MASS AND POWER ESTIMATIONS IN PRELIMINARY FLIGHT CONTROL SYSTEM DESIGN

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Abstract

Future aircraft will have to be lighter and more efficient to meet ongoing ambitions towards carbon neutrality as well as commercial demand. High aspect ratio wings are one way towards achieving more efficient commercial aviation. An important enabler for high aspect ratio wings are load protection functions, that are in turn implemented by multi-functional flight control systems.

Introducing load alleviation functions has significant impact on the necessary system performance, components and architectures, since the flight control system (FCS) in it's current implementation has a very strictly defined set of functionalities. Ultimately, accurate estimations of the resulting system's viability, mass and power requirements will be vital to coming designs. Accurate estimations for safety critical systems, such as the FCS, have to cover architecture attributes resulting from redundancy concepts and functional extent. Our research aims to increase analysis capacities for FCS and aircraft systems in general in a collaborative multi-discipline aircraft design environment. This paper demonstrates the system mass and power estimation for such a FCS with it's preliminary architecture design. The preliminary architecture design is part the DLR project oLAF and uses the generated iterations of aircraft design, including use cases and control surface layout, to give a tangible demonstration for the process. The aircraft design is an iteratively evolving aircraft design with an optimised wing employing load alleviation.

The preliminary design of the FCS's components was generated using various sizing models. The FCS architecture was modelled with Pacelab SysArc. The results of the system estimations of two iterations will be compared against one another and checked against mass estimation of classical system estimation methods. We propose, that early consideration of actual architecture candidates leads to more accurate estimates of realizable systems, and thus to more viable FCS and aircraft concepts.

Keywords: flight control system, load alleviation, mass estimation, preliminary aircraft system design

1. Introduction

Future aircraft will have to be lighter and more efficient to increase both ecological and economic efficiency[1, 2]. High aspect ratio wings can help to achieve more efficient commercial aviation[3]. Higher aspect ratio paired with aerodynamically optimised wings offer significant benefits in fuel consumption, resulting climate effect and cost effectiveness. Improved wings can further potentially enable design for new propulsion concepts by reducing necessary structure masses in relation to achievable take off weights. An expected important enabler for high aspect ratio wings are load alleviation functions[4], that are in turn implemented by multi-functional flight control systems.

The flight control system (FCS) in it's current implementation has a strictly defined set of functionalities. Recent advances in commercial aircraft have mostly addressed fly-by-wire implementation and the improvement of control computer architectures [5–7]. Introducing load alleviation functions significantly impacts necessary system performance, components and architectures. Ultimately, accurate estimations of the resulting system's viability, mass and power requirements will be vital to coming

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designs. Accurate estimates for safety-critical systems such as the FCS have to include early consideration of architectural attributes resulting from redundancy concepts and functional availability. Experience over decades of aircraft design have shown, that last minute safety-driven improvements are costly and time intensive and can sometimes undo whole aircraft designs that consequently have to be reiterated from very early stages.

Our research aims to increase analysis capacities for FCS in a collaborative multi-domain aircraft design environment. This paper demonstrates the system mass and power estimation for such a FCS with its preliminary architecture design. The preliminary architecture design is part of the German Aerospace Center (DLR) project oLAF (*optimal load adaptive aircraft*) and uses the generated iterations of aircraft design, including use cases and control surface layout, to give a tangible demonstration for the process. The aircraft design used is an iteratively evolving aircraft design with an optimised wing employing load alleviation.

The preliminary design of the FCS's components was generated using various sizing models. The FCS architecture was modelled using the software Pacelab SysArc [8]. The results of the system estimations of two iterations will be compared against one another and checked against mass estimation of classical system estimation methods. We propose, that considering actual architecture candidates early on leads to more viable FCS concepts and more accurate estimations of realisable system properties.

This paper is structured as follows: Section 2 describes the general concepts of the FCS's composition, it's components, it's functions and current implementations. A special focus lies on describing activity assumptions of the aircraft's actuators used for primary flight control. Additionally the assumed FCS architecture will be introduced. Section 3 summarizes the underlying aircraft design process and introduces the considered aircraft concept in the project to illustrate the aspired use case for the FCS. Following that, we lay out the basics of the architecture modelling, systems modelling and the analysis methods. Section 4 sets up the design study and highlights the applied changes over the different design iterations. Finally we showcase the results from both design iterations in regards to estimated system mass, power consumption and actuator size in Section 5. The results will be critically reviewed to show discrepancies between estimation methods, usually employed estimations and weak spots in the modelling method. The final Section discusses conclusions for system consideration in future aircraft design and research.

2. Flight Control in Commercial Aircraft

FCS in current commercial aircraft are responsible for the aircraft's stability and controllability in flight. This is achieved through control surfaces, actuated by hydraulic and electrical actuators, and flight control computers, commanding the necessary control surface deflections [9–11].

The moderns FCS is consequently mainly made up of

- Actuators and
- Flight Control Computers (FCC),

out of which the actuators make up most of the system mass. They further influence masses of other systems that are needed to supply them [5, 7, 12].

