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Influence of flight control laws on structural sizing of commercial aircraft

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1 Introduction

1.1 The need for a new simulation framework

The global market for civil passenger aircraft is growing steadily. In its global market forecast [Air19] Airbus estimates a rise of so-called *Aviation Mega Cities* from 66 to 95 until the year 2038 with the highest increase in the Asia-Pacific region. Currently these kind of cities, which usually have more than just one airport, account for 40% of the total number of aircraft passengers worldwide. Indeed, the increasing need for passenger aircraft can be explained by the economic growth of emerging markets and the related industrialization and urbanization across such countries. With more people living in cities and their need to travel from one location to another the local airlines have to respond to this demand by increasing their aircraft fleet. During the next 20 years approximately 40,000 aircraft of different types are needed with a market demand of 42% in the Asia-Pacic region (cf. [Air19]). In addition, established airlines in regions such as North-America or Western-Europe are by time faced with the need to replace their existing fleet with new innovative aircraft models due to aging or simply in order to reduce their operating costs and thus increase their profit margin. Another reason is the rise in worldwide tourism and with respect to this the demand for a proportional number of aircraft with different ranges has to be saturated. In this sense aircraft manufacturers like Airbus or Boeing are eager to deliver innovative aircraft models with for instance an improved lift to drag ratio, higher MTOW, less fuel consumption and less carbon dioxide emissions. As stated in [Air19] today's aircraft are already "75% quieter and 80% more fuel efficient per seat" than in the early days of civil aviation.

Innovative approaches by means of numerical simulation can be developed for different phases of the aircraft design process. The aircraft design process consists of the conceptual design, preliminary design and detail design phase. The conceptual design regards the overall aircraft configuration according to requirements and specifications. The preliminary design phase considers the detailed analysis and optimization of parameters from involved disciplines in order to fit the conceptual design. Finally the detail design phase targets a last refinement of structural elements. In terms of development costs late and unplanned modifications of larger scale can cause a high increase in expenses and affect the whole design process negatively. That is why especially the use of numerical simulation is a means of properly setting most of the design parameters in early design phases in order to keep development costs at a low level.

Examples for multidisciplinary problem sets are the optimization of the winglet design for the purpose of less induced drag and thus higher lift at the wing tip region or the update of the flight control system law for the purpose of load alleviation along the wing and thus achieving a structural mass reduction. In order to tackle such kind of problem sets various fields of analysis like the calculation of aerodynamic pressure distribution, the improvement of flight performance using a control system, the preparation of an accurate mass and structural stiffness distribution and the calculation of engine propulsion need to be taken into account. In industrial practice different departments tackle different disciplines separated from each other. The common means of interaction between departments is the delivery of results and requests. Using this way of working it can take weeks to receive a feedback for open issues. Another means of handling cross-department tasks and assessing the impact of limited changes on certain disciplines is to take advice from senior experts or use values from technical databases.

The motivation or rather the need for a new multidisciplinary analysis and optimization framework in the industrial aircraft design process arises from these circumstances. Multidisciplinary analysis and optimization has to be deployed in order to get simulation results for interdisciplinary parameter variations in a matter of hours instead of weeks. Especially in the scope of *incremental innovations* which is the working strategy of Airbus in the coming years such a framework makes the quantification of results possible. In this way improvements on the aircraft can be achieved effectively and thus manufacturers like in this case Airbus are able to fulfill the needs of the airlines for profitability in a shorter time frame.

In this sense the aim of this present PhD thesis is to develop a multidisciplinary analysis framework inside the Airbus Flight Physics department. This framework covers those major disciplines sequentially which are gone through during the industry standard development process. The original idea comes from the Component Loads team in Hamburg with the approach to develop a supporting tool for decision making by the chief engineer after preliminary design. The objective is to deploy a first prototype that uses a physically based approach without any surrogate models and in addition shows advancements in aircraft multidisciplinary analysis and optimization. The chosen use case in the frame of this thesis regards the quantification of the impact of load alleviation function parameter variations on the inner/outer stiffened wing box covers and stiffened aft fuselage shell of a generic long range aircraft. Here possible mass reductions along the wing component and related mass penalties for the dedicated fuselage section are quantified based on structural reserve factors and stress values.

Regarding the work at Airbus with an airframe lightweight structure that is getting more complex and engineers who are eager to find an optimal design with minimum weight it is clear that the future is a multidisciplinary one. Engineers need to take into account different disciplines at the same time in order to assess parameter changes more effectively and come to conclusions. In this sense the here developed prototype makes it possible to perform such simulations and to analyze dependencies across disciplines using real simulation models and data in a short time frame. In future studies this prototype can be extended for different types of analysis which can also be located in another phase of the aircraft design process.

1.2 State of the art

An active load alleviation system with varying aileron and spoiler deflection angles changes the lift distribution along the wing such that the center of pressure is located more inboard which yields a reduction of the wing root bending moment and torque. However, reactive elevator deflections are one side effect of this active load alleviation and lead to a force introduction at the aft fuselage section. Related possible mass reductions are calculated via a fully stressed design based structural sizing and mass penalties are estimated using finite element based internal loads exceedance values. Flight manoeuvres and continuous turbulence load conditions are chosen as test cases and the stiffness as well as mass values of the loads calculation model are updated based on the modified structural wing properties. In this section an overview of the state of the art literature and related developments is given.

