INNOVATIVE APPROACHES TO ELECTROMECHANICAL FLIGHT CONTROL ACTUATORS AND SYSTEMS

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ABSTRACT
This paper focuses on key challenges of electromechanical actuation systems with multiple degrees of freedom for two specific applications. One is an electromechanical fixed wing trailing edge flap actuation system enabling both differential and asymmetric flap setting for a transport aircraft. The second one is an electromechanical actuation system for the swashplate of a helicopter.

To optimize the system weight, initial fit cost and MTBF of the trailing edge flap actuation system different system topologies are investigated. Further innovative approaches are invented for feedback sensors, electric motors, mechanical transmissions and control systems trying to take benefit from the specifics of the electromechanical actuators like their inherent positioning accuracy, high control bandwidth and speed independent torque limiting capability. The swashplate system of a helicopter provides lift, pitch and roll control. The loss of any of these control functions is classified catastrophic mandating a very robust and fault-tolerant design of the 3-degree-of-freedom swash plate actuation system. Different architectures of such actuation system are presented that are fail-operative regarding major mechanical failures and dual-fail-operative for all other failure modes whose probability is not extremely remote. These architectures are evaluated in terms of technological risk, weight, and installation space.

KEYWORDS
EMA, flight control, swashplate, helicopter, actuator, actuation system, fault-tolerance, trailing edge flap

I INTRODUCTION
Future flight control system architectures will be based on “More Electric” or even “All Electric” concepts promising benefits mainly in terms of efficiency, weight and maintenance. Even though electric actuation is gaining considerable momentum competing with conventional hydraulic systems the big challenge in designing electromechanical actuation systems is to achieve both quantifiable improvements and compliance with the stringent requirements in terms of environment, operational reliability and safety [1].

1.1 Trailing edge flap actuation system
The high lift system of large transport aircraft comprises leading edge slats and trailing edge flaps and is deployed during take-off and final approach, providing additional lift to get or stay airborne at low speeds.

Most current production flap drive systems have a low efficiency, require a high installation effort with shafts and gearboxes distributed across most of the wing trailing edges and offer no functional flexibility like e.g. differential surface deflection. For some modern a/c designs (e.g. 787, A350) additional functions like differential flap setting are implemented by an evolutionary change to established flap drive system concepts [2, 3, 4, 5].

It is proposed and investigated in this paper to develop a distributed electrical flap drive system that is completely integrated with the flap support structures. This new technology is an enabler for new functionalities, which are or have been developed and assessed in related research (e.g. AWIATOR and NACRE [6] projects). It may also provide an increase in the fault tolerance of the high lift system.

The presented work was carried out under the NEFS project (New track integrated Electrical Flap drive System) which is funded under the 6th Framework Program (FP6) of the European Commission and Coordinated by EADS Innovation Works [7]. The project team involves 13 partners from industry and academia. The project duration is from March 2007 to June 2011.
1.2 Swashplate actuation system

One peculiarity of electromechanical actuators (EMAs) compared to well established and field proven hydraulic actuators is that the mechanical jam of an electromechanical actuator has to be considered as a credible failure with a probability of occurrence of larger than $10^{-8}$ per flight hour. This is due to the fact that EMA operation relies on mechanical components not being certified as critical parts – and thus not being trusted never to fail – e.g. ball screws or roller screws, respectively. Since in a conventional swashplate actuation arrangement comprising three actuators, the jamming of any one of those actuators would be catastrophic, the system has to be designed jam-tolerant – either by conceiving an appropriate actuator arrangement or by providing highly available, jam-tolerant actuators. Prior work is reported in [8], [9] and [10].

This paper focuses on the introduction of arrangement variants using customized EMAs based on existent technology and satisfying the safety requirements of a primary flight control system by providing sufficient system redundancy. A twofold strategy is pursued to identify promising actuation architecture variants. First, a top-down approach is made investigating several actuator arrangements operating the swashplate. Secondly, the design of possible system architectures is presented in a bottom-up approach. The need for additional safety devices is discussed, namely power-off brakes and disconnect devices. Availability requirements for these devices are derived from the safety analysis data of the respective system architecture. Finally, the results of both a quantitative weight assessment and a semi-quantitative evaluation based on defined target criteria are presented.

