An Integrated Design Approach for Advanced Flight Control Systems with Multifunctional Flight Control Devices

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Flight Control Systems (FCS) of today's commercial transport aircraft consist of highly optimized and mainly mono-functional flight control surfaces. The knowledge-based configurations and architectures are often limited to small and local improvements under high effort. Various research studies show the potential of functional enhancement of the FCS to increase the aircraft efficiency or performance. Consequently, the transition from a knowledge-based to a functional-driven design is recommended. The objective of this contribution is to enable an integrated design of advanced FCS with multifunctional flight control devices. This integrated design approach considers new technologies and concepts for innovative and advanced FCS in early aircraft design phases. Finally, a brief case study of a concept aircraft with advanced FCS is conducted and the preliminary results are presented.

I. Introduction

RECENT Flight Control Systems (FCS) of commercial transport aircraft consist of highly optimized flight control surfaces, which are conventionally classified as primary or secondary – depending on their function and criticality. This mainly knowledge-based design with generally mono-functional allocation is often limited to small and local improvements under high effort [1–3]. Consequently, various research studies present new technologies and concepts for functional enhancement of the FCS to increase the aircraft efficiency or performance during certain flight phases.

These aspects can be especially observed for the high-lift control systems of commercial transport aircraft: the complexity of the trailing-edge flap configurations has been continuously reduced in the last 25 years, see Fig. 1 (left). However, a plateau in terms of benefits on aircraft level has been reached. Whereas, the latest introduced transport aircraft provide additional control functions for further improvements. Examples are the Cruise Variable Camber (CVC) function for aerodynamic improvements or the Differential Flap Setting (DFS) function for wing load control to save wing structure mass, see Fig. 1 (right). In addition, future improvements are expected by blending primary and secondary control functions with distributed control surface architectures for trailing-edge flaps [4, 5].

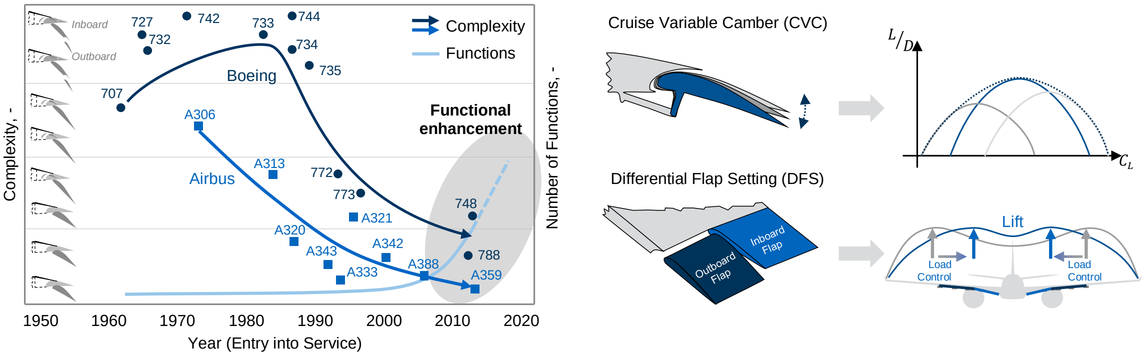

Fig. 1 Evolution of the trailing-edge flap configurations of the high-lift control systems and examples of functional enhanced trailing-edge flaps [5].

Beside the means of functional enhancement, the trend towards More-Electric Aircraft (MEA) leads to considerable changes on aircraft system level, and thus has a decisive impact on the FCS architecture design. Furthermore, to

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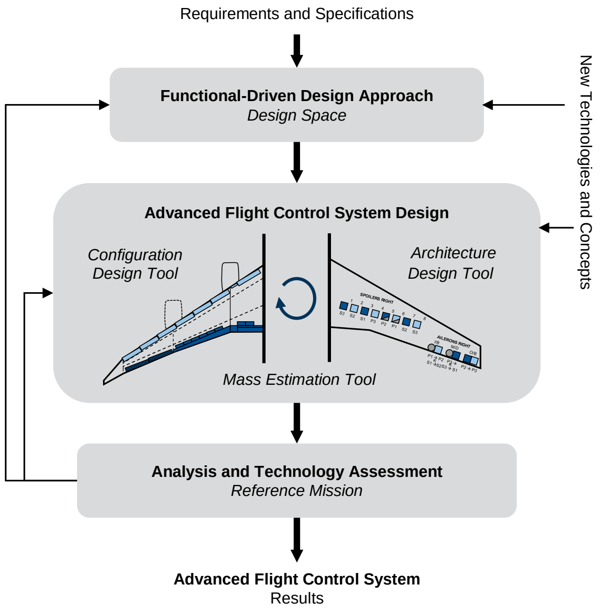
enable the assessment of new technologies and concepts, an early integration of the advanced FCS design into the conceptual or preliminary aircraft design is important.

However, only few studies show how functional enhancement or new technologies for FCS can be considered and integrated in early aircraft design phases. Based on these findings, a transition from a knowledge-based design to a functional-driven design of FCS is recommended. The intent of a functional-driven design approach is to increase the solution space and to enable multifunctional concepts [1, 6].

The overall design method for advanced FCS is shown in Fig. 2. The first stage of the design method is a functional-driven design approach to explore the potential design space, and to derive several concepts of advanced FCS [6]. In the second stage, the configuration and architecture of an advanced FCS concept is designed in an integrated and iterative design process. Finally, a reference aircraft with the advanced FCS and a reference mission can be modelled to create a basis for an aircraft-level analysis and assessment.



New Technologies and Concepts (examples)

- More Electric Aircraft (MEA)
- Electric Actuators
- Active Flow Control (AFC) technologies
- Functional Enhancement of the FCS
- Adaptive and flexible (wing) structures
- Novel propulsion concepts
- …

Definitions

- **Advanced flight control systems** consist of multifunctional flight control devices that have (“by design”) or fulfill (“by use”) multiple control functions
- **Flight control devices** are movables, surfaces or technologies which provide, support, or enable single or multiple flight control function(s).

Fig. 2 Overview of the overall method for the design and analysis of advanced flight control systems in early aircraft design phases [6] (modified).

The purpose of this contribution is to present the integrated design approach for advanced FCS in early aircraft design phases. Here, advanced FCS consist of multifunctional flight control devices that have (“by design”) or fulfill (“by use”) multiple control functions. Flight control devices are defined as movables, surfaces or technologies which provide, support, or enable single or multiple flight control function(s). The integrated design approach includes the FCS configuration design, the FCS architecture design and the FCS mass estimation, within the framework of conceptual or preliminary aircraft design. Finally, as a brief case study, the presented integrated design approach is applied to a generic transport aircraft with multifunctional trailing-edge devices and a distributed electric drive architecture. The preliminary results are compared to a baseline configuration with a conventional flight control system architecture.

II. Background and State-of-the Art

In general, Flight Control Systems (FCS) of commercial transport aircraft are divided in primary and secondary flight control. The primary flight control system consists of flight-critical flight control devices (or functions) and is continuously activated to enable the attitude and trajectory control of the aircraft. Whereas the secondary flight control system modifies the aircraft (wing) configuration during different flight phases (e.g. high-lift system, spoiler). They are classified as less critical, but in general they are not less essential for the sizing and efficiency of transport aircraft. Furthermore, with the introduction of electronic flight control systems and multifunctional flight control devices, a clear separation between primary and secondary is no longer possible or recommended. Hence, in the further course of this paper, the distinction between primary and secondary is only of limited relevance.

A. Flight Control System Design

The FCS is one of few aircraft systems with strong physical integration into airframe and structure (e.g. flight control devices) and information-based integration into avionics and mission systems (e.g. flight control computers). In this contribution, the FCS is divided into *configuration* and *architecture*, with strong interdependencies between both, see Fig. 3.

