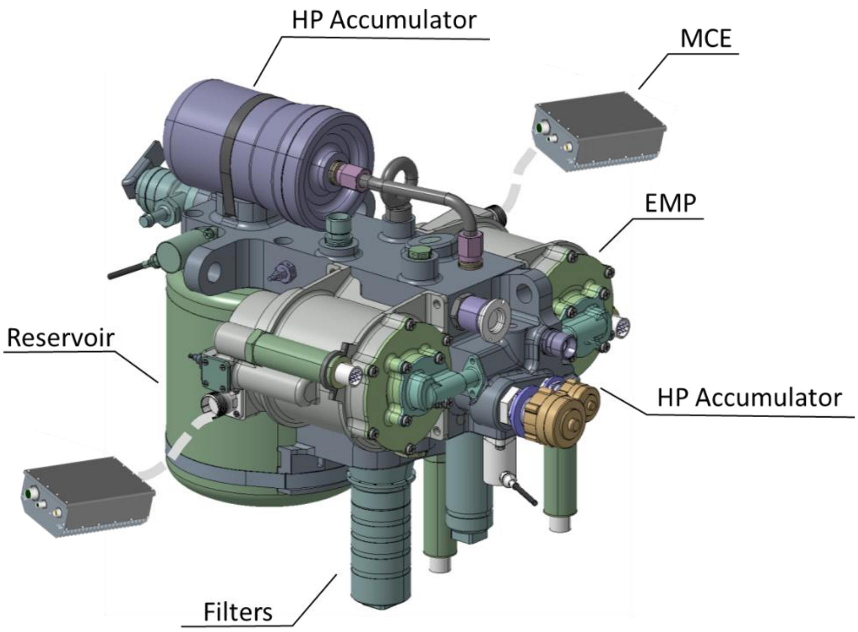


Figure 5 – HEPP-2 DMU

## 2.3 Electro-Motor Pump Unit (EMP)

EMPs are the heart of Liebherr’s HEPP units and, therefore, sound trade-studies have been conducted for exploring technology options and for expanding boundaries of efficiency, power-to-weight ratio, and low noise emissions. Legacy EMPs that are today used in various aircraft use a combination of variable displacement axial piston pumps with constant speed induction motors. This solution shows numerous disadvantages when utilized in combination with modern aircraft architectures with variable frequency and/or high voltage DC electrical supply [5].

As indicated by Dunke et al. [5], frequency inverters are required in a MEA electric power system. This opens the opportunity to explore the application of speed-controlled drives, such as synchronous motors, enabling alternative EMP concepts with variable speed and fixed displacement pumps (VSFD).

EMPs with variable speed were investigated in detail for general/industrial hydraulic applications by Neuberth [6] and Rühlicke [7], showing a great potential of energy savings. Low heat rejection (high efficiency) and high power density are key parameters for application in small decentralized hydraulic systems making VSFD EMPs very attractive.

In the frame of a German national civil aviation research program (LUFO IV) - KONKRET project, an extensive trade has been performed to identify the most promising motor-pump concept. Seven different concepts were compared against each other, as illustrated in Figure 6, and the favorite concept S3 was selected as result of a value-benefit analysis. It is a MCE, which powers a permanent magnet synchronous machine (PMSM), coupled to a fixed displacement pump (FDP). The MCE gets controller feedback from an electronic pressure output sensor and controls the speed of the PMSM. Performance analyses show that all specified requirements (dynamic and steady state) are met and that overall efficiency is significantly higher than of today’s legacy EMPs (concept S4: asynchronous machine with variable displacement pump).

