ADVANCED HIGH LIFT SYSTEM ARCHITECTURE WITH DISTRIBUTED ELECTRICAL FLAP ACTUATION

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Abstract

State-of-the-art high lift actuation systems predominantly consist of a mechanical transmission shaft with rotary or ballscrew actuators as well as synchronised hydraulic actuators with common control valves. These architectures assure a synchronous deployment of all flap and respectively slat panels but prohibits functional flexibility.

An advanced high lift actuation 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. Thus the distributed high lift system architecture is to be regarded as an enabler of above-mentioned benefits.

Different system architecture topologies that are based on similar building blocks are conceivable addressing the request for more flexibility and functionality. These building blocks were developed in recent national and European funded R&T projects. The concept of a distributed flap drive system architecture and underlying building blocks will be presented. Potentials on aircraft level and system repercussions will be discussed.

1 INTRODUCTION

Today's commercial airplanes are equipped with high lift devices to provide lift augmentation at low speed during takeoff and landing as the clean wing design is optimised for the cruise speed regime.

The introduction of jet engines in commercial airplanes led to the necessity to increase the cruise speed capability to operate the jet engine within the optimum working point according the engines characteristics. The increase of cruise speed was accomplished by wing sweep and airfoil optimisation; further performance optimisations also lead to increased wing loading. But increased wing loading

requires higher lift coefficients at low speed, whereas wing sweep actually decreases wing lift at low speed.

In order to keep takeoff and landing speeds within reasonable limits, more powerful high lift devices were required. Wing trailing edge devices evolved from plan flaps to Fowler flaps with single, double, and even triple slots. The complexity of high lift systems probably peaked on the Boeing B747, which has triple slotted flaps. Since then, with the exclusive requirement for low speed performance, the tendency in high lift system development has been to achieve high level of lift with simpler devices and optimised actuation systems in order to reduce complexity and therewith weight and maintenance costs (see Figure 1). [1]
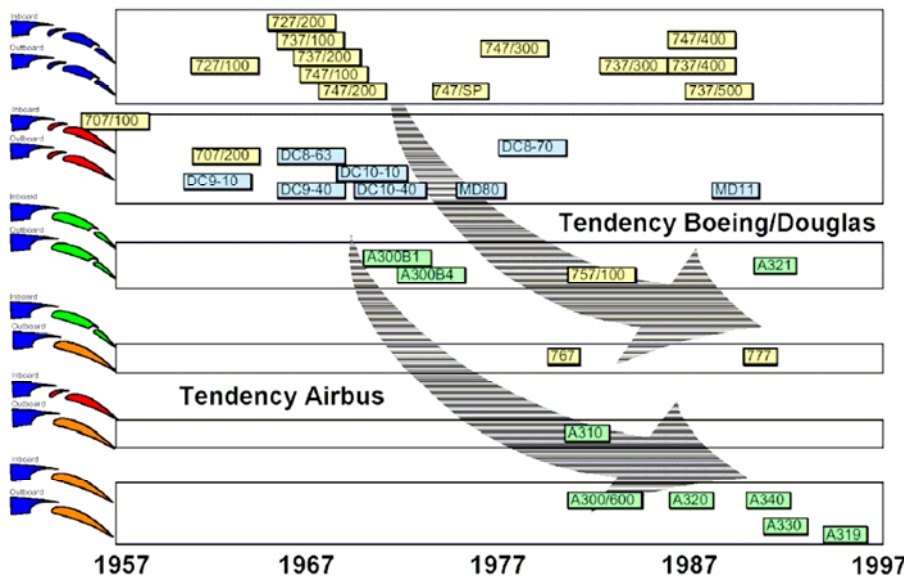

Figure 1 – Evolution of high lift systems [2]