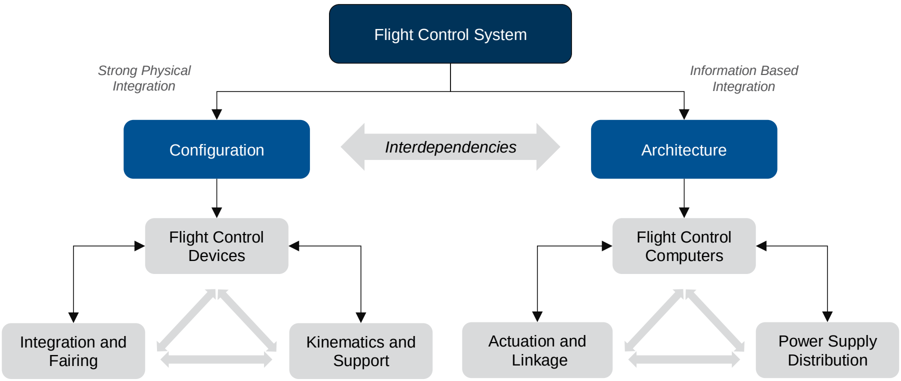


Fig. 3 Breakdown of a flight control system into configuration and architecture [6].

The configuration describes the type, allocation and positions of all flight control devices as well as the kinematics and support, fairings, and aspects of airframe integration. The architecture defines the number and redundant assignment of the flight control computers to dedicated flight control devices for reconfiguration in the case of an error. Also, the actuation systems, linkages and the redundant distribution of the power supply are attributed to the architecture.

B. Flight Control Functions

In general, the FCS provides directional control about all three axes of the aircraft, enables trim functions to maintain the flight attitude, and increases the lift during low speed operations (start and landing). These flight control functions can be classified as flight-critical or less-critical control functions to enable a safe flight. For example, roll, pitch and yaw are flight-critical control functions (attitude and trajectory control), and high-lift control is a less-critical control function for a safe flight. Based on the classification of the flight control functions, defined architectural design rules can be applied for a redundant and fault-tolerant FCS design. An overview of basic and additional flight control functions is given in Table 1.

Table 1 Overview of basic and additional flight control functions (selection).

Control Function(s)	Flight Critical	Control Device(s)	Characteristics
Basic			
Roll control	yes	Aileron	Deflections up/down
Pitch control	yes	Elevator	Deflections up/down
Yaw control	yes	Rudder (1/2)	Deflections left/right
Trim	no	THS	
Airbrake/Lift Dump	no	Spoiler	Deflections up
High-lift control	no	LE Flaps TE Flaps	Fowler/Deflections down Fowler/Deflections down
Additional			
Roll control[S]	no	Aileron (Flaperon) Spoiler	Deflections up/down Deflections up/down
High-lift control[S]	no	Aileron (Flaperon) Flap with AFC[FA]	Deflections down Fluidic actuators on[P]
Active load control	no	Aileron Spoiler	Deflections up/down Deflections up
Differential flap setting	no	TE Flaps	Deflections down
Cruise variable camber	no	TE Flaps Spoiler	Deflections down Deflections down[G]

AFC Active Flow Control
LE Leading Edge (wing)
TE Trailing Edge (wing)
THS Trimmable Horizontal Stabilizer
[FA] Fluidic Actuation (e.g. two-stage)
[G] Gap control (b/t flap and spoiler)
[P] Pulsed jet (e.g.)
[S] Supportive

C. New Technologies and Concepts

An overview of the main disciplines and enabling technologies for functional enhancement or efficiency improvement of the FCS are shown in Fig. 4. For example, aerodynamic and structural technologies have a major impact on the FCS configuration, whereas aircraft power system architecture has a major impact on the FCS architecture.

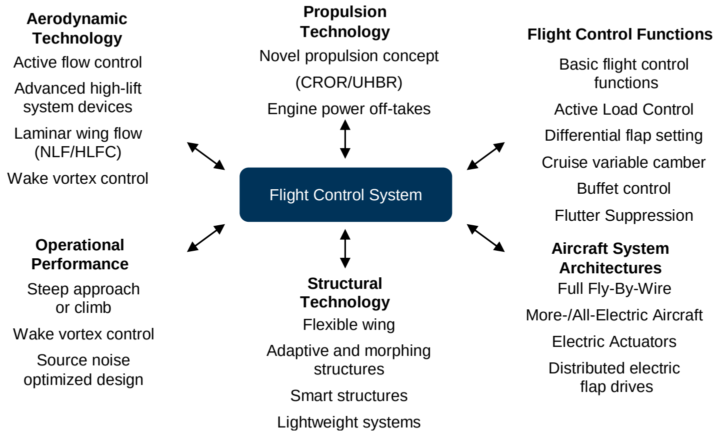


Fig. 4 Overview of enabling technologies, concepts, and disciplines regarding flight control systems design [6].

D. Requirements, Specifications and constraints

For a better understanding of the flight control systems, requirements should be specified on aircraft level, system level and device level. The results of the analysis provide an overview on primary, secondary, desired and undesired effects of each flight control device. Furthermore, design drivers, constraints and key parameters can be identified to enable a preliminary FCS design. An overview of requirements and specifications of selected flight control functions is shown in the appendix.

E. Previous Studies

Within the EU-project *AWIATOR* Miniature Trailing-Edge Devices (MiniTEDs) as a part of a multifunctional FCS were investigated [7]. The MiniTEDs are small split flaps (2% of the local chord, max. 7.5° deflection) located at the trailing-edge of the inboard and outboard trailing-edge flaps of the high-lift control system. As a case study, an A340-300 was selected and numerical simulations and wind-tunnel experiments were conducted to explore the effectiveness of these MiniTEDs. Results show that an increase of the lift and a shift of the lift distribution towards wing root could be achieved. Nevertheless, in real cruise conditions no improvements can be expected, because the MiniTEDs lead to significant drag increase. Furthermore, a high system integration effort of the MiniTEDs into the trailing-edge flaps is stated, leading to a complex and heavy design. A good overview of the project and the main results are published in the work of Richter and Rosemann [7].

A similar approach was pursued by the German Aerospace Center (DLR) in the national project *ProHMS* [8]. In this project, additional control surfaces (tabs) at the wing trailing-edge lead to improved aerodynamics. But in contrast to the MiniTEDs, the added tabs are much larger and distributed over the full wing span, see Fig. 5.

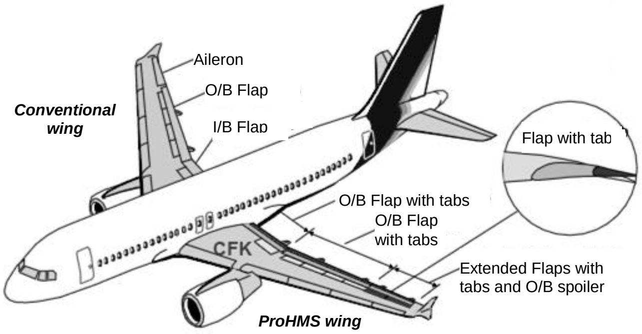


Fig. 5 ProHMS high-lift control system with multifunctional flight control surfaces [8] (modified).

During low speed phases, the tabs can be deployed additionally to the high-lift control flaps. In cruise conditions, the wing camber can be adapted by small deflections of the tabs. Finally, the authors emphasize the sophisticated design problem with multiple disciplines and their strong interconnections. A full documentation of the ProHMS aircraft configuration and the results are presented in the work of Dargel et al. [8].

With the experiences and results of the ProHMS project, Airbus started the *HICON* project – as part of the lead research project IHK – to develop innovative high-lift control system configurations for commercial transport aircraft [9]. One main objective was to reduce the highly complex systems and develop a single, but multifunctional flap design. Based on the demonstrated feasibility of the multifunctional concept, Airbus developed the Adaptive Dropped Hinge Flap (ADHF) which was first introduced on the Airbus A350 in 2014 [1]. Characteristic for the ADHF design is the simple hinge-mechanism, including the capability of spoiler downward deflections. Summarized, the ADHF enables following control functions:

- High-lift Control (HLC): Flap deflection down + spoiler deflection down (for gap control)
- Cruise Variable Camber (CVC): Control of the wing camber with small deflections up/down (± 3°)
- Differential Flap Setting (DFS): Control of the lift distribution with differentially deployed inboard and outboard flaps.
- Other functions: Air Brake (ABK) and supportive Roll Control (RLC)

A similar but more advanced concept is the Variable Camber Continuous Trailing Edge Flap (VCCTEF), investigated by NASA and Boeing [10]. The objective of this adaptive aeroelastic wing shaping control technology is to achieve optimal spanwise lift distribution for significant drag reduction by modifying the wing camber. Furthermore, the multifunctional concept enables HLC, RLC as well as flutter suppression. A comprehensive overview on the VCCTEF concept and detailed results are presented in the work of Nguyen et al. [10].