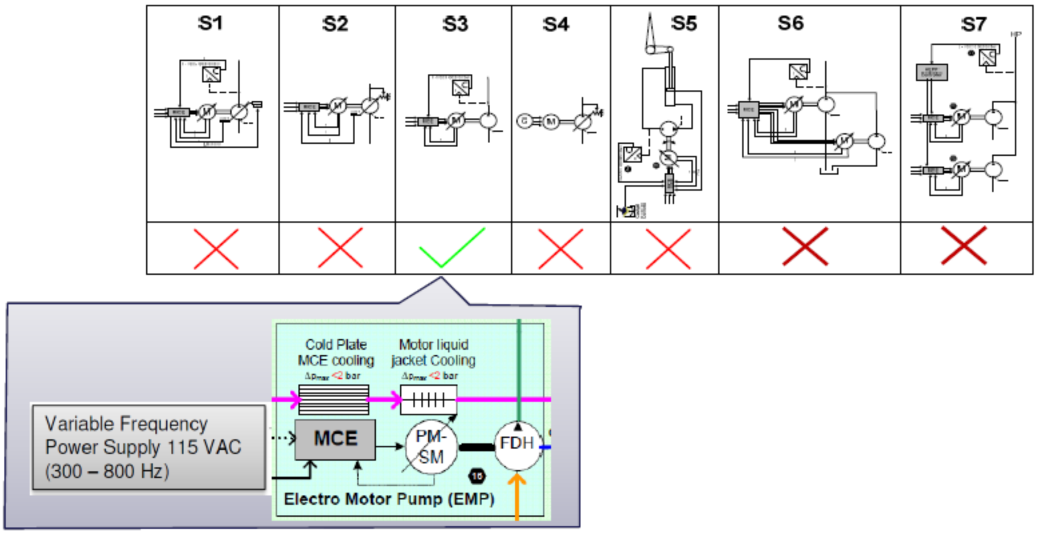


Figure 6 – EMP Trade

Table 3 shows the initial qualitative comparison between two different pump concepts for the FDP: axial piston pump (APP) and internal gear pump (IGP). The IGP was selected to further pursue based on the promising features of high reliability (low complexity) and low pulsation / noise on a comparable level of efficiency versus the APP type.

Table 3 – Comparison APP vs IGP

| Criteria | Axial Piston Pump (APP) | Internal Gear Pump (IGP) |
|---|---|---|
| Efficiency | > 85% | > 85% |
| Complexity | high | medium |
| Pressure range | < 500 bar | < 500 bar |
| Speed range | < 10.000 rpm | < 10.000 rpm |
| Installation volume | medium | low |
| Reliability | high | very high |
| Dynamic | low inertia -> fast response | low inertia -> fast response |
| Hydraulic pulsation | high | low |

As aforementioned, an EMP baseline has been chosen with the combination of a permanent magnet synchronous motor (PMSM) with a fixed displacement internal gear pump (IGP). Main benefits of the selected solution are summarized below:

- High efficiency across the whole flow regime due to the high-efficient nature of fixed displacement pumps
- High power-to-weight ratio characteristic of permanent magnet synchronous motors
- Flexibility to be adopted in any electrical power supply, including high voltage direct current and variable frequency alternate current
- Advanced pressure control laws allowing for flexible flow vs pressure curves, including real time adaptation to various different states
- Low heat rejection being ideal for small decentralized systems
- Lower hydraulic pulsation

## 3. Early EMP Proof-of-Concept

Early in the development phase, potential issues and risks were identified. These influenced the maturity campaign since simulation models were pending validation.

A proof-of-concept was successfully demonstrated [9] with an industrial IGP connected to an aerospace PMSM. All important aspects such as control performance, robustness, and noise/ pulsation were tested and evaluated on a sufficient level to reach a technical readiness level of 4 (TRL4).

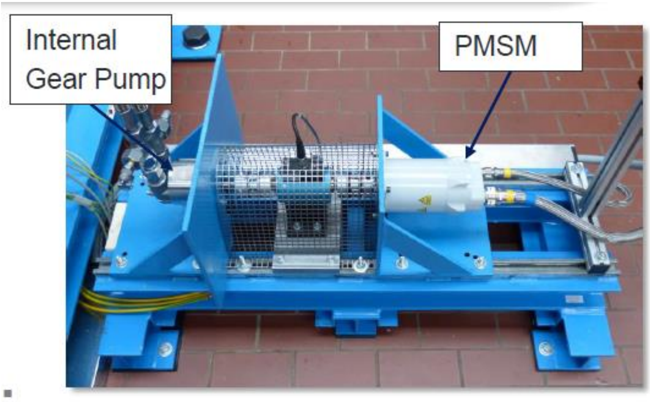


Figure 7 – early EMP proof-of-concept

A robust pressure controller was developed in order to meet the challenging SAE AS595 [12] dynamic requirements relevant for primary flight controls such as elevator, rudder or ailerons actuators. A nonlinear simulation model of the EMP was developed and validated to successfully assessment of dynamic requirements. Figure 8 shows an example of non-linear simulation results against the test measurements for a scenario of moderate load step from 10l/min to 25l/min and vice versa. It can be seen that the model simulates the pressure response quite well. This is true for the pressure over- and undershoot as well as for the response time.

