Abstract: Conventional flap and slat high-lift surfaces actuation systems in a commercial aircraft consist of actuators mechanically connected via a transmission system across the wingspan, driven from a centralised power drive unit comprising of a hydraulic, electric, or hybrid hydraulic/electric motor arrangement. The permanent coupling to the shafts makes the entire flap system move in unison, as do the slats. This paper will investigate and discuss different potential system architecture, and present the benefits associated with such architecture. It will also present the advantage that can be linked to a full electric flap configuration.

1 Introduction

One fundamental technology development area which will enable the shift towards full electric aircraft architecture is the motor drive technology. Robust, cost-effective, weight efficient, and reliable motor drive technology will contribute to the seamless migration from hydro-mechanical to more electric architectures.

The work herein presented describes the adoption of distributed motor drive architecture within the power drive unit (PDU) of a flap system and present a simple comparison table to highlight the different configurations currently available on the market.

A PDU is used to convert electrical or hydraulic power into mechanical motion, often rotational, and drive an actuation system. Usually, a PDU is fitted with dual hydraulic motors each providing independent power to the transmission system via a speed summing gearbox. Each motor is controlled by an independent motor supply via a dedicated valve block which ensures the hydraulic isolation between the two blocks. This paper presents the evolution of the PDU unit into a more electric one, whereby hydraulic motors are replaced by an electric motor.

2 High lift system

The flap system is part of the secondary flight control system, also known as high-lift system (HLS). High-lift devices are used in combination with aerofoils to reduce the take-off and landing speed by changing the characteristics of the aerofoil geometry during take-off and landing phases.

As commercial airplane cruise speed increased due to the development of more powerful engines, the need for control surfaces that could maintain take-off and landing speeds within reasonable speeds became apparent.

In particular, the development of jet engines contributed to the changes in aircraft wing configuration, from the introduction of the wing sweep and by further increasing the wing loading introduction of jet engines.

There are two main high-lift surfaces in a wing, the flap system and the slat system. The flap system is located at the trailing edge of the wing (back), and the slat system at the leading edge of the wing (front) as shown in Fig. 1.

HLSs operate by increasing the aerofoil chamber and exercising a boundary layer control through the improvement of the pressure distribution reducing the boundary layer separation effect, which causes additional drag to be generated, while enabling wing area increase. This is achieved by the deployment of the flap system, which in turns increases the stall angle of the aircraft and its lift coefficient as presented in Fig. 2.

Rudolph [2] identified the following possible trailing-edge devices, which will be adopted on different aircraft depending on flight envelope requirements as well as aircraft manufacturer requirements:

- Split flap;
- Plain flap;
- Simple slotted flap, single-slotted Flower flap;
- Fixed vane/main double slotted flap;
- Main/aft double slotted flap;
- Triple slotted flap.

Single-slotted flower flap, for instance, are used on the Boeing 747 Special Performance (SP), which is a long range version of the Boeing 747. With careful aerodynamic design, single-slotted flaps can be deflected up to 40° and they are the simplest of the fowler flaps, which can achieve significant advantages in terms of costs and weight as shown in Fig. 3.

Main/aft double-slotted flap configuration, on the other hand, has been applied in the design of Airbus A300B. The double-
The slotted flap has a larger main flap at the front followed by a smaller aft flap. The main flap overlaps with the wing cove, while the aft flap overlaps the aft end of the main flap. This flap design can achieve a deflection angle of 30° to 35° for the main flap and 28° to 30° for the aft flap, achieving a total deflection of 60° to 65° [2], which provides an increase in lift as well as an aid in maintaining the landing attitude. This is shown in Fig. 4.

The system is usually designed with gearboxes presenting high reduction ratios to induce a self-locking behaviour and with shafting generally designed to withstand jam failures. The system also presents a dual channel PDU to guarantee functional reliability of the system.

The HLSs experience maximum loads in low-speed manoeuvres with the devices deployed. Therefore, the design needs to follow fail-safe criteria, which implies that every critical structural element is duplicated. The failure of the HLS may have different impact depending on where the failure is experienced. For instance, an asymmetric failure of the outboard wing such as the loss of the outboard flap in the landing position on one side would cause very high rolling moments, which could be difficult to be controlled by the flight control system.

Given this short description of the mechanical complexity of the flap actuation system and the need for redundancy throughout its design to enable fail-safe criteria to be achieved, it is quite clear that this subsystem has a significant toll on weight and cost of the overall aircraft due to the complexity of their design and test requirements as well as for their maintenance. According to Rudolph [2], the HLS accounts for 6 to 11% of the production cost of an aircraft.

This can explain why there is an industry-wide effort in finding new design solutions that, while still supporting their functional needs, could provide a weight and cost reduction in their design. Hence, the research on more electric architectures for flight control systems.

### 3 High lift functional architecture

In order to describe the high-lift functional architecture, we will assume that the actuation system is linked directly to the pilot interface and the panel surface, effectively transferring the pilot's command or effort to surface movement.

The operational requirements for a high-lift system are to:

- Increase lift;
- Reduce stall speed;
- Move high-lift surfaces in response to pilot input.

In order to operate effectively, they need to be able to:

- Communicate surface position;
- Be controllable;
- Provide safety monitoring;
- Support data availability for condition and health monitoring;
- Actuate/move surfaces synchronously and symmetrically;
- Transmit power to surface;
- Arrest and hold system;
- Detect position;
- Demonstrate safe behaviour and operation.