Therefore state-of-the-art high lift actuation systems predominantly consist of a mechanical transmission shaft system (see Figure 2) that transmits the mechanical energy from a central motor to the rotary or ballscrew actuators, which are located along the transmission shaft and move the high lift surfaces.
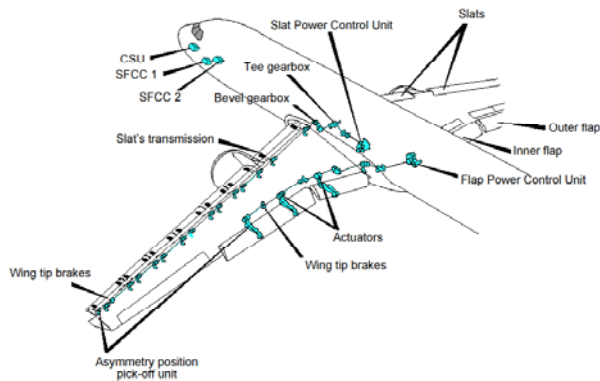

Figure 2 – A320 High Lift Actuation System

Further high lift actuation systems are known that make use of synchronised hydraulic actuators with common control valves. All these architectures assure a synchronous deployment of all flap and respectively slat panels but prohibit functional flexibility.

The optimisation capabilities of today's highly optimised high lift system architectures reached a plateau and are limited to small local improvements. An 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. Thus the distributed high lift system architecture can be regarded as a technology step change as enabler for further performance gains. Significant performance gains require a technology step-change as can be observed as a general trend (see Figure 3). Once additional flexibility is incorporated there is a potential for further high lift systems technology evolutions by extending additional functions with increasing confidence in this architecture. As analogy the fast integration of additional functions in primary flight control fly-by-wire-systems can be quoted, even if not fully comparable to high lift.
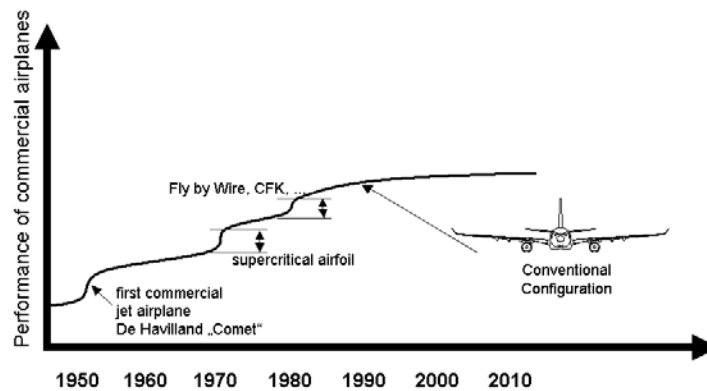

Figure 3 – Step changes of technology [3]

But at the end of the day, the new technology must pay off. To which extent improvements can be capitalized depends on the operational-, functional- and performance-requirements of the target aircraft as well as aircraft configuration and must be balanced against system repercussions due to increased system complexity.

2   STATE-OF-THE-ART HIGH LIFT ACTUATION SYSTEMS

Figure 4 depicts the A340 flap actuation system. The central hydraulic power control unit (PCU) supplies the power necessary to operate the flap panels on each wing.
A mechanical transmission shaft transmits the mechanical power to the rotary actuators, which move the flaps on the tracks. This shaft system consists of CFRP shaft elements with gearboxes necessary for larger direction changes as well as system torque limiters, wing tip brakes, universal joints, plunging joints and spline

joints to accommodate wing bending and temperature effects. The transmission system of each wing has five drive stations. The inboard flap has two drive stations and the outboard flap has three. Each drive station consists of a down-drive gearbox, a down-drive shaft, an input gearbox with a torque limiter, a cross shaft and the rotary actuator. An interconnection strut connects the inner flap to the outer flap on each wing and acts as an alternative load path in the event of a drive link disconnect in the drive stations 1 (inboard), 2 and 3.

The high lift system is controlled and monitored by two slat flap control computers (SFCC) using sensor information from several analogue and discrete sensors.