II TRAILING EDGE FLAP ACTUATION SYSTEM – NEFS PROJECT

2.1 Objectives and expected benefits

The main objective of NEFS is to develop an alternative to a “traditional” flap drive system comprising a distributed electrical flap drive system that is completely integrated into the flap support structure (Figure 1). This includes a redesign of the flap beam providing the opportunity for an innovative composite design and enabling an optimized system-structure solution. The focus in this paper will however be on the project activities regarding system design.

The expected benefits of the proposed flap drive system are:

⇒ new functionalities of the high lift system via differential flapping setting (DFS), like accelerated vortex decay, roll trim and roll control support
⇒ reduced operational interruptions caused by high lift systems
⇒ improving the drive system efficiency
⇒ L/D improvement in cruise
⇒ weight reduction of the flap track beam due to highly integrated composite design
⇒ cost reduction in the manufacturing and assembly of the flap track beam due to the minimized number of parts
⇒ improved maintainability

⇒ reduced installation effort (for design and manufacturing).

The joint research effort of the consortium members will enable them to evaluate the benefit of the investigated approach and to apply the validated technologies for future advanced aircraft and wing configurations.

Figure 1: Main objectives of the NEFS project

2.2 Project Consortium

To achieve the objectives set out in the previous chapter, a consortium was formed comprising EADS and Airbus as the system integrator and producer of the end-product, major players and expert SMEs (Small and Medium sized Enterprises) of the European aircraft system supplier industry (Diehl, Saab, Goodrich, BAE-Systems, Stridsberg), aerospace structure suppliers (RUAG, ACE) as well as universities and research institutions providing front end research in the affected fields of technology (DLR, University of Kaiserslautern, Aalto University (Helsinki) and Warsaw University of Technology).

An overview on the national composition of the consortium and the budget breakdown by type of organization is shown in Figure 2.

Figure 2: Budget share by nationality and organization type

2.3 System Architecture

Symmetric flap actuation on both wings is paramount for safe flight and is traditionally assured by coupling all flap surface actuators to a torque shaft system, which extends along the rear spar of both wings and is driven by a centralized hydraulic, electric or hybrid motor (PCU). The actuators are located at or near special flap support structures which transmit the lift produced by the movable flap surfaces to the wing. The system architecture of a conventional flap drive system is displayed in Figure 3. The system features
the shaft assembly including several gear boxes (BGB, KGB), rotary actuators at the flap support stations, wing tip brakes (WTB) to account for shaft system or gear box failures and several sensors for system control, cockpit display and failure detection (FPFU, IPPU, APPUs). Further important elements are the interconnection struts between inner and outer flap panels (to safely block and a flap panel after an actuator free wheel failure) and several torque limiting devices (STLs=system torque limiters and torque limiters at all the actuators). These torque limiters are needed to protect the drive train elements of one wing or one actuator from excessive loads in case of a jam at that wing or actuator.

As in the NEFS approach the failure of any drive station is catastrophic if it cannot be transferred into a safe locking in position of the panel, a multitude of additional feedback and control lanes as well as safety devices have to be applied and a dual-load path design of the actuators is necessary. Regarding this additional hardware effort and complexity compared to more conventional flap drive systems and implications on cost, weight and MTBF the MPP architecture is superior to the MPS architecture and was selected for further investigation and hardware validation after a detailed evaluation study. An envelope allocation and integration model for the hardware validation platform is shown in Figure 5. It is worth noting that also the number of electronics units (power and control) and computer lanes could be substantially reduced by applying the MPP approach while retaining individual controllability of each flap panel. A further reduction is possible by combining the functions of the ACSs and PCEs in one electronics unit then denoted Flap Actuator Control Unit (FACU).