The FCS's activity varies over flight mission. The paper by Simsic [13] illuminates this by describing the mission regimen for their tests of aileron electro-mechanical actuators (EMA). It depends on flight speed v and air density ρ. We will describe flight control activity using deflection δ, deflection rate $\dot{\delta}$ and resulting control surface load $M_{CS,Hinge}$

$$(\delta, \dot{\delta}, M_{CS,Hinge}) = f(v, \rho). \tag{1}$$

These parameters are not independent. Control surface load consists of aerodynamic loads and kinematic loads. Aerodynamic control surface load typically results from deflection, while deflection rates can usually be neglected. Kinematic loads include friction and inertia, and are dependent on deflection speed and acceleration, but difficult to estimate in early stages. We describe activity over the flight mission by assuming budgets for control surface deflection and deflection rate for different flight points.

Table 1 – Example flight cases covered by the model

Flight phase	Flight speed	Flight altitude	$\frac{\delta}{\delta_{max}}$	$\frac{\dot{\delta}}{\dot{\delta}_{max}}$
take-off	0.3 Ma	300 m	50%	50%
cruise	0.7 Ma	10 000 m	10%	10%
landing	0.3 Ma	300 m	50%	50%

This is central to system estimation, especially considering novel flight control functions, as they will demand different deflections and deflection rates throughout the flight mission. A more detailed description of the system's activity is consequently needed to quantify their impact. Table 1 demonstrates our simplified assumptions of an aileron's flight control activity for defined flight points. Air density is instead described by flight altitude to give a more intuitive approach to the described flight cases. The control surface load is a function of deflection, flight speed and density, but also the aircraft's geometry, which means that it has to be calculated for every aircraft specifically.

These assumptions are applied to our system design to evaluate the FCS power requirements and to support the sizing process. Flight cases can be checked against assumptions of nominal parameters such as load and speed of the actuators. Additionally performance points enable sizing of power transferring components (e.g. cables) and power supplying components, such as generators. The budgeting in Table 1 applies to FCS with current function extent.

Active gust load alleviation functions will likely demand increased control surface rates, as demonstrated in numerous studies about potential active load control concepts [14–18]. The same has to be considered for deflection ranges throughout the flight envelope.

Manoeuvre load alleviation in contrast does not necessarily require significantly higher deflection rates. It may instead demand differential deflections, higher absolute deflections or deflections in specific flight points, that might exceed existing flight cases [19, 20]. Manoeuvre load alleviation has already seen applications in current fly-by-wire aircraft, such as Airbus' A320 [21] and A350 [22, 23]. The detailed changes on activity assumptions throughout the flight mission resulting from considered load alleviation functions are defined in Section 4.

2.1 System and Component Sizing Methods

This subsection elaborates on sizing methods for components and architectures for FCS. The components can be divided into two groups: actuation systems themselves and power supply systems including generators, cables, and pipes.

As actuation systems, typically Electro-Hydrostatic Actuators (EHA), Electro-Mechanical Actuators (EMA), and Electrohydraulic Servo Actuators (EHSA) are used. Typical topologies of these actuator types are depicted in Figure 1. To size the components, the requirements for control surfaces regarding deflections, deflection rates, and aerodynamic loads must be determined. These requirements are derived from prior analyses in aerodynamic aircraft design and flight control design. Via kinematic mechanisms the necessary stroke, actuation speed, and stall load of each actuator are calculated from the control surfaces requirements. These are the key factors for the preliminary sizing of the actuators. Additionally, differences between electric and hydraulic actuation systems must be considered. Electric actuation systems show a different performance curve due to electric motor limitations, such as peak current capability, maximum motor temperature ratings, and maximum mechanical speed compared to hydraulic actuators controlled via servo valves. The qualitative force-deflection rate profiles of electric and hydraulic actuators are depicted in Figure 1. The performance curve of a hydraulic actuator can be approximated based on maximum stall load (a_1) and maximum speed at no-load (a_2), whereas this definition is not suitable for electric actuators. For electric actuators, the defining points are maximum load at a given speed (b_1) and maximum speed at a given load (b_2). Consequently, specific performance points of the actuators are increasingly important to the system design.

The sizing methodology employed is based on physics- and scaling-law-based sizing models, implemented within the software Pacelab SysArc, supporting FCS analysis for mass properties, spatial restrictions, and power supply requirements. Various sizing methods exist in literature for dimension-