The mechanical transmission shaft as depicted in Figure 4 assures synchronous deployment of all flap panels but prohibits functional flexibility. This type of mechanical transmission shaft system consists of a high number of components with different part numbers and requires high design-engineering and installation effort.
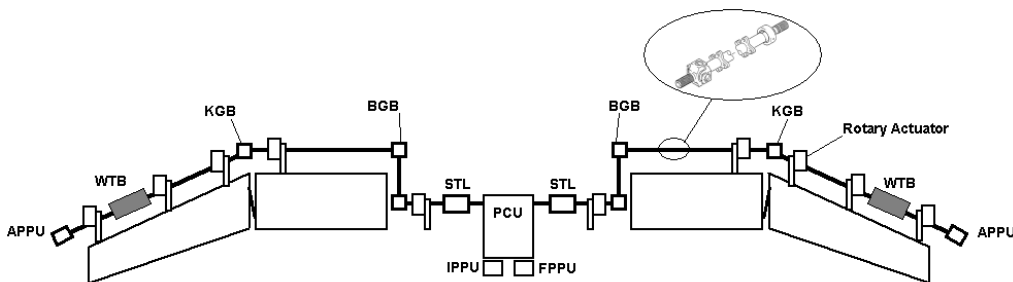

Figure 4 – A340 Flap Actuation System

Further high lift actuation systems are known that make use of synchronised hydraulic actuators with common control valves like the high lift systems of the MD87, DC9, DC10 and MD 11 aircraft. Figure 5 depicts the high lift actuation system of the MD87. Each panel is connected to two actuators, which are supplied by redundant hydraulic systems but controlled by a common mode control valve. Mechanical synchronisation assures synchronous deployment of all flap panels.
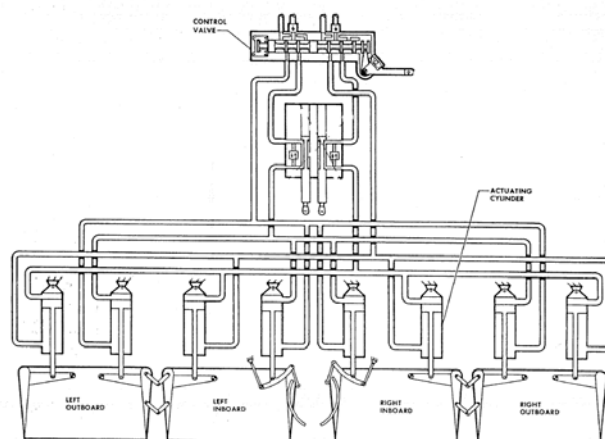

Figure 5 – MD87 Flap Actuation System

3 DEVELOPMENT TRENDS

Recent development programs at Airbus and Boeing extend the functional capabilities of the flap system. The A350 XWB as well as the B787 high lift system will incorporate additional functionalities that provide aircraft performance optimisation. Additional functionality is achieved with an evolution of the traditional mechanical transmission shaft system and additional active components.

The A350 XWB's high lift system adds more functionality to the wing, allowing for greater dynamic response and flexibility [4], [5]. Compared to state-of-the-art track-carriage kinematics or simple dropped-hinge kinematics the A350 XWB has dropped-hinge kinematics, designated as the "advanced dropped hinge flap", with spoiler droop functionality using a "software coupling". Depending on the flap setting, the computer-controlled spoiler automatically moves into the most efficient position.

The advanced flap concept provides benefits during cruise as well. Rather than having a static wing profile, the new flap allows varying camber (wing profile) options as the aircraft burns fuel and loses weight during flight. Drag can be reduced by up to two per cent at high gross weights, resulting in considerable fuel economies. This is achieved by moving both flaps together a small amount - either up or down - which allows to tune the peak lift over drag to improve the performance.