Many of these elements are no longer necessary in the system architectures investigated in NEFS – one denoted Motor Per Station (MPS) and the other one Motor Per Panel (MPP) approach (Figure 4).

The schematics show the flap panels, the actuators at the support stations comprising ballscrew assembly, gearbox, motors (M) and brakes, the Power Control Electronics (PCEs) driving the motors and the Actuator Control Electronics (ACEs) controlling and monitoring the individual flap panels. The SFCCs (Secondary Flight Control Computers) were taken from a reference aircraft and are out of the scope of this work. Common to both architectures is that they dispose of the interconnection struts and (most of the) shaft system which enables individual positioning of each flap panel and eases a/c integration of the flap drive system respectively. The torque limiters are no longer needed because the central shared drive unit being overpowered for the individual actuator is replaced by local electric motors featuring reliable torque limiting.

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2.4 Innovative Technology Features

Trajectory
The control bandwidth and accuracy of EMAs are typically superior to comparable hydraulic systems. For the distributed flap drive system also the transfer function of the drive train allows for a much better control bandwidth as compared to a system with an extensive and relatively compliant shaft system. One consequence of these facts is that the operation trajectory, i.e. the function of commanded position and speed over time, can be changed in a way that reduces impact loads on and fatigue of the actuation system. Figure 6 shows a typical trajectory of a conventional flap actuation system according to Figure 3 (orange plot) compared to the trajectory realized for the MPP architecture (green plot).

For the studied electromechanical actuation systems it is well possible to control the system to arrive at its target position at zero speed and to apply the brakes only when the system has
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In the conventional system the central motor is throttled down to a lower speed when approaching the target position. Once the target position threshold is reached the brakes are applied into the running system causing impact load peaks and possibly fatigue to the brakes.

**High performance brakes**
The distributed flap actuation system under investigation features a much lower system inertia and higher stiffness than architectures with a central drive unit and an extensive shaft system. While this is beneficial for a good control performance it also has drawbacks: In case of free wheel failures of individual actuators or mechanical failures of drive train components the low inertia in combination with high aerodynamic loads on the flaps leads to a very rapid acceleration and development of asymmetry between or twisting/skewing of flap panels. Both are potential catastrophic hazards for the aircraft. Thus brakes are designed into the actuation system that are capable of arresting the flap panel through a secondary load path. The requirements for these brakes are quite challenging. Their torque must be high enough to overcome aerodynamic loads and to quickly decelerate the system while at the same time their reaction must be extremely swift to limit asymmetry/skew/twist built up before the brake torque is being applied. Further the maximum torque applied from the brake may become a limit load for drive train components. Figure 7 displays the maximum allowable time until the brake starts to exert force after a free wheel failure. This time includes the built up of a detectable error signal, propagation delays and confirmation cycles in the control system and the engagement delay of the brake itself. The k-factor provided in Figure 7 and Figure 8 is defined by the maximum brake torque related to the maximum torque required to react the aerodynamic loads and is thus a measure of brake authority. The higher the brake authority and the higher the mass moment of inertia of the system the longer is the allowable total brake engagement delay. A typical value for the system investigated in this paper is 20ms.

Making assumptions for the aerodynamic loads, the engagement delay associated with the brake and the “propagation delay” in the control system one can deduce the necessary monitoring thresholds when using the speed or position signal to detect the free wheel failure. The results for values typical for the investigated system are shown in Figure 8.

**Magnetic gear unit**
Gearboxes are a typical element of EMA systems to adapt the high speeds and low torques of an electric motor in a weight optimized system solution to the actuation loads and speeds actually required.

In the NEFS project Goodrich Actuation Systems is investigating the application of a magnetic gear unit instead of a mechanical one (Figure 9). Advantages of magnetic gear boxes are the inherent torque limiting feature and the absence of mechanical contacts and play. The first may lead to lower design loads and reduced weight of system components whereas the latter avoids fatigue problems common with mechanical gears.