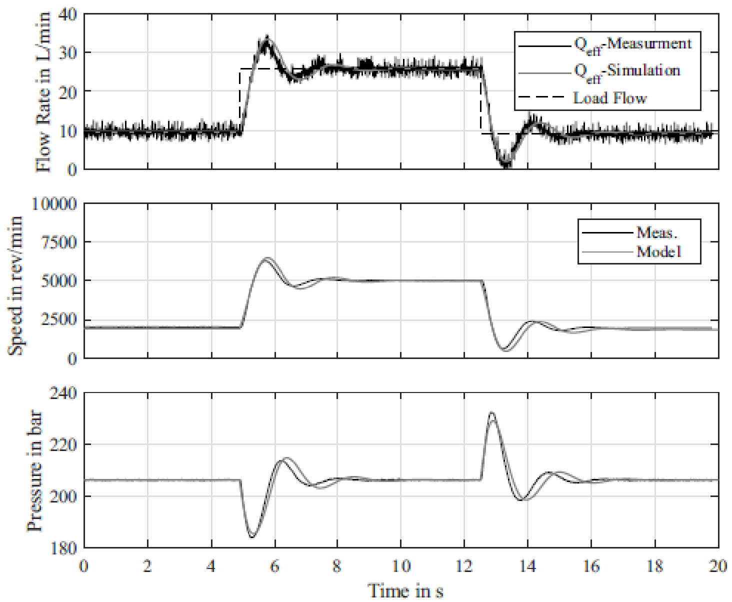


Figure 8 – Non-linear simulation

# 4. Proof of concept demonstration in a representative environment

## 4.1 EMP Testing

An aerospace EMP prototype was designed that matches the baseline described in chapter 2.3, and an intensive test campaign conducted to demonstrate the robustness of the concept and design when operating in relevant environment. Figure 9 depicts the Liebherr EMP prototype.


Figure 9 – EMP prototype

To achieve the target TRL of 6, a series of tests were deemed necessary all of which were successfully completed. These included:

- Pump cavitation robustness in low suction pressure conditions
- Flow control within the motor pump to assure proper cooling of the internal components
- Accelerated endurance tests to anticipate potential issues in ageing units
- Operation in the extremes of the temperature envelope
- Operation under extreme vibration and shock conditions
- Explosion proofness
- Humidity, salt fog and water proofness
- Hydraulic pulsation and noise

In addition, a back-to-back test campaign was conducted with the Liebherr EMP prototype (Figure 10 a) versus a legacy aerospace EMP (Figure 10b) with variable displacement pump of similar hydraulic power class (max flow 44 lpm).

(a)

(b)

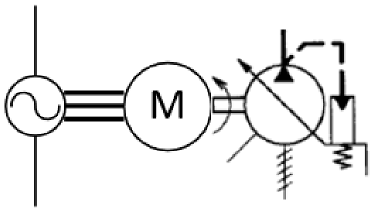


Figure 10 – EMP back-to-back test (a) Liebherr EMP; (b) Legacy EMP

As indicated in Figure 11, Liebherr EMP has higher efficiency over entire flow range, with delta between 21% and 37% for mid-low flow demand. The achieved net efficiency improvement increases significantly with low operating flow. This directly translates into energy, and thus fuel savings on aircraft level. Furthermore, high efficiency at low flow operation regime becomes more important for de-centralized hydraulic architectures where the average flow demand tends to be significant lower as in today's centralized hydraulic systems, because of the reduced number of connected hydraulic consumers to each HEPP.

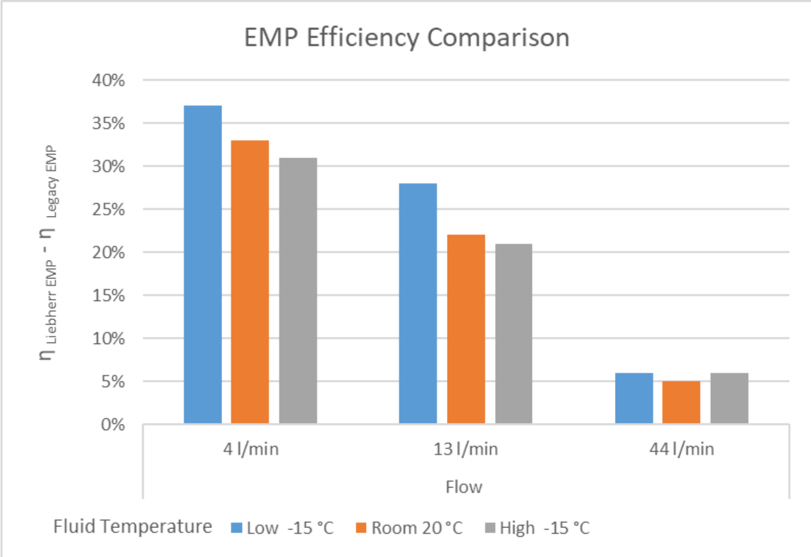


Figure 11 – EMP back-to-back test - Efficiency

In addition, the heat rejection of the Liebherr unit is 65% lower at the same operating conditions c.f Table 4. This has a directly effect in the sizing of cooling systems. Hence, again enabling weight and energy/fuel savings on overall aircraft level.