And for the first time on an Airbus, the flap system will have the capability for differential inner and outer flap settings (DFS). Weight savings on the order of half a tonne for the wing box are feasible by using differential flap settings to alleviate loads by changing the centre of lift for loads management. DFS is achieved by a gearbox with a motor mounted between the outer and inner flap.

From [6] and [7] it is understood that the B787 incorporates a trailing edge variable camber (TEVC) function that enables drag reduction in cruise. The motion is driven by an electric power drive unit integrated in the transmission shaft.

4 DISTRIBUTED FLAP DRIVE ACTUATION

An advanced high lift system architecture with distributed active controlled flap actuators is rather a leap in high lift system technology than an evolutionary step. Motivation for the development of this topology was the vision of a highly flexible system with independent controlled flap panels as enabler for additional functionalities for the wing trailing edge as well as improvements at design-engineering, manufacture and assembly. Different system architecture topologies that are based on similar building blocks are conceivable offering more flexibility and functionality. These building blocks were/are developed in recent national and European funded R&T projects ProHMS (Lufo2), HISYS (Lufo3) and NEFS (FP6 3rd Call) since 1999/2000.

4.1 System topologies for individual controlled flap panels

Several system topologies have been designed and evaluated within the above-mentioned R&T projects, ranging from local shafts on each flap panel with different actuation arrangements to fully independent actuated drive stations as depicted by

some examples in Figure 6. Within this manuscript the system architecture, developed within the HISYS project, will be presented in more detail. This concept is characterized by complete independent drive stations thus getting rid of the complete transmission shaft and assuring highest flexibility with reduced design-engineering and installation effort. This actuation system was developed as prototype and tested on an integration test rig at Airbus.
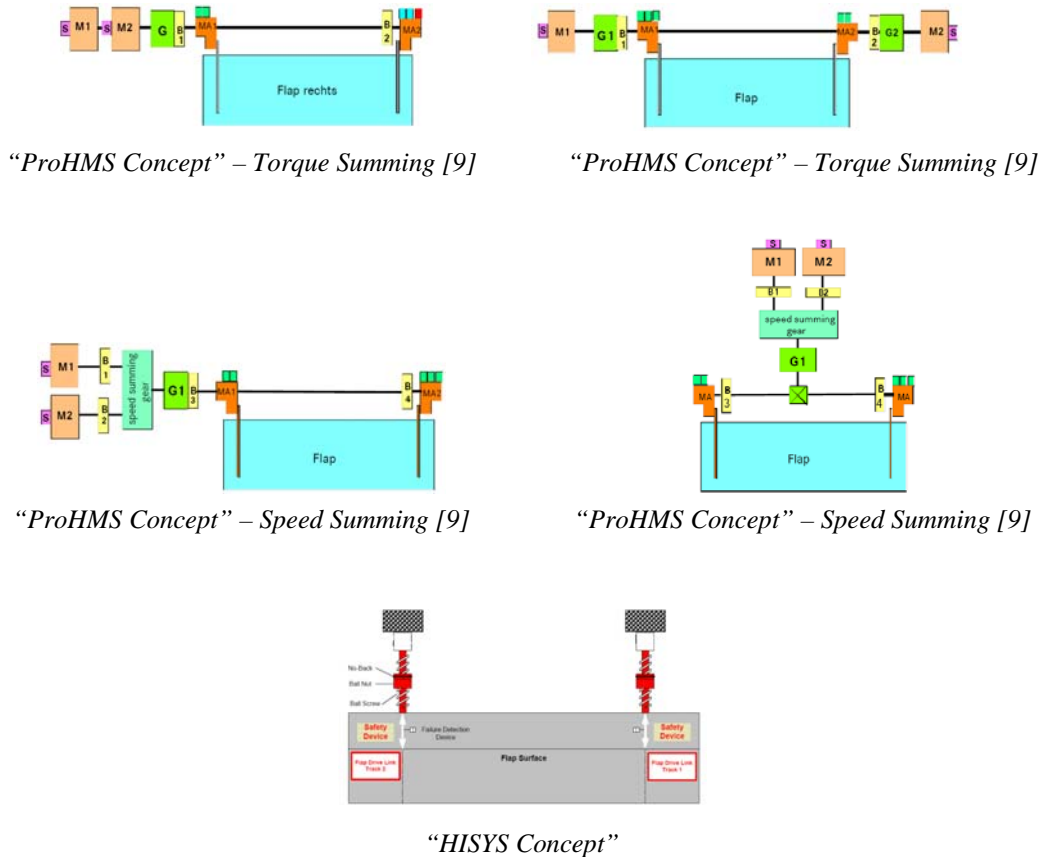