**Geared GMR duplex position feedback**
Another innovation applied in the NEFS project to a flap actuator developed by Saab Avitronics is a duplex GMR (giant magnetoresistive effect) based geared multi-turn angular position transducer (Figure 10) which is more compact and lightweight than conventionally used LVDTs or RVDTs. Further it features multiple sensing stages, internal signal processing and digital communication interfaces providing for a much better resolution especially at a high range of revolutions.

**High p.u. inductance motor designs**
High p.u. inductance motor designs along with some other special motor design features like mechanical, magnetic and thermal segregation of the stator phase windings are common to applications where for safety and system availability reasons several redundant electric motors are used in a torque
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summing arrangement [11]. This is the case for the actuation systems investigated in this paper. In a torque summing arrangement a failed motor with a short circuit fault will still continue to turn driven by the redundant unit. When applying the very weight efficient permanent magnet synchronous motor (PMSM) technology this results in the failed motor, phase winding or winding turn to operate in a generator mode. Standard electric motors feature per unit phase inductances in the order of magnitude of 0.1 p.u. which corresponds to the lines plotted in blue in Figure 11. One can easily see that the normalized thermal losses (left) and braking torque (right) become prohibitive. Suitable per unit inductances are in the range of 0.7 to 1 p.u. Higher values – although beneficial for motor thermal losses and braking torque – have negative implications on the motor drive electronics (PCE) as at a given available voltage level this results in a higher necessary current rating of the unit. Within the NEFS project Goodrich Actuation Systems and Saab Avitronics in cooperation with Stridsberg AB are responsible for the development of bespoke electric motors. The designs are already successfully validated by simulation.

III SWASHPLATE ACTUATION SYSTEM

3.1 Actuation Arrangements

EADS IW designed a set of possible actuation arrangements emerging from the top-down approach. Three concepts are shown in Figure 12 – Serial, Parallel, and Grouped positioning of the actuators. They all rely on the basic idea to provide jam tolerance by means of redundant actuators, whereas their operation philosophies differ substantially.

The failure management of all three concepts relies on the fact that each actuator is capable of compensating the performance of a faulted adjacent actuator. As to the Serial and Parallel arrangement, the mechanical jam of a single actuator can be tolerated. However, a free wheeling actuator would result in the free wheel of one of the three legs, being tantamount to the loss of control of the entire flight control system. As a consequence, an additional power-off brake is required as a safety device blocking the screw of the affected actuator. Since each of the six EMAs of the Grouped concept has its own attachment point at the swashplate, a free wheel could be compensated, whereas a mechanical jam would be catastrophic. Thus each actuator must be equipped with a disconnect device mechanically converting the jam into a free wheel.

3.2 Optimizing Redundancy

The required number of redundant components for the different swashplate actuator arrangements can be determined by combining the quantified failure modes of mechanical and electrical components [12] with simple Markov models. As to the electric motors, this analysis indicates the need for at least two motors per actuator, i.e. 12 motors in total for the actuator arrangements displayed in Figure 12. Each of them needs its associated power stage. A straightforward approach would require the same amount of Actuator Control Electronics (ACEs) each providing two lanes (command and monitor) to facilitate failure detection. This yields 24 computer lanes in total, with the corresponding negative implications on weight, cost and MTBF (mean time between failures). However, the command functions can be integrated in a reduced number of ACEs while still complying with the safety requirements. The reduction potential is assessed by means of a permutation analysis. Figure 13 shows two examples for the Serial and the Parallel concept (identical control architecture) with the vertical rectangles and the adjacent circles representing actuators (mechanical part) and motors.

Using six ACEs, three different degraded modes are possible after the failure of two ACEs (which is more severe than the failure of two electric motors or power stages). Reducing the number to a total of only three ACEs and applying the proper mapping of ACEs to electric motors, just one scenario has to be taken into account. Even though component losses are...
more severe than for system architectures comprising a larger number of ACEs, safety requirements can still be met – and at a better system MTBF due to lower part count.