III. Integrated Design Approach

The integrated design approach for advanced FCS is part of the overall, functional-driven design approach (see Fig. 2). The objective of this approach is to enable a quick design and analysis of advanced FCS with multifunctional devices in early aircraft design phases. To cope with the sophisticated and multidisciplinary design problem, the design approach is divided in three different methods/tools: the *Configuration Design Tool,* the *Architecture Design Tool,* and the *Mass Estimation Tool,* see Fig. 6.

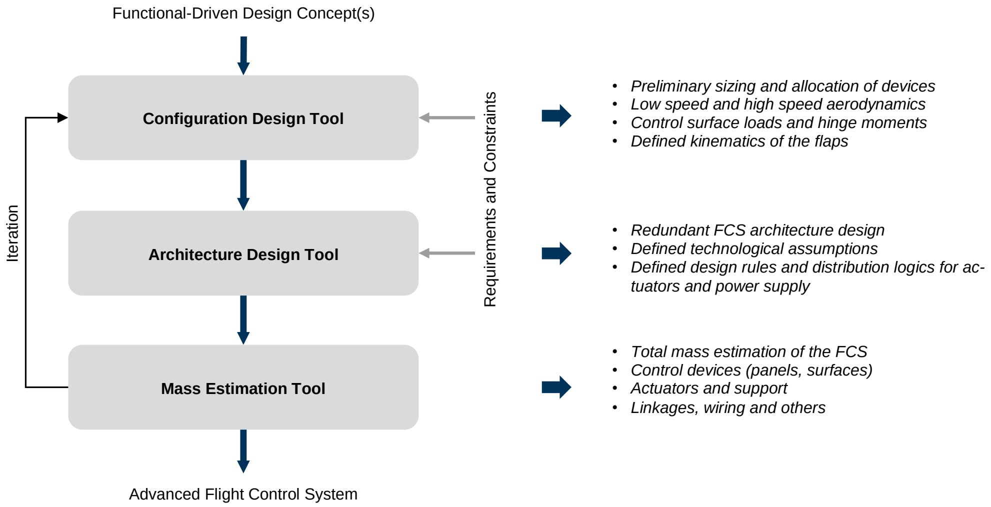


Fig. 6 Schematic overview of the integrated design approach for advanced flight control systems.

In a first step, the FCS configuration design (“layout”) is defined. Then, the FCS architecture can be generated by defined rules and technological assumptions. In the next step, the mass of the FCS is estimated and the overall FCS design can be evaluated. To optimize the resulting FCS design (e.g. towards minimum mass), the segmentation and distribution of flight control devices can be iteratively modified, and the process starts again.

A. Configuration Design

The configuration design tool calculates the low speed and high speed aerodynamics of the aircraft model, see Fig. 7. Since the integrated design approach should be applicable in early aircraft design phases, only limited available geometry data can be considered. Therefore, handbook methods, semi-empirical approaches, statistical data, and vortex lattice models are used. Finally, if a valid configuration is found, the control surface loads and hinge moments are determined for later actuation system sizing within the architecture design.

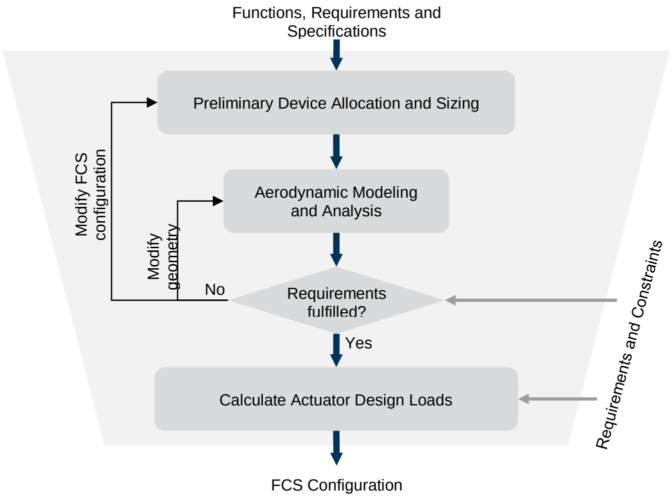


Fig. 7 Flight control system configuration design method.

The aerodynamic modeling is implemented in an object-oriented programmed MATLAB®-Tool, using the Athena Vortex Lattice (AVL) program as a "black-box" to perform the vortex lattice calculations [11]. All required input/output data for AVL are generated/extracted from/to MATLAB®.

Preliminary Device Allocation and Sizing

The design space of the FCS configuration is very limited due to the wing design, the front and rear spar, or fuel tanks. That's why the configurational designs of the FCS of recent transport aircraft are very similar and innovative solutions or new technologies are generally introduced on system or device level.

Here, it is assumed, that the main aircraft and wing geometry data are given. Furthermore, following constructional constraints and limitations are perceived, see Fig. 8. The distances, spaces and gaps can be estimated on the basis of historical data found in literature. For commercial transport aircraft, the position of the wing front spar is between 15-20% of the local wing chord, and the position of the wing rear spar between 65-75% of the local wing chord [12, 13].

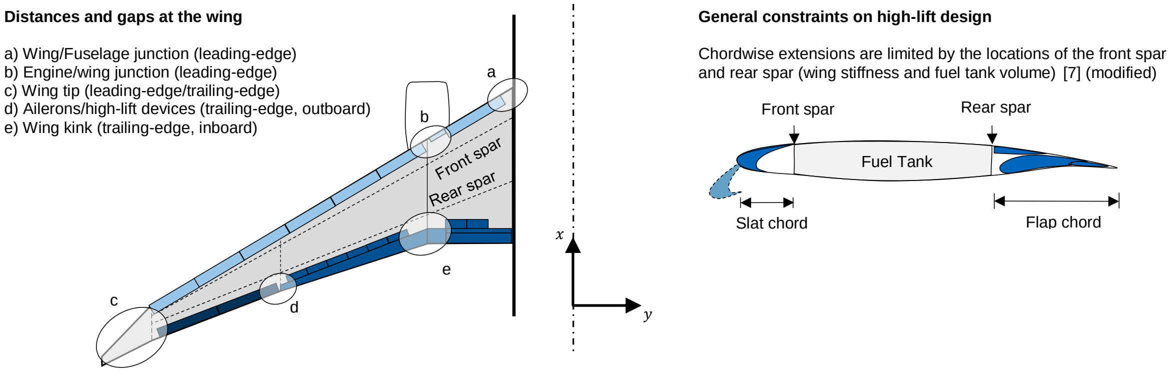


Fig. 8 Constructional constraints and limitations of the flight control system on the wing.

Considering these limitations and constraints for the FCS configuration design, following conflicts, allocation criteria and prioritization are recognized:

Wing Leading-Edge

- The leading-edge devices of the high-lift control system are the only flight control devices at the wing leading edge. That implies, that the design problem is reduced to the sizing, segmentation and the selection of the type of leading-edge devices.
- Nevertheless, it should be considered that the maneuverability of the aircraft should be available as long as possible during low speed phases – by continuously reducing the wing angle of incidence towards the wing tip (washout) – and to keep the ailerons at the outboard of the wing effective. The aerodynamic performance of the leading-edge devices should not counteract that effect.
- Additionally, strakes at the engine nacelles or small Krueger-flaps at the engine pylon can locally improve the flow pattern behind the engine/wing-junction.

Wing Trailing-Edge

- At the wing trailing-edge the ailerons and high-lift control system have to share the available space alongside the span.
- Flight control devices on the wing upper side (spoiler) are generally located in front of the trailing-edge devices of the high-lift control system.
- In contrast to the high-lift control system, the required performance for roll control and the geometric constraints of the wing, mostly defines the (minimum) size of the main roll devices. For a first guess, it is recommended to allocate about one third of the wing trailing edge for roll control devices.
- After the minimum size of the main roll devices are defined, the remaining space at the wing trailing-edge is available for the outboard and inboard high-lift devices.
- Finally, after sizing and allocation of the high-lift control system, the spoilers can be arranged.