"ProHMS Concept" – Torque Summing [9]

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"ProHMS Concept" – Speed Summing [9]

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"HISYS Concept"

Figure 6 – Examples of distributed flap actuation topologies

4.2   Fully independent flap actuation system

Overview

The Airbus A320 was selected as reference aircraft for the development of the distributed flap drive system technology. Requirements for the distributed flap drive system (DFDS), derived from the reference aircraft, comprise installations space, loads, aero and system performance requirements as well as competitiveness in terms of weight. The fully independent flap actuation system (see Figure 7) is built with an electromechanical actuator at each drive station without a mechanical linkage (transmission shaft) between the stations. Thus synchronous deployment or controlled differential deployment has to be ensured electronically by actuator control electronics (ACE) and slat flap control computers (SFCC).
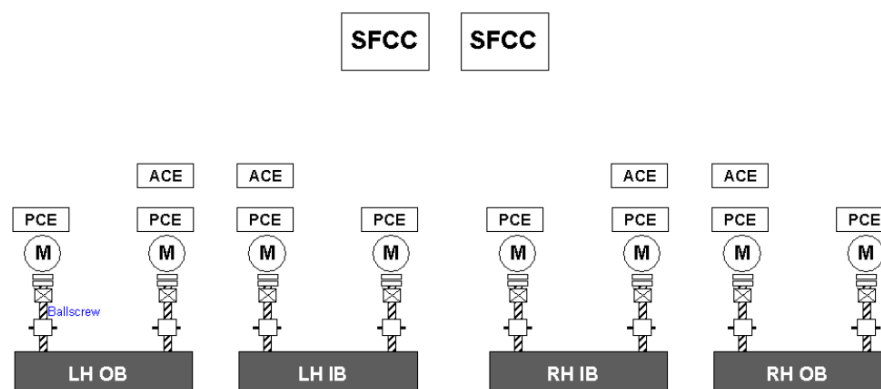
Figure 7 –Fully independent flap actuation system

Controlled differential flap setting (DFS) requires suppression of the interconnection strut between inboard and outboard flap panels used in Airbus state-of-the-art high lift system design. This interconnection strut acts as a fail-safe load path in case of a single structural failure like a drive strut rupture or "free wheel" within an actuator. These failure cases would cause twist of the flap panel in case of a fowler kinematics or 4-bar linkage kinematics due to a statically undefined situation. For DFDS with DFS capability fail-safe actuators at each drive station must compensate the missing fail-safe load path.

Fail-Safe Actuation Concept

Several fail-safe actuation concepts have been studied and finally a fail-safe ballscrew was selected. Compared to other possible fail-safe actuation solutions, fail-safe ballscrews can be regarded as state-of-the-art as they are used for trimmable horizontal stabilizer actuators (THSA) and some flap actuation systems. Nevertheless avoidance of hidden failures becomes a more and more challenging certification requirement thus imposing additional monitoring capabilities compared to former design solutions.