Design load assessments considering the relevant failure cases of all concepts reveal that a reduced number of ACEs results in significantly increased motor and actuator loads for some of the variants and permutation mappings, whereas it does not have any effect on the design loads for others. Thus, the benefits in terms of mass and cost reduction achieved by the reduced number of ACEs can be fully exploited for the latter. For the first group of system architectures these benefits have to be traded against the increased design loads of power electronics, motors and actuators and their implications.

An exemplary system architecture for the Serial arrangement is shown in Figure 14. It is apparent that the utilization of a reduced number of ACEs is reasonable for this design variant. Relying on the shown permutation, the system is capable of surviving even two arbitrary component failures (except a jam).

3.3 Safety Analysis

In order to quantitatively prove compliance with the certification specifications, safety analysis in terms of a Fault Tree Analysis (FTA) is performed. A combination of FTA and Markov models according to the standard EN 61025 is conducted, allowing to simplify the fault trees significantly [13]. All actuators being identical in terms of components and operation, it is sufficient to model a single actuator and to insert a Markov model above acting as a multiplicator. The safety analysis proves the required system availability to be achieved, and identifies the weak spots within the architecture. For each of the investigated concepts, the particular safety device, i.e. the power-off brake or the disconnect device, respectively, turns out to be by far the most critical component. Two main requirements emerge from the analysis.

First, the respective safety device may not fail in case it is needed. For instance, the power-off brake of one actuator in the Serial arrangement may not fail to engage if both motors of this actuator failed. Second, the safety device must not unintentionally be activated. E.g. two unintended brake engagements at the same leg of the Serial concept would be catastrophic. Figure 15 shows the according Markov models for the described scenarios.

3.4 Evaluation and mass assessment

To perform a down-selection of the devised system concepts a suitability score for each of the concepts is calculated using a method for technical evaluation. The global score for each concept is determined as a weighted average of a set of defined target criteria:

- Mass
- Installation space
- Technological Risk
- Complexity

To obtain a representative collection of technical parameters a selection of easily quantifiable technological characteristics is defined, e.g. number of motors, design power, actuator stroke etc. These parameters are assigned to a consistent scale by applying an evaluation metrics based on guideline VDI 2225 [14]. By means of an “Influence matrix” the influence of each characteristic on the particular target criteria can be modeled. Depending on the number of characteristics impacting a target criterion, an internal weighting factor is calculated. A balanced score card including the presented variants is shown in Figure 16.

As to the overall system mass, detailed analysis has been performed by means of a mass assessment of some concepts. It is based on the loads derived under consideration of all relevant failure cases and the corresponding models. Using the mass of a corresponding hydraulic system as a 100%
reference. Figure 17 reveals that some of the conceived electromechanical actuation systems are capable to compete with their hydraulic counterpart in terms of system mass. Arrangement 3 refers to the Grouped arrangement introduced earlier in this paper whereas arrangements 1 and 2 are further concepts that were investigated. The fourth bar represents a 3-EMA arrangement which is 1 fail-operative with respect to all electrical and some mechanical failures but without any jam tolerance (similar to present hydraulic swashplate actuation systems). It is obvious that – if applying the same redundancy level than provided in today’s helicopters – an EMA system could well compete with its hydraulic counterpart in terms of weight.

CONCLUSION

“More Electric” and “All Electric” concepts for a/c flight control applications are evolving rapidly and promise higher efficiency while constantly improving system weight, envelope, MTBF and cost. This will eventually – rather sooner than later – result in electromechanical flight control actuation systems replacing their hydraulically power or hybrid predecessors. Improvements of EMA systems are taking place both on the architecture and on the component level. Some aspects of this evolution process have been presented in this paper.

NOTATIONS

Variables and parameters

$\lambda_{\text{Brake.SP1}}$ Safety device requirement No. 1 (failed to engage) for Serial concept

$\lambda_{\text{Brake.SP2}}$ Safety device requirement No. 2 (uncommanded engagement) for Serial concept

$\lambda_{\text{FW.SP1}}$ Free wheel rate of an arbitrary actuator of the Serial concept (both motors free wheeling)

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