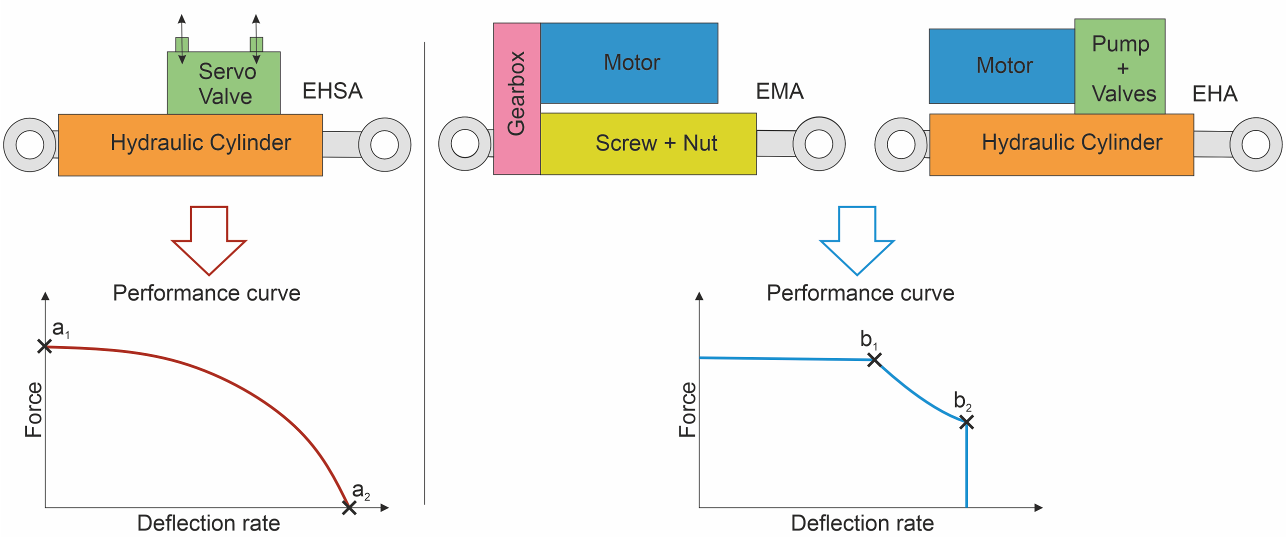

Figure 1 – Actuator types used in sizing process and associated qualitative performance curves

ing FCS during preliminary design. For EMA components, databases containing component such as motors, gearboxes, and screws are often used [24]. For the design of hydraulic cylinders a physics-based approach based on material strengths can be used (e.g. [25]). For EHA, which consists of complex components like pumps and motors [26] alongside hydraulic cylinders, both approaches are combined.

From the power requirements during different flight phases, the maximum power demand that the power supply system must meet can be derived. This power requirement drives the sizing of generators. Cables supplying electric actuators are chosen according to the power demand. Hydraulic actuators require central pumps and pipes. The pumps are sized based on the maximum volume flow, while the pipes are selected based on the system pressure and maximum allowed speed of the fluid. Titanium alloys are used for pressure pipes, whereas aluminum tubing is used for return lines.

Several considerations must be noted regarding the sizing results, which are currently either rudimentary or not fully represented. Commercial Off-The-Shelf (COTS) components are used for sizing. These components are not optimized for mass and size, resulting in dimensions corresponding to the upper limit of mass and spatial constraints. Additionally, the quality of sizing depends on the available system requirements. In cases where aerodynamic loads are not provided, they are rudimentarily estimated using handbook methods, such as e.g. Roskam [27] for assumed control surface hinge moment derivatives. A simple method is used for routing the cables and pipes, determining the minimal path to the components. Thus, the calculated length sets the lower bound of the expected masses for these components. Furthermore, not all components of a system are considered. For instance, smaller components like bearings are currently not accounted for in EMA sizing. Similarly, small components such as clamps are not included in pipe sizing.

2.2 Flight Control System Architectures

A FCS architecture is mainly characterized by the type and amount of control surfaces and actuators it contains. The design of any FCS architecture is significantly driven by redundancy requirements, as the FCS in modern aircraft is crucial to the safe operation of such. Every potential architecture candidate has to be validated against allowed failure rates for all flight control functions. Considering architecture types of commercial aviation only, that use actuation, they can be divided by type of power supply into hydraulic architectures, hybrid electric architectures and all electric architectures. *

Hydraulic architectures constitute the majority of current aircraft FCS architectures. Hydraulic architectures use at least duplex actuator redundancy of all primary flight control surfaces and at least two separate hydraulic supply systems. The usage of three separate hydraulic supply systems is standard for most Airbus and Boeing aircraft for redundancy reasons [12, 28].

*Further classification by e.g. redundancy or means of signal transfer will be omitted in this paper.