Prototypes of the actuation system have been developed for track 3 and track 4. Due to different load requirements and installation space of these stations two different arrangements were selected. Figure 8 and Figure 9 depict the arrangements of track 3 and track 4 actuators. In both cases the actuator consists of a fail-safe ballscrew with an inner tie-rod, fail-safe nut, fail-safe u-joint (resp. fail-safe gimbal) and two brakes. The primary brake is connected to the primary load path of the ballscrew, the secondary brake is connected to the inner tie-rod, assuring that the flap panel can be safely locked wherever a possible rupture occurs within the actuator.

The track 4 actuator is a side attached direct drive assembly with the motor located on the centerline of the ballscrew. The track 3 actuator is side attached with the motor located at the opposite side of the track. The motor is connected to the ballscrew by a right angle gearbox.

Monitoring of the ball circulation assures detection of possible ball migration and thus avoids possible hidden failures of this critical area.
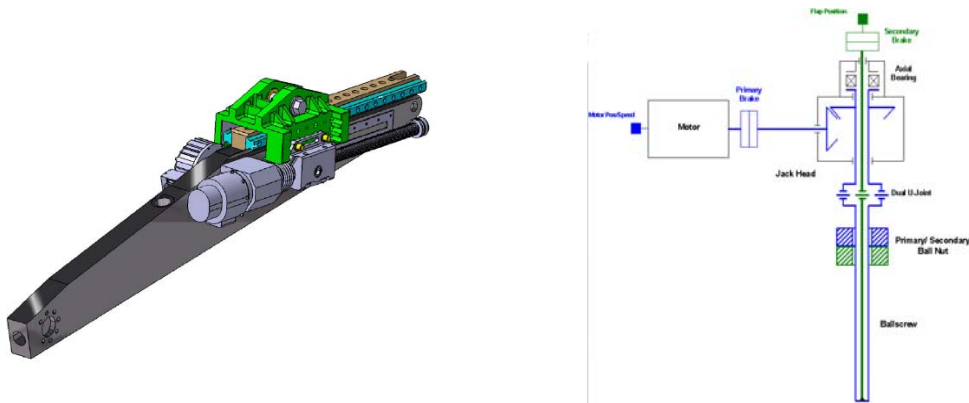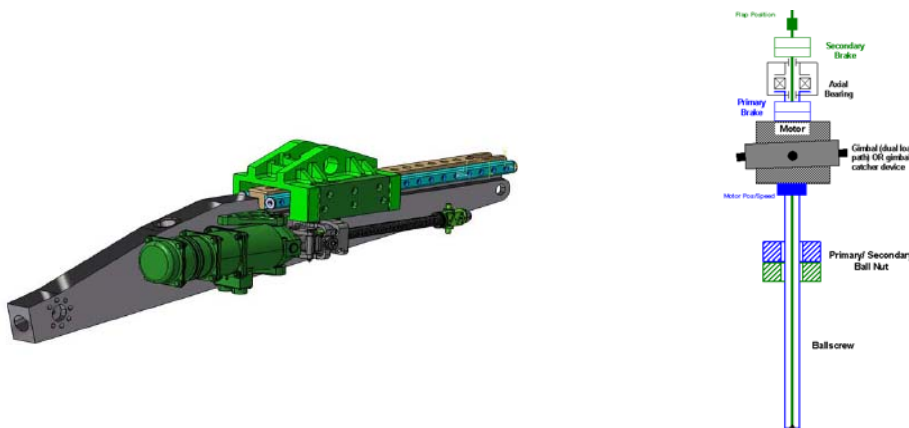
Figure 8 – Track 3 Actuator

Figure 9 – Track 4 Actuator

Redundancy Concept

Contrary to the current PCU design (refer to Chapter 2) where two (hydraulic) motors are coupled by a speed-summing differential gearbox the electric motors of the DFDS system are built with intrinsic redundancy. In a standard motor, one motor phase consists of several series- or parallel-connected windings spreading over several slots. To accomplish integrated redundancy each stator tooth is equipped with one concentrated winding. In addition, each of these coils must then be excited autonomously to be truly independent from other coils – both galvanically and thermally. Thus, a failure like open- or short-circuit in one coil cannot propagate or affect other coils, which makes the machines fault tolerant to some extent. The performance in degraded modes improves with the degree of partitioning and autonomization. While a conventional solution with active/standby redundancy would result in 200% weight and 50% performance for a single electric failure compared to one single standard motor designed for 100% performance, 120-140% weight and appr. 70-90% performance should be achievable with intrinsic redundancy for a single electric failure. Of course, this is strongly dependent on the diameter of the machine and the number of coils per independently supplied phase [10].