Aerodynamic Modeling and Analysis

The aerodynamic modeling and analysis is done in two steps. In the first step the preliminary allocation of the flight control surfaces described above are considered and the initial aerodynamic performance is calculated on the basis of handbook and semi-empirical methods. In the second step, a vortex lattice model of the full aircraft is used to analyze the three-dimensional lift and drag coefficients. This approach works well for the overall aircraft aerodynamics with simple hinged control surfaces.

More challenging – in the context of early aircraft design phases – is the aerodynamic modeling of different high-lift control configurations during low-speed phases. Therefore, an approach based on the work of Olson [14] is applied to determine the low-speed aerodynamics of the aircraft. In this semi-empirical methodology, empirical correlations for flap effectiveness, chord extension, drag and lift-coefficient increments as a function of flap deflection are combined with the characteristics of the clean airfoil. With the aerodynamic characteristics of the flapped airfoil sections, a vortex-lattice model is set-up to calculate the three-dimensional lift and drag coefficients of the full aircraft configuration [14]. Examples of a resulting vortex-lattice models of an aircraft in cruise (left) and landing configuration (right) are shown in Fig. 9. In a case study conducted at our institute [15], the methodology and results of Olson [14] have been confirmed.

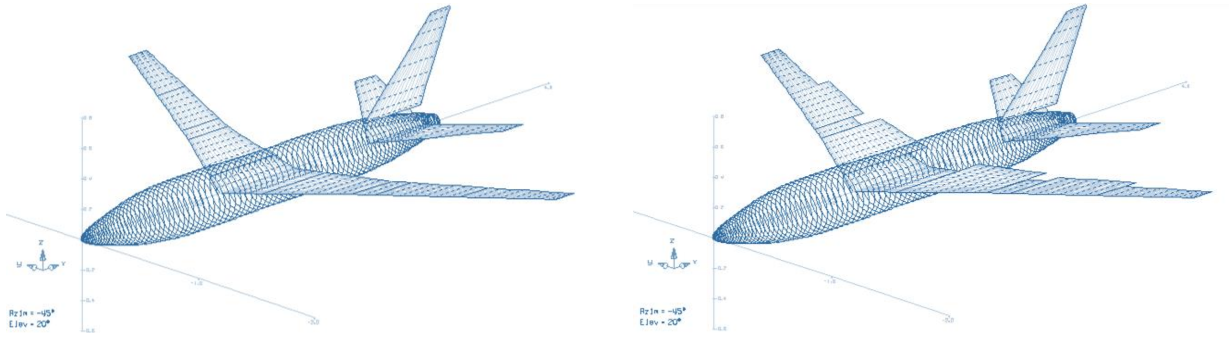


Fig. 9 Vortex lattice models of an aircraft in cruise configuration (left) and in landing configuration (right).

A similar approach is recommended if new technologies or systems should be considered; especially if only few data are available or the modeling is too costly for early aircraft design phases. In that case it is recommended to use the (estimated) aerodynamic performance results of the technology/concept and consider local drag and lift coefficient increments once the technology/system is activated.

The modeling of additional flight control functions using AVL is limited, because complex control surface configurations or aerodynamic interactions cannot be modelled due to the linearity of the vortex lattice method. However, the active load control function (or load alleviation) of the ProHMS aircraft can be successfully demonstrated. In Fig. 10 (left) the lift distribution of the clean ProHMS wing (half-span) compared to the ideal ellipse is shown. On the right, the same wing with two different tab configurations shows a better approximation towards the elliptical lift distribution, resulting in a decrease of induced drag.

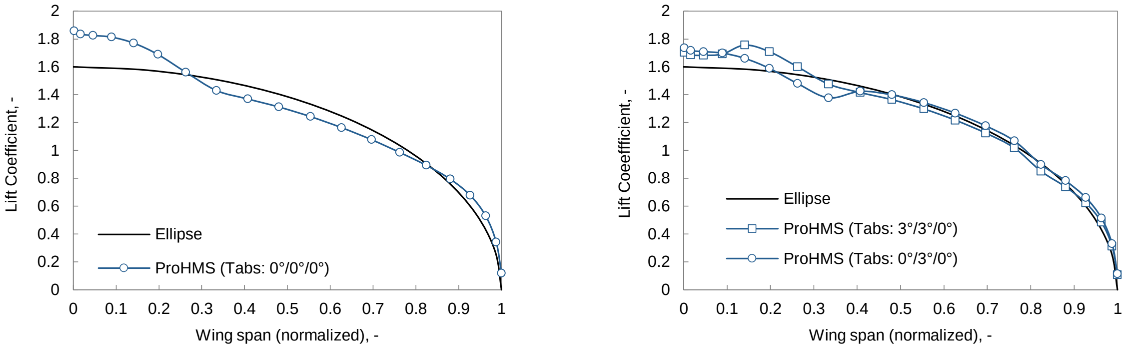


Fig. 10 Results of the ProHMS wing lift distribution for different tab configurations.

Calculate Actuator Design Loads

Finally, if all necessary requirements of the FCS configuration are fulfilled, the design loads for the flight control device actuators are calculated. The actuation design loads for hinged control surfaces are characterized by the maximum hinge moment. Therefore, the results of the AVL model with defined control surfaces or different handbook methods can be used, depending on the type of the flight control surface and available data. To determine the design loads for unconventional flight control device (e.g. fluidic actuators for active flow control) a system model must be set up to estimate the requirements (e.g. design pressure, max. mass flow rate).

B. Architecture Design

The design of the FCS architecture is mainly driven by functional and safety requirements. Whereas technological constraints and top-level aircraft system architectures restrict the design space. The design method for the preliminary design of FCS architectures is based on a top-down approach [16], using defined technological assumptions, defined design rules and distribution logics for redundancy and reconfiguration, see Fig. 11.

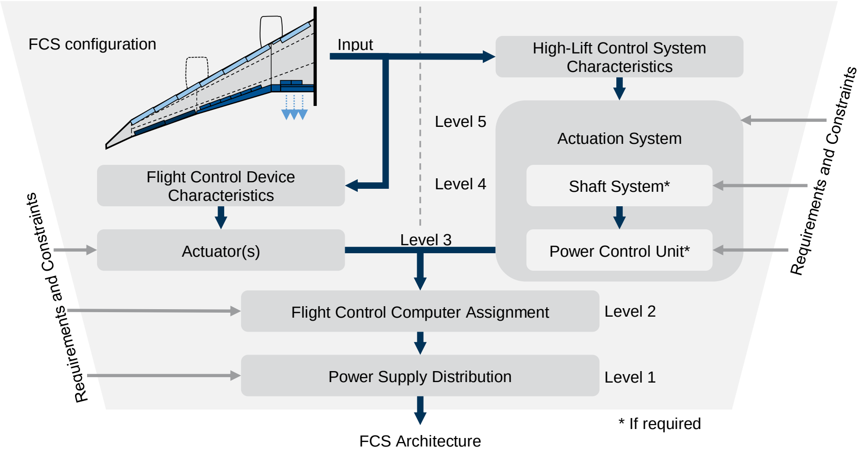


Fig. 11 Flight control system architecture design method [16] (modified).

Due to the very different design aspects of the primary flight control devices and spoilers, and the high-lift control system, the top-down approach is divided into two parts. On the one hand, the actuator types are selected and arranged to the dedicated flight control devices. On the other hand, the high-lift control system characteristics define the kinematic and actuation requirements, including the transmission shaft and PCU if required.

Finally, the FCCs are assigned to each flight control device per defined redundancy and reconfiguration rules. The distribution logics defines the power supply assignment to each flight control device and its actuator(s), and completes the architectural design. This architectural design approach is also implemented in MATLAB®. More details of the design method are shown in a previous work of Lampl et al. [16].

C. Mass Estimation

The parametric estimation tool calculates the total mass of the FCS configuration and architecture, including linkages, wiring, and others. The mass estimation method includes different parametric methods, which were researched and evaluated [17]. The main methods included are based on the works of Torenbeek [12], Rudolph [18], and Anderson [19].