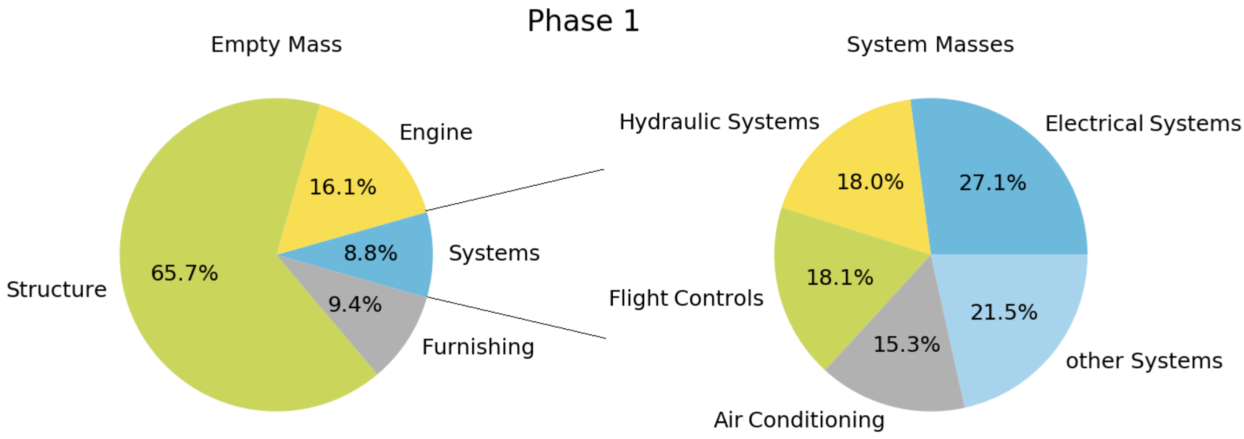

Figure 2 – Initial mass breakdown of the oLAF A/C

More electric architectures mainly use electro-hydrostatic actuators, such as EHAs, together with hydraulic actuators. Power from the engines is transferred electrically from the engines to either distributed pumps (e.g. B787) or pumps inside of actuator packages (such as EHAs in the A380 and A350). Introduction of partial electrical power supply in the A380 allowed for the reduction of used hydraulic circuits to only two, resulting in the 2H2E[†] architecture [12, 21].
All electric architectures, where all necessary power for the actuation of the FCS is transferred from the engines to the actuator electrically, currently do not exist for commercial aircraft. They are subject of numerous research projects for their potential in power consumption and potential inter-system synergies. All electric architectures for FCS are one of the central pieces towards the industry goal of the *all electric aircraft* (AEA) [29]. Ultimately, all electric architectures are envisioned to exclusively utilize electro-mechanical actuation [6]. Because of this, FCS architectures that use both EHAs and EMAs are also dubbed as more-electric architectures, for still containing hydraulic elements. They are a central part of current implementations of more electric aircraft [30], such as A380 and A350 [21].

3. Aircraft Design

The design of a new aircraft is generally a complex and iterative process. Design methods have been established over the years to effectively evaluate the feasibility and potential benefits of new aircraft programs. They start from a desired payload and range for a new aircraft, enriched with additional Top Level Aircraft Requirements. From this an initial description of the aircraft's shape, mass estimation and propulsion requirements can be established. Following design and analysis processes progressively increase the fidelity of the aircraft design. Based on the desired flight mission and wing parameters, the wing shape is optimised. This yields results for the wing mass of higher fidelity, that replace the initial assumptions [31, 32]. Mass estimations for other weight groups in aircraft design are commonly determined by using data based approaches as described by Raymer [31] or Torenbeek [32]. This is still true for more modern design tools such as MICADO [33, 34] and OpenAD [35], and mainly motivated by the scarcity of useful data in early stages. A normalized mass breakdown of the aircraft into the different mass groups used in this paper is shown in Figure 2. The Empty Mass (EM) is broken down into the groups

- Structure,
- Engine,
- Systems and
- Furnishing.

For readability, several considered systems, namely Auxiliary Power, Deicing, Fire Protection, In-

[†]Named for having 2 hydraulic channels and 2 electrical channels.