The PCE constitutes of a PCE controller and a PCE amplifier. The PCE amplifier converts the current command into corresponding voltage excitation of the motor and is also built as internal redundant unit according the motor redundancy.

Control and Monitoring
The flap panel actuators are controlled and monitored by power electronics (PCE) and actuator control electronics (ACE). ACE and PCE build a cascading control loop structure with current and speed control closed within the PCE and position control and trajectory targets within the ACE (see Figure 10). The ACE's assure a synchronous deployment of both actuators of one flap panel thus avoiding twist or skew of the flap panel. The ACE's receive the position command from the SFCC's, which control and monitor the complete high lift system and assure synchronous deployment or controlled differential deployment of all flap panels.
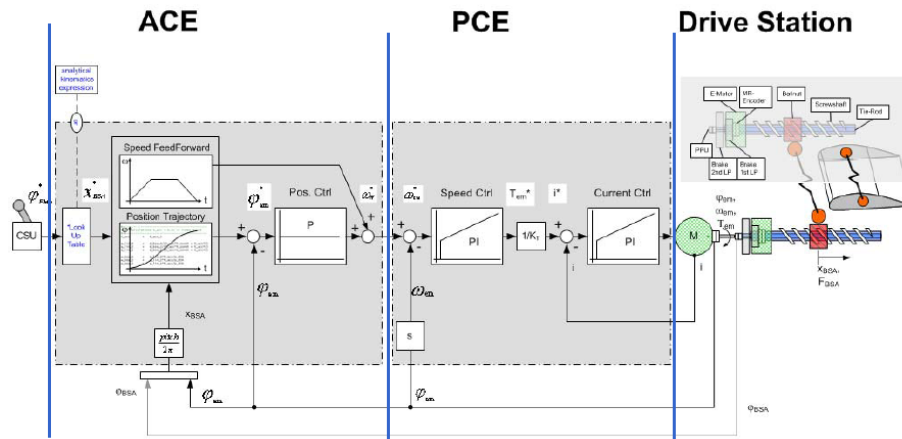

Figure 10 – Cascading control structure

4.3   Potential benefits of the distributed high lift actuation system

A brief summary of the expected essential benefits is given in the following subchapters. Which of these benefits can be capitalized at the end for a target aircraft depends on the operational-, functional- and performance-requirements as well as aircraft configuration and must be balanced against system repercussions due to increased system complexity.

Operation in degraded mode with only one flap panel pair
Due to complete independence of all flap panels the aircraft could be operated for a limited period of time with only one flap panel pair (inboard or outboard) in case one drive station is lost (e.g. due to a jam of an actuator). This would not be possible with a central transmission shaft system where a jam of one actuator or a gearbox would result in a loss of the complete flap system due to an immobilization of the transmission shaft.
Operation in degraded mode would increase operational reliability (OR). Nevertheless this degraded operation mode is only possible if the high lift performance of the aircraft is sufficient with one flap panel pair. Probably the wing and high lift configuration has to be designed to utilize this potential.

Load control -> structure weight reduction
DFS enables loads management by adjusting the center of lift (CoL) to reduce the

wing root bending moment in critical load cases. Therewith the structure weight can be reduced. The quantified weight potential for the A350 XWB wing box is roughly 500 kg, as described in chapter 3.