Table 4 – EMP back-to-back test - Heat rejection

| | ΔQheat [%]<br>Liebherr EMP / Legacy EMP | Flow<br>4 l/min | <br>13 l/min |
|---|---|---|---|
| Fluid temperature | Low -15 °C | 18% | 31% |
| | Room 20 °C | 22% | 39% |
| | High -15 °C | 24% | 43% |

The 3rd main advantage lies in the 3-times higher power-to-weight ratio of the Liebherr EMP directly yielding weight savings on aircraft-level. Further, the hydraulic pulsation is significantly reduced, which translates into lower noise emissions, and thus improved passenger comfort. This advantage is, of course, especially important for the HEPP-1 variant, which is installed in the belly fairing directly below the cabin. Also the Liebherr EMP is further simplified when compared to the legacy EMP. It does not require a case drain and cooling pump.

## 4.2 HEPP V&V Testing at TUHH

In collaboration with Airbus Operations GmbH and the Technical University of Hamburg (TUHH) a proof-of-concept test rig of HEPP-1 and HEPP-2 was created to investigate the system behavior when powered by Liebherr’s EMP. Real consumers such as elevators, rudder and landing gear actuators were integrated for bringing the tests to a high level of representativeness of the conditions the power pack would face when installed in the aircraft c.f Figure 12.

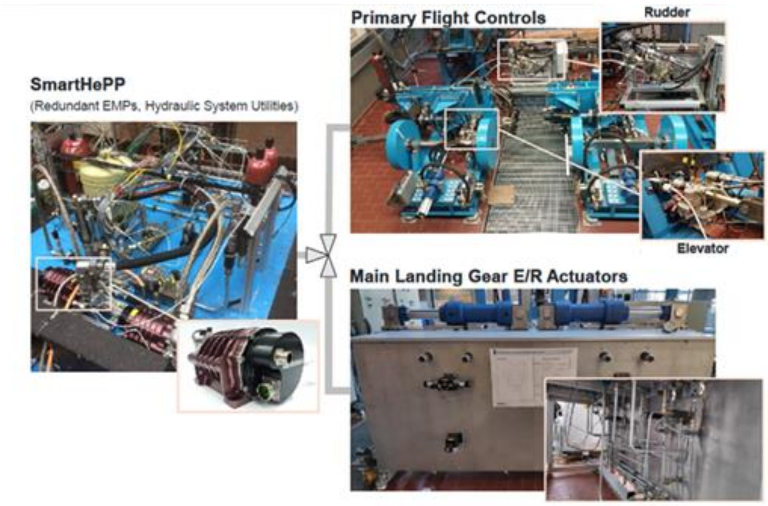


Figure 12 – PoC power pack demonstrator

Initial testing was carried out with HEPP-1 isolated from real consumers and a load valve was used to set the flow demand and evaluate system performance behavior for HEPP operation with one EMP active (simplex) and two parallel EMPs (duplex). Figure 13 demonstrate the stable system pressure control for sudden flow change. The pressure under and overshooting are within the specified limits, however the response time is ~0,1 second higher than the limits indicated in [12]. The effects of response time is further evaluated on tests with real consumers.

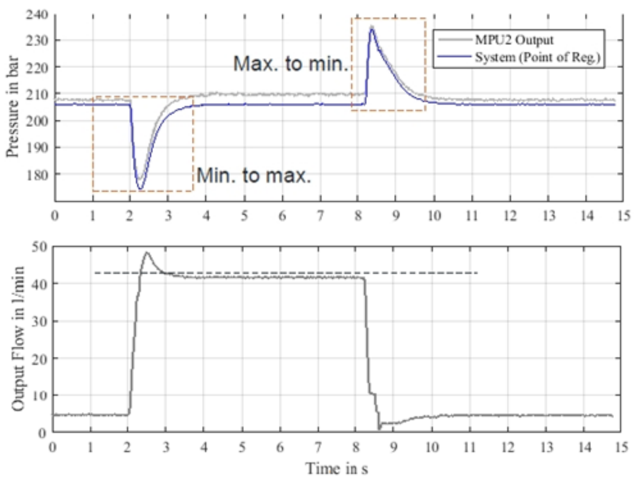


Figure 13 – HEPP-1: EMP2 Step Response

The following tests explored the system behavior when supplying real consumers. Figure 14 shows HEPP-1 reaction to main landing gear operation. Due to high flow demand, both EMPs are active providing the maximum HEPP-1 flow capacity. The system pressure drops to 165 bar during the initial transient and recover to nominal pressure after approximately 0.5 second. The MLG retraction and extension time and the system pressure are within the acceptable limits. This test demonstrates the high power capability of selected HEPP technology in maintaining the system nominal pressure at high flow.