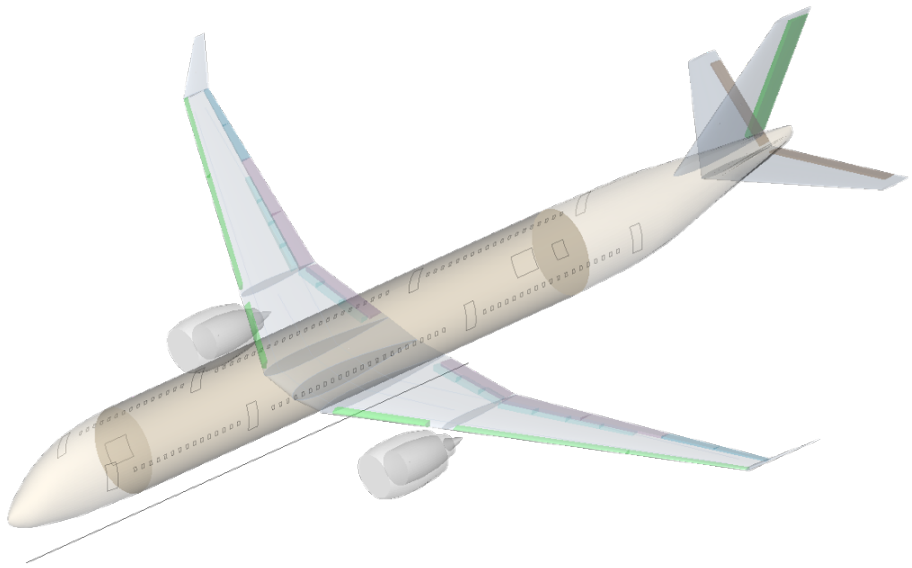

Figure 3 – Initial iteration of the oLAF aicraft

strument Panels, Automatic Flight, Navigation, and Communication, have been grouped into "other Systems" in Figure 2.
The aircraft's systems are presumably hard to quantify for modern aircraft, because the systems' functionality and components may significantly differ from previous aircraft systems. Paired with ongoing ambitions of using aircraft systems' functionalities to open up potential new wing designs, this raises the question of applicability of statistics based system estimation methods for aircraft systems in novel aircraft. To demonstrate the necessity of more detailed modelling in early stages we compare the mass assumptions from these statistic based models to more detailed component sizing models.
For the demonstration we use iterations of an existing aircraft design. The aircraft design, shown in Figure 3, is part of the internal DLR project oLAF. Goal is the establishing of a viable concept for future aircraft that employ load alleviation technology.
The aircraft design involving various disciplines is carried out collaboratively by several DLR institutes. It starts from TLAR descriptions of required cabin layout, payload and range, from which an initial estimation of wing, fuselage and mass description can be derived. Based on this, detailed optimisation of the aircraft and its components is carried out. The aircraft design uses CPACS[36] (Common Parametric Aircraft Configuration Schema) as central information collection and exchange format between disciplines.
Detailed descriptions of the aircraft and design processes can be found in Schulze et al. [37, 38] and Wunderlich [19]. The detailed optimisation schedule and the overall aircraft context are described in Himisch et al.[39]. The aircraft is expected to require extended flight control functions as enablers for improved wing and structure design. These novel flight control functions are *gust load alleviation* through aileron and elevator deflection and *maneuver load alleviation* using all trailing edge devices on the wings. The extent of existing and improved FCS capabilities resulting from this are discussed in Section 4. There are, however, some noteworthy differences to be considered for the mass evaluation.

3.1 Hydraulic vs More-Electric Aircraft Systems

In the assumed aircraft design, a more-electric FCS architecture is assumed, where all primary FCS functions are actuated through electro-hydraulic actuators (EHA). It creates a considerable difference in initial mass estimation. This is illustrated in Figure 4. By integrating components, such as pumps, into the actuators, they are effectively relocated from the hydraulic system into the FCS.

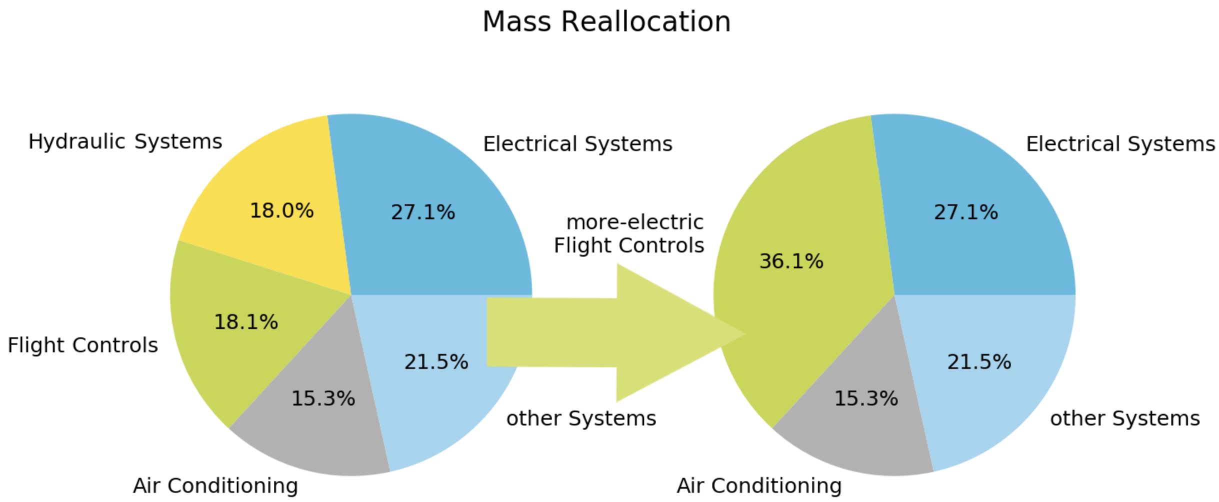

Figure 4 – Assumed redistribution of masses caused by transition from 3H to 2E architecture

It means, that in an all electric architecture masses are relocated from the hydraulic systems to other systems, that locally transform the necessary power from electric power supply. To cover this, the modelled FCS is considered a subset of the combined masses of FCS and hydraulic systems. Occurring mass differences between iterations will be propagated towards the system mass and compared against the independent aircraft level estimations. An integral part of the design process is the tracking of estimated mass components on aircraft level. As part of this, the estimated masses for the FCS $m_{A/C,FCS}$ and hydraulic system $m_{A/C,hyd}$ are recorded. The sum of component masses in our model $m_{FCS,model}$ constitute a combined subset of these two masses.

$$m_{FCS,model} \leq m_{A/C,FCS} + m_{A/C,hyd} \tag{2}$$

The data based mass estimation from handbook methods include all components of the FCS. In contrast, our analysis is focused on actuator masses on the wing trailing edge. Handbook methods assume a state of the art FCS architecture, which separates power distribution (hydraulic system) and power consumption (FCS).