In general, the development of a mass estimation tool is hampered by the few available data and parameters in early aircraft design phases. Therefore, most methods start with a “should weigh” approach based on the technology level and are statistically expanded. For the extent of the mass estimate, the FCS are divided into panels, supports, fairings and actuation systems; each subsystem is considered separately but not independently from the others.

Because the control surface area is essential for the applied calculation methods, a complete parametric model of the wing and the control surfaces is set up. In order to ensure a wider range of use, the parametric model is implemented as flexible as possible to cover different wing and surface configurations. For a quicker and easier modeling, all surfaces were represented as polygons with straight edges in MATLAB®, which allows the definition of a simple column vector containing all the vertices coordinates. The objective is to represent the wing planform geometry and the FCS configuration as accurate as possible with the minimum amount of required input parameters [17]. Some examples of different wing planform and control surface models are shown in Fig. 12.

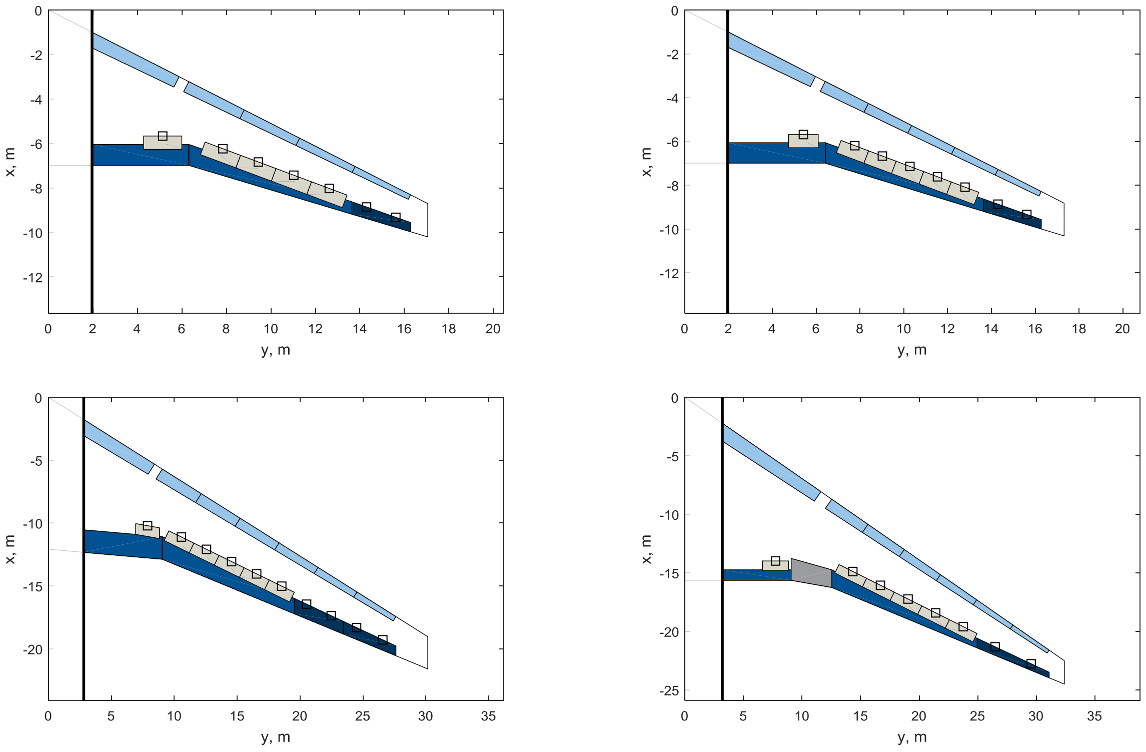


Fig. 12 Different examples of the wing planform and control surface model (half-span).

The number of required parameters to model the wing are kept within a reasonable amount, and only those strictly necessary for an accurate and effective modeling are needed as input. The main parameters required for the geometric definition of the wing are based on the work by Platz [20]. Nevertheless, some adaptions and simplifications are necessary to integrate the method in the mass estimation tool. Following main parameters and definitions are required for the wing planform model:

- Wing span and wing area
- Wing sweep at 25% chord
- Wing taper ratio
- Wing chord at the fuselage and tip
- Relative wing kink position
- Sweep angle of inboard trailing edge
- Span of the thrust gate (if required)

The first step of the control surface modeling is the determination of the position relative to the wing span. If it is located before the wing kink/first engine, the control surface is assigned to the inboard wing, otherwise to the outboard wing. This definition allows the simplified application of defined rules. For example, all outboard control devices are assumed to have constant chord relatively to the local wing. The inboard trailing-edge devices and spoilers are assumed to have a constant chord. Further details on the wing planform and control surface models are explained in the work of Graiff [17].

IV. Case Study

In this section a brief case study is conducted to show some of the steps and preliminary results of the integrated design approach. Therefore, an advanced FCS model with multifunctional flight control devices and MEA technologies is developed. Additionally, an aircraft with conventional flight control system serves as a reference. The conventional FCS fulfills the basic control functions with mainly mono-functional flight control devices. Whereas the advanced FCS enables new control functions or supports the basic flight control functions by using multifunctional flight control devices, see Fig. 13. This simplified functional allocation of the flight control system (wings only) is used as a starting point of this case study.

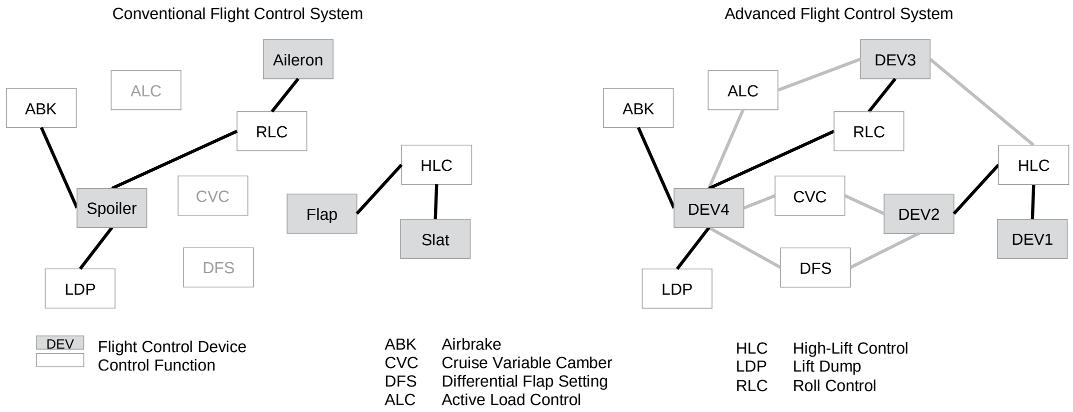


Fig. 13 Simplified functional allocation of a conventional (left) and an advanced (right) flight control system.

In the following, the focus is on the consideration of the Distributed System Architecture (DSA) for the high-lift control system and the integration of additional flight control functions, e.g. Differential Flap Setting (DFS). Here, the baseline aircraft with the conventional FCS is named the Reference Aircraft (RA), and the aircraft with the advanced FCS is referred to as the Concept Aircraft (CA). The baseline aircraft and the main technological constraints are defined in the next section.

A. Baseline Aircraft and Technological Constraints

The baseline aircraft used for the case study represents a typical medium-range transport aircraft, comparable to a Boeing 737-800 or an Airbus A320-200. A high-lift system architecture with distributed electrical drives will offer the capability for implementation of additional control functions, especially for the trailing-edge devices [2]. A high-lift system with distributed electric drives has potential benefits resulting from the unique system architectures and its characteristics. Furthermore, the largest benefit is gained, if all systems on aircraft level are designed for the MEA approach [5]. In general, the aircraft power generation and distribution system architecture is defined either as 3H (3 hydraulic circuits) or as 2H-2E (2 hydraulic – 2 electrical circuits) and has a major impact on the FCS architecture design [16]. In this case study, the baseline aircraft has a 2H-2E architecture as illustrated in Fig. 14.

Table 2 Main parameters of the baseline aircraft.