L/D improvement, drag reduction
DFS as well as variation of the wing profile can be used to optimize the lift distribution to reduce drag during cruise. The quantified drag potential is up to two percent at high gross weight for the A350 XWB, as described in chapter 3. This drag reduction results in considerable fuel savings.

Accelerated vortex decay
The differential deflection during approach results in an additional vortex that interferes with the outboard vortex resulting in accelerated vortex decay. This effect was successfully demonstrated within the European funded AWIATOR project on an A340 aircraft and can be regarded as an enabler to reduce the separation distance after mid to heavy weight aircrafts.

Electronic rigging & lateral trimming
A limited differential flap setting between LH and RH wing utilizes electronic rigging to compensate for manufacturing tolerances instead of the use of wedges that would conventionally be fixed under the trailing edge or adjustable bearings. Electronic rigging saves weight and reduces the rigging effort during assembly.
Furthermore LH/RH DFS can be used to compensate One Engine Inoperative (OEI) or fuel imbalance situations.

Reduced installation effort
As described in chapter 2 the state-of-the-art transmission system consists of a high number of different transmission shaft elements with joints, bearings, attachment-brackets, gearboxes, torque limiters, etc. The distributed flap actuation system, installed at the track beams, would drastically reduce part numbers and the installation effort at the trailing edge of the wing due to reduced amount of components and therefore supports the "Flash FAL" (FAL = Final Assembly Line) strategy. Furthermore the design-engineering effort for the routing of the shaft along the wing trailing edge is drastically reduced.

DFS could also support Clmax increase as well as reduced THS (trimmable horizontal stabilizer) sizing by appropriate CoL adjustment. These benefits will not further be discussed in this manuscript.

5   CONCLUSION

State-of-the-art high lift system optimisation capabilities reached a plateau and are limited to small local improvements. Further aircraft performance improvements and improvements at design engineering, manufacture and assembly, enabled by the high lift system, require a technology step-change.
An advanced high lift system architecture with distributed active controlled and mechanically independent flap actuators was presented. This distributed architecture is more a leap than an evolutionary step. Once additional flexibility is incorporated

and developed towards state-of-the-art there is a potential for further technology evolutions by extending additional functions with increased confidence in this architecture.

Nevertheless the higher number of active components (motor and power electronics) results in slightly higher system costs and DMC's that must be weighted against the functional benefits and reduced manufacturing effort. Depending on the requirements of a target aircraft different arrangements of the distributed actuation concept are possible, using the building blocks of the distributed flap drive system. One example of an architecture with reduced number of motors and power electronics is an architecture with a local shaft (see Figure 11), but this architecture requires a slight increase of manufacturing effort compared to the fully distributed actuation system.
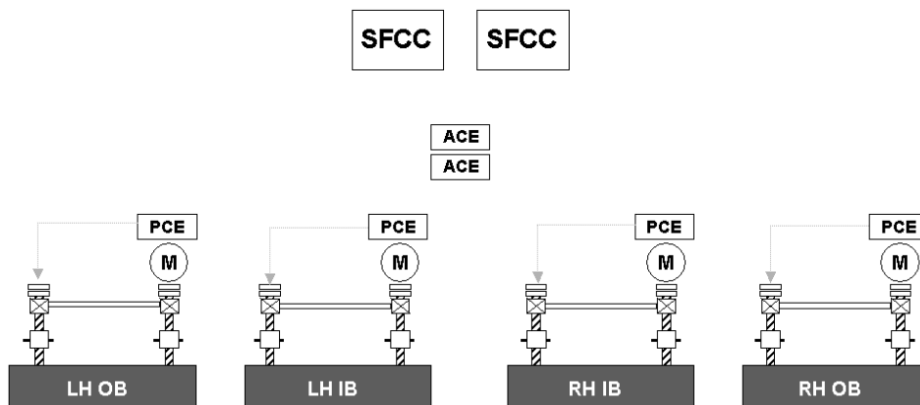

Figure 11 – Distributed flap drive system with local shafts

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