$$m_{FCS,model} = \sum m_{component,i} \tag{3}$$

The difference of mass estimations Δm between iterations should adhere to this relation, so that

$$\Delta m_{FCS,model} = m_{FCS,model}(n) - m_{FCS,model}(n-1), \tag{4}$$

$$\Delta m_{A/C,FCS} = m_{A/C,FCS}(n) - m_{A/C,FCS}(n-1), \tag{5}$$

$$\Delta m_{A/C,hyd} = m_{A/C,hyd}(n) - m_{A/C,hyd}(n-1) \tag{6}$$

and

$$\Delta m_{FCS,model} \leq \Delta m_{A/C,FCS} + \Delta m_{A/C,hyd}, \tag{7}$$

where $m_i(n)$ is the mass of a system *i* of the *n*-th iteration. A higher mass difference in our model would constitute an additional mass increment on aircraft level. In the overall design process this approach allows to consider mass changes to the systems introduced by new technologies more accurately.

Figure 5 – Wing change from Phase 1 (grey) to Phase 2 (green)

3.2 Achitecture Analysis Methods

The considered aircraft are evaluated using a specific set of analysis methods, that help to evaluate the FCS and related systems. The main focus of the analysis lies on the mass descriptions of the considered systems. The modelled system components are

- control surfaces,
- actuators,
- cables and
- generators.

All relevant components are described by at least mass, center of gravity and connection to other system components in the software Pacelab SysArc. Actuators and generators are furthermore described by their calculated nominal power. Required power is calculated from assumed loads and deflection rates of control surfaces, that is propagated through the system. Power transfer and transformation over components such as busses, cables or generators is further augmented through component specific efficiency coefficients. This also allows for the description of the system architecture, resulting power distribution and system reliability. The applied sizing models are described in Section 2.1. The used electrical architecture meets the redundancy requirements of all primary flight control functions in addition to the load alleviation functions.

4. Design Study

We examine a design study, that demonstrates the usefulness of mass increments from component based system sizing. Two iterations of the oLAF design loop are calculated with component based system sizing. The first iteration (Phase 1) is the initial design with a load alleviation implementation without increased FCS activity demands. It serves as a baseline for the mass estimation and evaluation. The second iteration (Phase 2) has a higher aspect ratio, as can be seen in Figure 5. It is considered with two different assumptions for it's FCS capabilities - normal FCS activity demand and increased FCS activity demand - to analyse the detailed effects. Higher activity demand encompasses increased deflection budgets and increased deflection rate budgets. Combined with the aircraft level mass descriptions for Phase 1 and Phase 2, three data sets are generated in total. The architecture of the FCS remains unchanged between versions. It is designed to fulfill necessary redundancies of actuators and supply channels for primary flight control and active load alleviation. This results in active-passive duplex actuation of all primary control surfaces except for the rudder,

Table 2 – Applied rate and deflection limits in Phase 1, Phase 2n, and Phase 2a

Design stage	Control surface	δ_{max}	$\dot{\delta}_{max}$	$\frac{\dot{\delta}_{cruise}}{\dot{\delta}_{max}}$
Phase 1	Aileron	$\pm 25°$	$50\frac{°}{s}$	10%
	Spoiler	$-50°$	$30\frac{°}{s}$	10%
	Elevator	$-20..30°$	$50\frac{°}{s}$	10%
Phase 2n	Aileron	$\pm 25°$	$50\frac{°}{s}$	10%
	Spoiler	$-50°$	$30\frac{°}{s}$	10%
	Elevator	$-20..30°$	$50\frac{°}{s}$	10%
Phase 2a	Aileron	$\pm 25°$	$150\frac{°}{s}$	10%
	Spoiler	$-50°$	$30\frac{°}{s}$	10%
	Elevator	$-20..30°$	$150\frac{°}{s}$	10%

which is actuated by three actuators. Further, two generators per engine are assumed to ensure sufficient power supply in case of a single engine failure, aided by an APU-driven generator.
For both iterations mass estimations on aircraft level were collected and evaluated using CPACS and OpenAD. The underlying mass equations use the common proportionality between operating empty mass m_{OEM} and the system mass. *Phase 2n*[‡] is the new aircraft iteration without additional activities of the FCS considered, *Phase 2a* includes increased activity necessary for load alleviation.

4.1 Phase Details

This subsection briefly summarizes the relevant context and properties of the model used for each phase.

Phase 1

The Phase 1 design constitutes the initial aircraft with state-of-the-art features and respective system capabilities. Resulting masses from structure and aircraft sizing are used as improved masses for the aircraft, while system mass estimation is generated from the initial openAD-model. From the given shape and mass model of the aircraft, the FCS architecture is sized in SysArc, calculating component masses and power consumption, as described Section 2.1. The applied deflection limits and rate limits per flight phase are summarised in Table 2. They enable state-of-art-flight control and load alleviation.

Phase 2n

Phase 2n design includes improved aircraft shape and masses for structure and engine. As seen in Table 2 the FCS's activity, deflection ranges and speeds, is identical to Phase 1. The system masses and power consumption are calculated and compared against Phase 1 to determine the necessary increments.