Parameter	Value	Unit	Parameter	Value	Unit
General			***Wing***		
Crew [a]	2/4	–	*Span*	34.8	m
Capacity [b]	189/184/162	–	*Area (ref.)*	124	m^2
Length	38.5	m	*Sweep (25%)*	25	°
Height	12.2	m	*Aspect ratio*	9.6	–
Mass			*Taper ratio*	0.25	–
MTOW	76390	kg	***Engine*** *(2)*		
MLW	65220	kg	*Number*	2	-
OEW	42120	kg	*Max. T/O-Thrust*	130	kN

[a] *Number of Crew-members: Cockpit/Cabin*

[b] *Number of PAX: 1-class (max) / 2-class / 3-class*

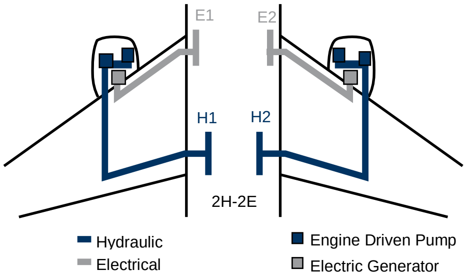


Fig. 14 2H-2E architecture of the baseline aircraft [16].

In Fig. 15 (left) the Reference System Architecture (RSA) of the high-lift control system is shown. The trailing edge flaps are actuated by a mechanical transmission shaft, which is actuated over a central Power Control Unit (PCU). The right-hand side (not shown) will be symmetric and powered by the same drive shaft to prevent any asymmetry.

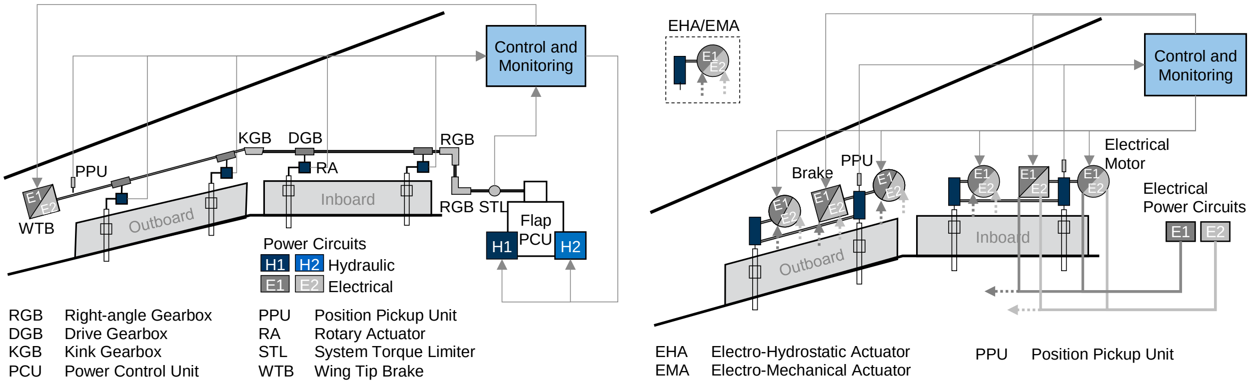


Fig. 15 Schematics of the conventional system architecture (left) and the distributed system architecture (right) for high-lift control systems [5].

For the Distributed System Architecture (DSA), the transmission shaft system and the centrally located PCU are removed. The DSA concept shown in Fig. 15 (right), has two drive stations for each inboard or outboard flap, which are connected via a local drive shaft. This ensures a synchronous deployment of both actuators. For each flap, only one brake and on position sensor are required. In the case of a failure of one electric actuator, the other actuator can drive the flap in a degraded mode. For the DSA concept, either EMAs, EHAs or a combination of both can be chosen for actuation. The analysis of the DSA concept for high-lift control systems show weight savings up to 30% and benefits in direct operating costs up to 20%, compared to the conventional system architectures with mechanical transmission shaft and PCUs [5].

Before the preliminary results are presented, following assumptions and simplifications are defined. The functional allocations (see Fig. 13) for both aircraft are given. The FCS configuration (layout only!) of the reference aircraft and the concept aircraft is assumed to be the same. Also the empennage, including the horizontal and vertical tail with rudder and elevators, are identical. This allows us to set the focus in this brief case study on the different high-lift system architectures and the additional flight control functions.

B. Preliminary Results

The next step after the preliminary device allocation is the aerodynamic modeling of the aircraft. Therefore, a simplified vortex-lattice model is set up. The baseline aircraft in high-lift configuration with extended inboard and outboard flaps is shown in Fig. 16 (right). This model enables the aerodynamic calculation of the concept aircraft in start or landing configuration. The examplary results of the high-lift configuration and different flap settings during the climb phase at $Ma = 0.25$ and $C_L = 1.395$ are shown in Fig. 16 on the left. The inboard (IB) and outboard (OB) flaps are set to 30°/30° (IB/OB), 30°/15°, and 15°/15° downward deflections. The result of the 30°/15° (DFS) configuration shows expected the shift of the lift distribution towards the wing root, resulting in a reduction of the wing root bending moment (compared to the 30°/30° configuration). Nevertheless, a higher angle-of-attack α is necessary to achieve the required lift coefficient. A similar tendency can be recognized for smaller flap deflection angles (15°/15°).

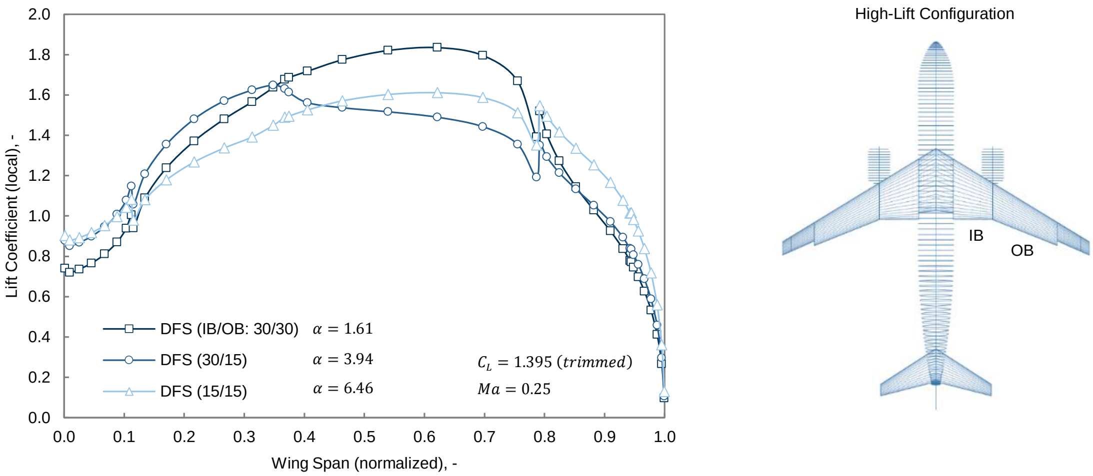


Fig. 16 Lift distribution over the wing half-span for different flap configurations (left) and the overall vortex-lattice model of the aircraft with extended Inboard (IB) and Outboard (OB) flaps.

The modeling of the CVC function by using the vortex-lattice method is not suitable, due to transonic effects occurring during cruise. Consequently, for this case study, a drag reduction of 0.5 drag counts is estimated if CVC is active during the cruise phase.

Mass Estimation

The results of the FCS mass estimation of the reference aircraft and concept aircraft are shown in Fig. 17. The mass estimation includes the panel and actuation mass for each FCS device. Furthermore, support and fairing masses are considered for the leading-edge and trailing-edge devices of the high-lift control system. The results show, that for both aircraft, high-lift system has the largest shares (46% and 42%) of the estimated total FCS masses.