A schematic representation of the high-lift architecture drawing only the flap systems to reduce the diagram complexity is shown in Fig. 6 [4].

The key functionalities as highlighted in Fig. 6 are:

- Central source PDU, which provides the power drive actuation to the system and has position sensing capability. The PDU is dual channel for redundancy.
- Transmission shafts connect the PDU to the actuators on the mechanical wing actuation with four rotary geared actuators (RGA) per wing. This enables the transmission to drive aerodynamic loads with large torques.

### 4 PDU functional architecture

#### 4.1 Hydraulic flap actuator

The optimisation capabilities of today's highly optimised high-lift system architectures reached a plateau and are limited to small local improvements. Advanced high-lift system architecture with distributed active controlled flap actuators offers the capability for implementation of additional functionalities for the trailing edge with benefits on aircraft level and improvements at manufacture and assembly [5].

A functional architecture for the PDU driving a fully hydraulic architecture as found on many existing aircraft is presented in Fig. 7.

The configuration shown in Fig. 7 is mainly driven by the aircraft architecture, the availability of the hydraulic supply as well as the power density of hydraulic systems.
4.2 New electric flap system architecture

The simplest approach to integrate a high-lift system (HLS) in a more electric aircraft is to exchange the hydraulic drives and brakes for electric units. Unfortunately, the power density for an electric system would not be able to match the density of the existing hydraulic system, but a trade study done under the power optimise aircraft (POA) [3], and new electric flap system (NEFS) revealed that a distributed HLS for both the inboard and outboard flap panels provides an opportunity to reduce the peak power consumption of the aircraft by operation of the inboard and outboard flaps in a sequence. The advantage of a more electric HLS is to be further seen at the aircraft level. Another major advantage of the distributed system as presented in Fig. 8 is the ability to move individual flap surfaces to different angles, and this can be utilised during the flight since varying the angle between inboard and outboard surfaces may give aerodynamically advantageous which is not possible with current HLS architecture.

Fig. 9 shows a hybrid hydraulic-electric functional architecture. An electric motor is combined to a hydraulic motor to drive the load through a differential gear box. In case of a failure of either the electric channel drive or the hydraulic one, the system will drive the load at half speed.

The move towards a hybrid system on an A380 slat system was driven by the aircraft architecture (two hydraulic and three electric channels).

A distributed system is shown in Fig. 8 requiring more motors than the conventional hydraulic architecture (Fig. 7) or the hybrid hydraulic and electric (Fig. 9) architectures, but for such system each motor will only be rated for the torque of a single flap surface, and, therefore, will carry a much smaller power requirement than a centralised unit [6].

A distributed system allows the elimination of the common shaft and all the complexity of mechanical torque limiters which have considerable mass, and also require manual inspection and resetting following a trip.

It should be noted that the architecture presented in Fig. 8 can be further simplified by sharing functionality between the different parts of the system rather than duplicating.

This work will need to assess the system requirements, and the optimisation will need to meet the safety and reliability needs, hence further simplification is possible.

Under the UK Department of Trade and Industry (DTI)-funded programme, a research project entitled distributed electrically actuated wing system (DEAWS) was launched in order to investigate the feasibility of electrically powered flap and slat systems, dispensing with the shafts across the wingspan and central motor systems and instead distributing electrically driven actuators across the flap or slats as shown in Fig. 10 [6].

The topology for flaps and slats is very similar; hence the topology proposed under DEAWS is suitable for either system.

In other work within the same topic and presented in a published work, M. Recksiek [7] from Airbus Germany discusses distributed flap architecture; the author illustrates several system topologies that have been designed and evaluated within few Research & Technology projects, ranging from local shafts on each flap panel with different actuation arrangements to fully independent actuated drive stations as presented by some examples shown in Fig. 11.

These different system architecture topologies, based on similar building blocks, are conceivably offering more flexibility and functionality. These building blocks were developed in recent national and European-funded R&T projects ProHMS (Lufo2), HISYS (Lufo3), and NEFS (FP6 3rd Call).

5 Case study

Under the European-funded technology programme named New Electrical Flap System (NEFS), United Technologies Aerospace Systems have developed a system that can be mounted on a fully distributed flap actuation system. The system layout considered is presented in Fig. 12. As it can be seen that the system uses a single motor configuration, but in order to meet the reliability requirements for this architecture, a fault tolerant motor drive system is considered, and the motor configuration is shown in Fig. 13.
The motor torque speed characteristics under no fault or short-circuit fault condition is given in Fig. 14. In case of a three-phase short circuit, the current in the healthy channel will need to be increased in order to produce the excess torque needed to overcome the drag torque developed by the faulty shorted second lane.

It can also be seen from Fig. 12 that a magnetic gear box is used in the system. This device has two functions, it acts as a gear box with the advantage of having no friction especially at low temperatures, and it also acts as a torque limiter in case of a jam. The flux density plot is shown in Fig. 15, while the torque characteristic of this device is given in Fig. 16.

6 Conclusions

This paper presents an overview of the high-lift system technology and discusses other potential system architectures that may give a benefit of weight and cost reduction. It presents a case study undertaken by United Technologies Aerospace Systems and shows characteristics of some of the components used in the system.

7 Acknowledgments

The authors would like to thank the European commission for funding some of this project.
8 References


Fig. 15 Flux density plot

Fig. 16 Torque output from the magnetic gear box