Phase 2a

Phase 2a describes the improved wing and structure design of the initial aircraft with aggressive load alleviation implications considered. This specifically means increased available deflection rates for primary flight control and additional activity of high lift devices. Deflection rates of ailerons and elevator were increased by 200% to enable aggressive load alleviation, including gust alleviation and flutter suppression. Other mass groups, structure, engine and furniture, remain unchanged to Phase 2n. The system masses and power consumption are calculated and compared against both preceding phases to determine the resulting increment to be fed back into the Aircraft Level Design.

5. Results and Evaluation

The modelled FCS in SysArc fulfills the condition of staying within the assumed mass budget of Equation 2 for all three phases. As already pointed out earlier, Figure 6 compares the calculated component masses in the model to the given mass budget generated on aircraft level. It also includes

[‡]2n as shorthand for *normal*, as opposed to 2a for *aggressive*

the agnostic mass estimation for the relevant system groups for Phase 2, if the usual statistics based estimation were used. It shows a significant increase in assumed component masses between the assumption for Phase 2n and Phase 2a, especially when compared to the overall budget for the system.
Figure 7 shows the development of component weights from different groups between phases. The actuators have been grouped for their primary function, except for the spoilers, which are collected under a separate group. Cabling and generators have been recorded in their own weight group respectively. There are several important details to point out. The masses for the component grouped under "Spoilers" and "YawControl" remain unchanged. "Cabling" mass increases from Phase 1 to Phase 2 because of increased cable length, and again between Phase 2n and Phase 2a. "Generators" increases in weight because of higher power demand in Phase 2a, which is not present in Phase 2n. Masses of high lift components have not increased between phases 2n and 2a, but decreased compared to Phase 1. Weight increase for Phase 2a in "PitchControl" and "RollControl" are caused by higher actuation speed demands.
There are several issues with certain weight groups that have to be pointed out: The component models for high lift actuation do currently not cover weight impact of increased actuation speed, that is expected to be required for more sophisticated load alleviation functions. The size loss of control surfaces should be taken with a grain of salt, since central requirements of effectiveness especially for maneuvers were not part of the aircraft evaluation. More detailed evaluations of the aircraft's in-flight behaviour could potentially require a resizing of control surfaces on the wings trailing edge.
The results for generator masses carry strong uncertainties in the current evaluation. The working assumption applied in this study is, that the FCS dominates the overall power demand over the mission . Accordingly, FCS power demand significantly drives the nominal power for the respective generators. Different power supply architectures in combination with the usage of other systems, that have to be supplied simultaneously, such as landing gear or future propulsion systems, significantly change the nominal cases, that have to be considered.
The actuator masses are currently calculated without considering imperfections in kinematic translation. These commonly result from demanding space integration requirements, that high aspect ratio wings potentially cause.
On aircraft level, the generated mass increments are implemented into the collected mass description as part of the *systems* node. The mass increment shows relevant changes in the aircraft level mass evaluation, as depicted in Figure 8, between Phase 2 based on traditional estimation methods (yellow) and the improved mass description with applied mass increments (green). Both have to be compared to the initial aircraft baseline of Phase 1 (blue). Effectively, benefits from the updated aircraft design are dampened when incorporating the Phase 2a mass increments, as compared to the naive mass improvement from Phase 1 to Phase 2n. Instead of a weight reduction of the m_{OEM} of 4.45

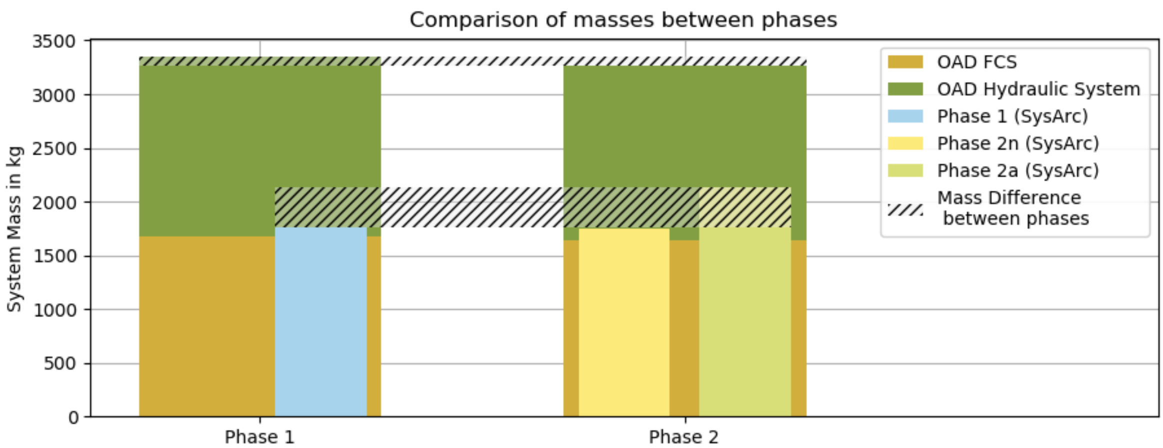

Figure 6 – Preliminary results of the mass comparison in kg

t, the corrected weight difference is reduced to 3.6 t, which still constitutes a sizeable improvement on aircraft level.
The system design additionally bears room for further improvement of masses on aircraft level. Additional generator mass could potentially be reduced by more detailed sizing. Cable sizes might be reduced by changing voltage levels and detailed optimizing actuator load cases. Necessary power requirements potentially benefit from aircraft wide synergy, which improves the overall system mass. In the current analysis no conclusions could be made about under- or oversizing of the control surfaces and actuators. This could be achieved in future work by comparing the provided actuator performance to detailed time-simulations of the flight control and gust load alleviation performance.