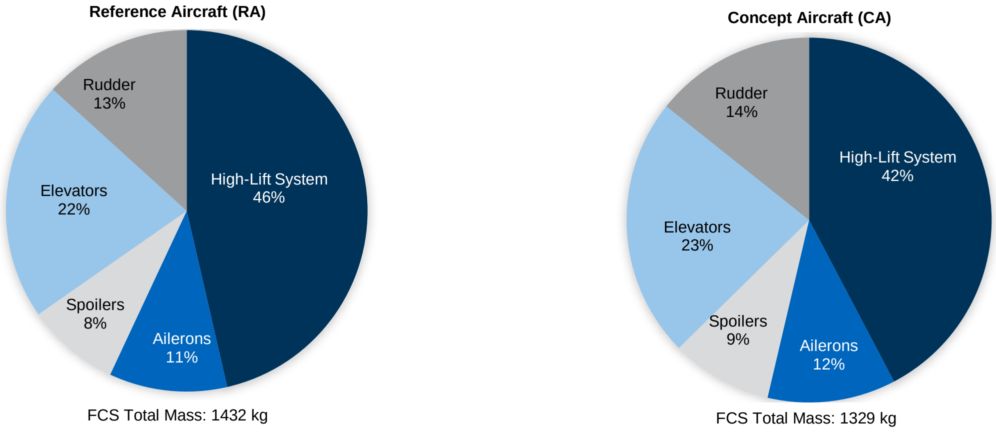


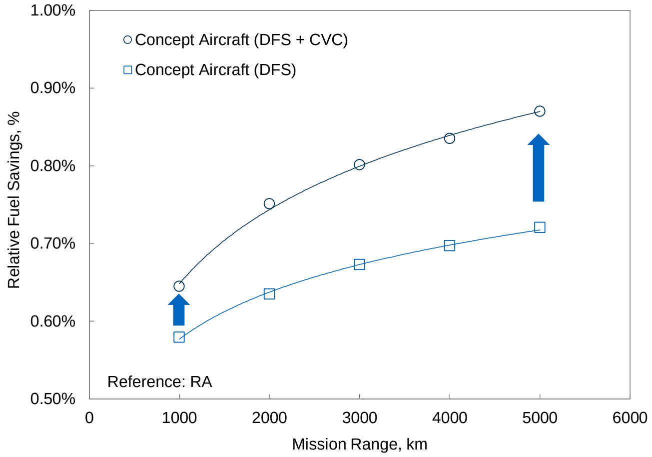
Fig. 17 Overall mass distribution of the Flight Control System (FCS) of the reference aircraft (left) and of the concept aircraft (right).

The integration of the DFS results in estimated weight savings of approximately 500 kg for the wing structure (wing box) [2]. Together with the weight savings of the DSA concept for the high-lift control system, the overall wing weight (including the FCS) is reduced by 6.5%.

Analysis and Technology Assessment

For the preliminary analysis and technology, the Aircraft System Technology Analysis and Assessment Tool (ATAX v2.0) developed at our institute is used. The tool considers the aircraft aerodynamics, aircraft systems, and the used engine technology to calculate the fuel flow and fuel consumption for defined missions.

The following calculations are conducted for mission ranges from 1000 to 5000 km, a cruise altitude of 36000 ft and constant Cruise Mach number of 0.8. In Fig. 18 the relative fuel savings of the concept aircraft for different mission ranges compared to the reference aircraft are shown. The points are calculated values, whereas the curves are trendlines. The bottom curve, shows the fuel savings due to the integration of the DFS and as a consequence thereof the overall wing mass reduction. The top curve shows the fuel savings of the concept aircraft with DFS and CVC.



Reference Aircraft (RA)

- Max. Take-off mass: 76390 kg
- Operating empty mass: 42120 kg
- Max. Fuel capacity: 25402 liter
- Flight Control System: conventional

Concept Aircraft (CA)

- Max. Take-off mass: 76390 kg
- Operating empty mass: *41520 kg* ← (weight reduction)
- Max. Fuel capacity: 25402 liter
- Flight Control System: *advanced* ← (DFS and CVC)

Reference Mission

- Mission Range: 1000 … 5000 km
- Cruise Altitude 36000 ft (const. level)
- Cruise Mach 0.8
- Payload mass: 17120 kg

Fig. 18 Relative fuel savings of the concept aircraft with Differential Flap Setting (DFS) and Cruise Variable Camber (CVC) compared to the reference aircraft for different mission ranges.

As expected, the fuel savings are increasing as the mission range increases. Furthermore, it can be seen that the two curves diverge with increasing mission ranges: The effect of the wing mass reduction (DFS) is relatively smaller for greater ranges, because more fuel is required and the take-off mass increases. In contrast, the effect of the aerodynamic improvement (CVC) during the cruise phase is relatively larger for greater ranges.

V. Conclusion

This contribution presents an integrated design approach for advanced Flight Control Systems (FCS) with multi-functional flight control devices in early aircraft design phases. The approach is divided into three main design methods (tools): The FCS configuration design, the FCS architecture design, and the FCS mass estimation. In the first step, the FCS configuration – the allocation and sizing of flight control devices – is defined and aerodynamic calculations can be performed. In the second step, the FCS architectures are designed in a top-down approach, using defined rules, technological assumptions, and distribution logics. In the third step, the mass of the FCS is estimated and the design can be analyzed, evaluated, or iteratively optimized (e.g. towards minimum mass).

The aerodynamic modeling of additional flight control functions, e.g. Differential Flap Setting (DFS) or Active Load Control (ALC) could be demonstrated. However, the aerodynamic modeling of flight control functions in high-speed conditions, e.g. Cruise Variable Camber (CVC) are limited. In that case, the aerodynamic improvements are estimated, based on published data.

In a brief case study, some steps of the integrated design approach are applied and the preliminary results presented. A concept aircraft with a distributed system architecture for the high-lift control system and additional flight control functions are modeled and compared to a reference aircraft with conventional FCS. The preliminary results show, that the relative fuel savings of the concept aircraft with advanced FCS for different mission ranges can be shown. Even if the absolute values are not exactly enough, the relative trends are meaningful enough to enable the evaluation and assessment of advanced FCS with new technologies and concepts in early aircraft design phases.

Appendix

It is recommended to set up a general flight control functions “catalogue” with the main requirements, classifications, constraints and potential technologies. To get an idea of such a catalogue, the flight control functions Roll Control (RLC) and High-Lift Control (HLC) are presented, see Table 3 and Table 4. Examples of additional flight control functions – e.g. Differential Flap Setting (DFS) and Cruise Variable Camber (CVC) – to improve the overall aircraft efficiency/performance are shown in Table 5 and Table 6. Further examples of flight control functions are Active Load Control (ALC), Air Brake (ABK), or Lift Dump (LDP).

Table 3 Flight Control Function Catalogue – Roll Control

Flight Control Function	**Roll Control (RLC)**
Aircraft Level	
Requirements, Specifications	EASA CS 25.147, Flight critical, Handling Qualities → Control of the bank angle
Model, Objectives	Roll moment/rate is a function of: Surface deflection angle, deflection speed, surface area, surface lever-arm (wrt. the longitudinal axis), air speed, wing configuration
Parameter	Roll moment, Roll rate, Bank angle
Interactions	Yaw control, lateral stability, directional trim
System Level	
Conventional Configuration	Outboard wing: aileron(s), Inboard wing (thrust-gate): High-speed Aileron (optional), Supportive: Spoiler
Integration, Constraints	Wing design (span, elasticity, space, rear spar, airfoil…), Winglets, high-lift system (trailing-edge), engine configuration
Redundancy, Reconfiguration	Different control surfaces (redundancy), segmented ailerons and spoilers, redundant actuators, power supply, flight control computers
New Technologies	Flexible (morphing) wing, active flow control, tailerons, electric actuators
Device Level	
Control Devices	Ailerons, spoilers, flaperons, tailerons, fluidic actuators
Deflection, Operating	Deflections up/down (ailerons), Asymmetric Deflection up (spoilers), Jet (fluidic actuators)
Aerodynamics, Aeromechanics	Control device effectiveness, aileron reversal, flow detachment
Multifunctionality	Active Load Control (maneuver, gust), support high-lift control, air brake, lift dump

Other flight critical flight control functions are Yaw Control (YWC) and Pitch Control (PTC). Also Trim Control (TRM) around the three axis can be defined as flight control functions in the catalogue (not shown).