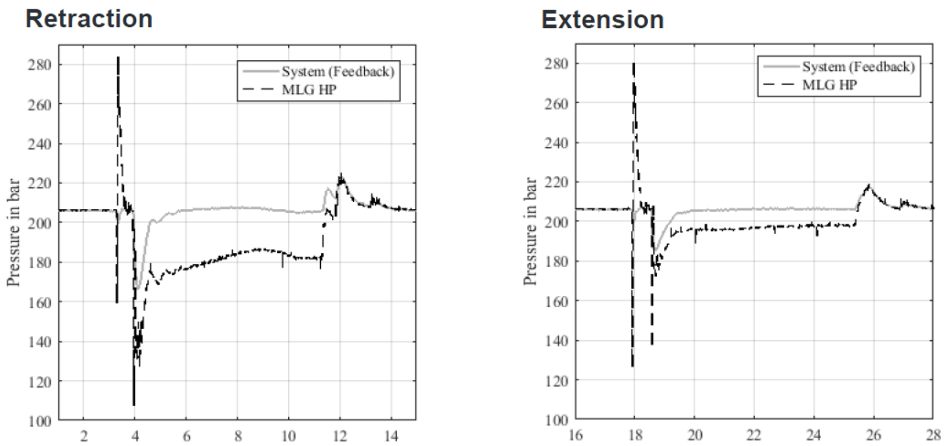


Figure 14 – HEPP-1 Landing Gear Operation

To emulate the performance characteristics of HEPP-2 (smaller power pack) using the existing HEPP-1 EMP hardware, the maximum EMP motor torque and flow were limited to values representative of a machine sized for HEPP-2 application. Figure 15 shows the system behavior during a simulated aircraft landing with cross-wind. The upper plot depicts the system and consumers pressures, below the HEPP-2 output flow and EMP speed (simplex operation). It can be remarked that there is low pressure transients in systems and upstream of actuators. This evidences the stability and the acceptable response time of the HEPP pressure control when supplying consumers with highly dynamic profile of operation.

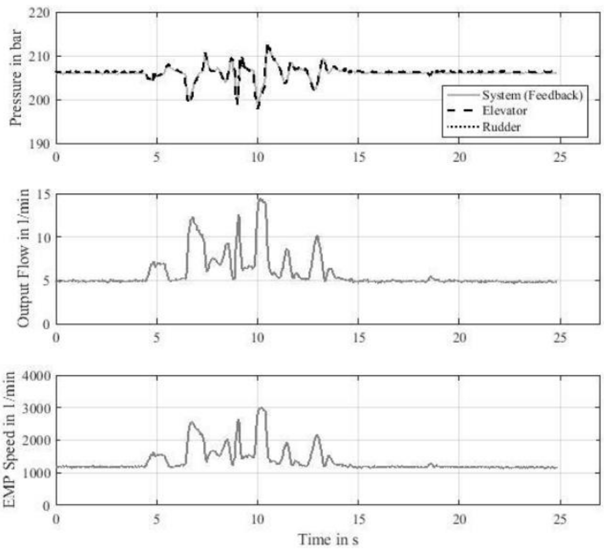


Figure 15 – HEPP-2 Cross-wind Landing

All tests passed successfully except the EMP response time as per [12], however the testing with real consumers confirms the insignificant effect of the increased response time to the landing gear and flight controls system performance.

## 5. Conclusion and outlook

The power pack technology is a key enabler for electrification of new aircraft platforms. It merges the benefits of mature and reliable hydraulic actuation with installation flexibility provided by the electrical system. Compared to centralized hydraulic systems the de-centralized architecture offers significant advantages: power on demand, system (pre-) integration, reduced installation effort, less hydraulic piping and elimination of direct interface to engine system. Additionally, the combination of a fixed displacement pump with a speed variable motor offers high efficiency, high power-to-weight ratio and robust EMP solution to be integrated in local hydraulic power packs. Finally yet importantly, the proof-of-concept testing results on EMP and HEPP system-level, achieving TRL6 and 5 respectively, demonstrates the potential of this technology and suitability for supplying critical aircraft systems such as primary and/or secondary flight controls. Future work exploring means to further increase the maturity of Liebherr EMP and HEPP technology need be conducted.

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## 8. Copyright Statement

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