6. Conclusion and Outlook

The presented work demonstrates the usefulness of applying component sizing methods in iterative multi-discipline aircraft design in early stages. After outlining the modeling principles for the necessary sizing models, necessary assumptions about the used aircraft were presented. The aircraft considered in the project was presented briefly. Based on the involved data, a demonstrator study has been described to compare the results from two iterations of aircraft design with and without using component sizing models. They are used to generate mass increments for the iterative mass description on aircraft level. Using mass increments, the influence of increased system activity and higher deflection rates necessary for active load alleviation can be accounted for. They generally cause an increase in system mass, that is not covered by statistics based estimation alone. The generated information can also be fed back into other design disciplines, which increases the usefulness in iterative aircraft optimization. The generated data shows overall reasonable physical behaviour, despite the omission of not analysed systems.
A significant shortcoming of the presented design study is the disregard of landing gear system, as landing gear systems also partially size supply system's nominal power. They were omitted for lack of modelled landing performance within the project. Potential synergy between the systems should be addressed in future research.
In summary, the component based estimation method for mass increments caused by design changes of the aircraft yields design consequences, that help the iterative design. Design consequences of increased system activity, leading to higher actuation speeds and in turn power requirements, can be evaluated for their impact on aircraft level and tracked to their respective cause. This enables a more holistic aircraft design over iterations.

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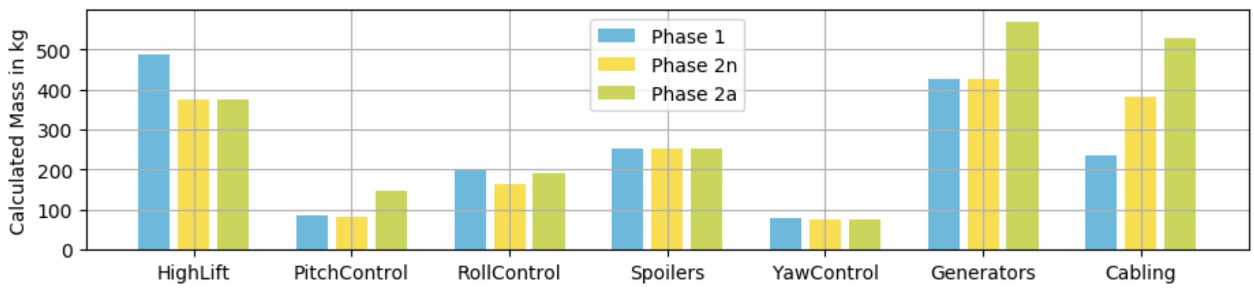

Figure 7 – Summed component masses per group

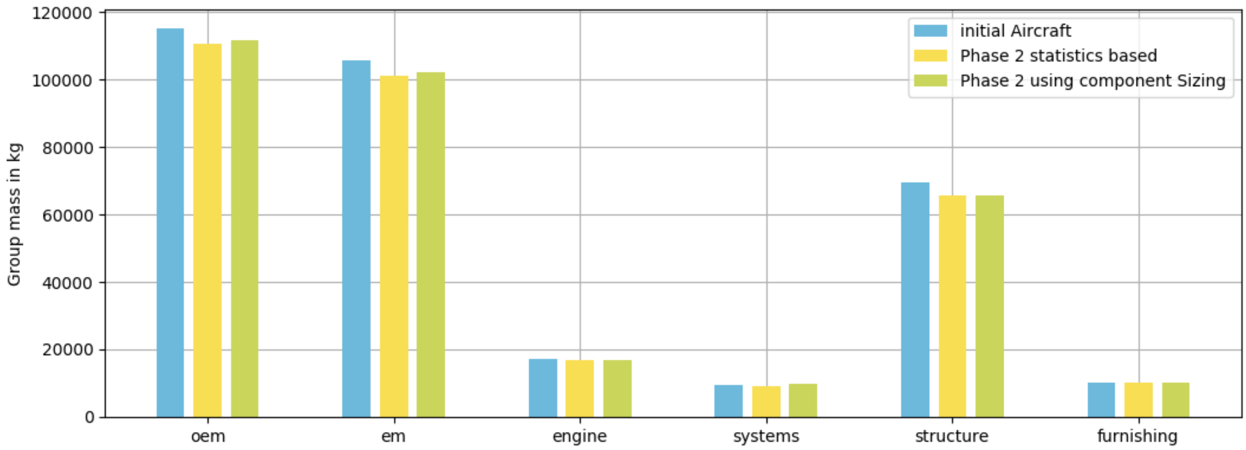

Figure 8 – Resulting Masses on Aircraft Level

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