Table 4 Flight Control Function – High-Lift Control

Flight Control Function	**High-Lift Control (HLC)**
Aircraft Level	
Requirements, Specifications	EASA CS 25.105, CS 25.107, CS 25.109, CS 25.111, CS 25.113, CS 25.115, CS 25.117, CS 25.119, CS 25.121, CS 25.125, CS 25.701, Handling Qualities
Model, Objectives	Enable low speed phases for safe start and landing, steep climb-out, steep approach, minimum weight (low complexity), minimize start and landing distances
Parameter	Lift Coefficient, Drag Coefficient, Lift over Drag, Lift-off speed, touchdown speed, climb rate, angle of attack,
Interactions	Flight control, stability, trim
System Level	
Conventional Configuration	Leading-edge and trailing-edge control devices (slats/flaps), different positions (discrete)
Integration, Constraints	Wing design (span, elasticity, space, airfoil, wing sweep), winglets, front/rear spar (hinge line), ailerons, engines, landing gear, MTOM
Redundancy, Reconfiguration	Segmented high-lift control devices (inboard/outboard), redundant actuation and flight control computers, electronic rigging
New Technologies	Flexible (morphing) structures, active flow control, distributed electric drives,
Device Level	
Control Devices	Leading-edge devices (Krueger-Flap, Slat, Droop nose) and trailing-edge devices (single-slotted flap, double slotted flap, fowler flap)
Deflection and Motion	Different kinematics: dropped hinge, linkage, track, fowler motion: translation, rotation
Aerodynamics, Aeromechanics	Pressure distribution (airfoil, wing), reduction of suction peaks, delay of flow detachment at the outer wing (to keep ailerons effective), boundary layer control
Multifunctionality	Cruise variable camber, differential flap setting (load alleviation)

Table 5 Flight Control Function – Cruise Variable Camber

Flight Control Function	**Cruise Variable Camber (CVC)**
Aircraft Level	
Requirements, Specifications	EASA → CS 25.701
Model, Objectives	Increase the efficiency during cruise (drag reduction)
Parameter	Lift over drag, Drag, Wing camber
Interactions	Longitudinal Trim
System Level	
Configuration	Adjust the wing camber using the trailing-edge flaps and the spoilers (gap control)
Integration, Constraints	Wing design, high-lift control system design (actuation system architecture), spoiler design, simplified kinematics
Redundancy, Reconfiguration	Segmented high-lift control devices (inboard/outboard), redundant actuation and flight control computers, electronic rigging
New Technologies	Flexible structures, shock bump device
Device Level	
Control Devices	Trailing-edge high-lift devices (flaps), spoiler
Deflection and Motion	Small deflections up/down (flaps), gap control (spoiler)
Aerodynamics, Aeromechanics	Drag, wave drag
Multifunctionality	High-lift control, active load control, differential flap setting

Table 6 Flight Control Function – Differential Flap Setting

Flight Control Function	**Differential Flap Setting (DFS)**
Aircraft Level	
Requirements, Specifications	EASA → CS 25.701
Model, Objectives	Load alleviation in spanwise direction, optimize the load distribution, reduce the wing root bending moment, electronic rigging
Parameter	Lift distribution, Lift over drag, bending moment
Interactions	Longitudinal trim
System Level	
Configuration	Differential setting of the inboard and outboard flaps
Integration, Constraints	Wing design, high-lift control system design (actuation system architecture, kinematics)
Redundancy, Reconfiguration	Segmented high-lift control devices (inboard/outboard), redundant actuation and flight control computers, electronic rigging
New Technologies	Flexible structures, active flow control
Device Level	
Control Devices	Trailing-edge devices
Deflection and Motion	Deflections down
Aerodynamics, Aeromechanics	Lift distribution, wing root bending moment
Multifunctionality	High-lift control, cruise variable camber, active load control

References

[1] Kreitz, T., Bornholdt, R., Krings, M., Henning, K., and Thielecke, F., “Simulation-Driven Methodology for the Requirements Verification and Safety Assessment of Innovative Flight Control Systems,” *SAE 2015 AeroTech Congress & Exhibition,* SAE International, Warrendale, PA, United States, 2015.

[2] Recksiek, M., “Advanced High Lift System Architecture with Distributed Electrical Flap Actuation,” *Proceedings of the 2nd International Workshop on Aircraft System Technologies,* edited by O. von Estorff, Shaker, Aachen, 2009, pp. 49–60.

[3] Reckzeh, D., “Multifunctional Wing Moveables: Design of the A350XWB and the Way to Future Concepts,” *29th Congress of the International Council of the Aeronautical Sciences,* International Council of Aeronautical Sciences (ICAS), St. Petersburg, Russia, 2014.

[4] Lammering, T., and Weber, G., “Liebherr State-of-the-Art Fly-By-Wire Flight Control System for Commercial Transport Aircraft,” *Proceedings of the 4th International Workshop on Aircraft System Technologies,* Shaker, Aachen, 2013, pp. 127–137.

[5] Lampl, T., Königsberger, R., and Hornung, M., “Design and Evaluation of Distributed Electric Drive Architectures for High-Lift Control Systems,” *66. Deutsche Luft- und Raumfahrtkongress,* edited by Deutsche Gesellschaft für Luft- und Raumfahrt (DGLR), München, Germany, 2017.

[6] Lampl, T., Sauterleute, D., and Hornung, M., “A Functional-Driven Design Approach for Advanced Flight Control Systems of Commercial Transport Aircraft,” *Proceedings of the 6th International Workshop on Aircraft System Technologies*, edited by O. von Estorff and F. Thielecke, 1st ed., Shaker, Herzogenrath, 2017, pp. 3–12.

[7] Richter, K., and Rosemann, H., “Steady Aerodynamics of Miniature Trailing-Edge Devices in Transonic Flows,” *Journal of Aircraft*; Vol. 49, No. 3, 2012, pp. 898–910. doi: 10.2514/1.C031563.

[8] Dargel, G., Hansen, H., Wild, J., Streit, T., Rosemann, H., and Richter, K., “Aerodynamische Flügelauslegung mit multifunktionalen Steuerflächen,” Deutscher Luft- und Raumfahrtkongress DGLR-2002-TP2, September 2002.

[9] Airbus Deutschland GmbH, “Schlussbericht zum Technologievorhaben HICON - Neue Konzepte für Hochauftriebskonfigurationen,” 2008.

[10] Nguyen, N., Kaul, U., Lebofsky, S., Chaparro, D., and Urnes, J., “Development of Variable Camber Continuous Trailing Edge Flap for Performance Adaptive Aeroelastic Wing,” SAE Aero Tech Congress & Exhibition 15ATC-0250, September 2015.

[11] Drela, M., “Athena Vortex Lattice (AVL),” http://web.mit.edu/drela/Public/web/avl/, [retrieved September 2017].

[12] Torenbeek, E., *Synthesis of subsonic airplane design. An introduction to the preliminary design, of subsonic general aviation and transport aircraft, with emphasis on layout, aerodynamic design, propulsion, and performance*, Delft University Press; Nijhoff; Sold and distributed in the U.S. and Canada by Kluwer Boston, Delft, The Hague, Hingham, MA, 1982.

[13] Torenbeek, E., *Advanced aircraft design. Conceptual design, analysis, and optimization of subsonic civil airplanes*, John Wiley & Sons, Inc, Delft, Netherlands, 2013.

[14] Olson, E. D., “Semi-Empirical Prediction of Aircraft Low-Speed Aerodynamic Characteristics,” *53rd AIAA Aerospace Sciences Meeting*.

[15] Bunk, T., *Erweiterung eines aerodynamischen Berechnungstools zur Integration und Analyse von Hochauftriebsklappen im Flugzeugvorentwurf*, Munich, April 2016.

[16] Lampl, T., Wolf, T., and Hornung, M., “Preliminary Design of Advanced Flight Control System Architectures for Commercial Transport Aircraft,” *6th CEAS Air & Space Conference,* edited by Council of European Aerospace Societies (CEAS), Bucharest, Romania, 2017.

[17] Graiff, M., *Development of a Tool for the Parametric Mass Estimation of Flight Control Systems in Preliminary Aircraft Design*, München, Germany, November, 2016.

[18] Rudolph, Peter K. C., “High-Lift Systems on Commercial Subsonic Airliners,” NASA Contractor Report 4746, September 1996.

[19] Anderson, R. D., Flora C. C., Nelson, M., Raymond, E. T., and Vincent, J. H., “Development of Weight and Cost Estimates for Lifting Surfaces with Active Controls,” NASA Contractor Report NASA CR-144937, March 1976.

[20] Platz, P., *Flächen- und Volumenberechnung charakteristischer Komponenten von Passagierflugzeugen*, Hamburg, Germany, September 1999.