1.2.1 Multidisciplinary analysis and optimization in aeronautics

In their conference papers [dWASS$^+$07] and [ML13] the authors emphasize that the origins of multidisciplinary optimization can be traced back to structural analysis since in any system an available structure most often interacts with another subsystem. Non-linear programming with its objective function and constraints is among the first approaches to solve a three bar truss problem. Accordingly the mass is minimized with varying geometrical dimensions while stress constraints have to be kept. With a growing number of use cases and maturity the concept of non-linear programming for structural optimization is applied in aeronautics, too. Indeed, when working on structural optimization problems less computational resources make engineers rather work with gradient-free optimality criteria like the fully stressed design approach (cf. [Ven89], [PH98], [PGB93], [RZ91]) instead of time and resource consuming non-linear programming. In his paper [Joh02] E. H. Johnson states that although no mathematical proof is given for the fully stressed design approach to yield a minimum weight design it is still an option in practice to apply it in a first step beforehand any non-linear optimization.

This kind of single discipline optimization has an obvious impact on other disciplines like aerodynamics or performance due to changes along the airframe. As described in [dWASS$^+$07] this respectively leads to an extension of the design space to the related quantities of interest. With respect to existing technical limitations different approaches are suggested to handle these interdisciplinary dependencies. In this sense linear decomposition methods as proposed in [SS82], [WD90], [SJR78], [SS88] and [SSBA83] are brought into practice in order to split the optimization of a larger system into a set of standalone problems, simply to overcome limited computational power. Indeed, this way of decomposition also allows the use of multiple processors in order to speed up calculation time. The idea is to establish an iterative process in which local parameters on subsystem or component level are optimized and wherein these tuned values are then passed to the upper system level for another optimization. In this sense for instance the complete wing box with its stringer cross section area and inertia values is regarded as system level whereas each stringer with its cross sectional dimensions is treated as a subsystem. This linear decomposition approach is applicable to any kind of discipline or aircraft component.

Another factor for the rise of multidisciplinary analysis is the technological advancement in computational resources like more available memory for data storage, the advent of computer clusters or rather super computers, the standardization of parallel processing (cf. [Lub94], [And02]) and the use of high level graphical visualization. This development has two major impacts as described in [MC02] and [dWASS$^+$07]. The first one is the change from low- and medium-fidelity, analytical and database driven approaches and simulation models to high fidelity ones with sophisticated graphics, larger design vector and increased design space. The second impact is a change of the way of working in engineering itself. The trend is towards the use of more simulation models and less physical experiments, mock-ups and technical drawings which then leads to a time and cost reduction of the whole industrial aircraft development process. Considering these aspects multidisciplinary simulation frameworks are enhanced successively for the analysis not just of local structures but of whole systems and rather aircraft configurations.

Different types of analysis sequences are put forth with the rising possibilities of multidisciplinary analysis. In the journal paper [ML13] an overview of different monolithic and distributed architectures with associated ways of model coupling and solutions is given. In the case of monolithic architectures the optimization of different disciplines is performed in just one problem formulation. For instance in his PhD thesis [Jam12] K. James shows the simultaneous topology and aerodynamic shape optimization of an aircraft wing box using the *multidisciplinary feasible* architecture in which "all objective and constraint functions, as well as their sensitivities, are computed in a way that takes aerostructural coupling into account". Both disciplines are coupled by computed forces and displacements. The author states that a better optimization result is achieved when applying this kind of monolithic architecture for his use case (2g manoeuvre case) compared to a sequential optimization of the same model. Especially the benefits of the resulting lift distribution are pointed out with the center of pressure shifted inboard which then leads to less drag due to smaller wing tip deflection and yields a mass reduction, too. Similar approaches are demonstrated in [KM12] and [KKM12]. In the case of distributed architectures each discipline is analyzed and optimized separately whereupon values of design parameters are passed from one discipline to another (cf. [CRR09], [GCdCV08] and [SSF$^+$16]). Simulation models of various disciplines can be coupled based on different fidelity levels. In particular the design of aircraft wings with minimum weight and drag is a widely considered use case. In this sense the authors of [KM12] run simulations of metallic and composite materials for the structural optimization of the wing using a panel aerodynamic model, whereas in [KKM12] the application of high fidelity models for both CFD and structural analysis combined with parallel computing for a highly flexible wing is shown. Aeroelastic tailoring of a composite wing is performed in [DKAG13]. Furthermore reduced order models using various surrogate modeling techniques are investigated in [YM12], [Giu97], [Rum12], [PJB$^+$13], [LHH15] and [SML$^+$16] in order to replace time consuming and intense aerodynamic CFD analysis by cheap function evaluations. Multidisciplinary analysis is an enabler for the investigation of innovative aircraft configurations like BWB (Blended Wing Body) civil airplanes as shown in [HHH08] and [ÖHH01] or other flying wing configurations for military vehicles as investigated in [VK17]. Next to gradient based optimization algorithms also derivative free techniques like *particle swarm* can be used in order to find the global optimum as demonstrated in [VSS04]. Indeed, multiple disciplines can also be combined with algorithms from multi-objective optimization (cf. [KV06]) or multi-body simulation (cf. [Krü08]).

Another trend is the implementation of flight control into multidisciplinary considerations. In this sense R. E. Perez et al. present in their journal paper [PLB06] a developed framework in which flight control during the conceptual design phase is considered. Here they claim that a "sequential process may lead to suboptimal designs" and instead present an optimization framework for simultaneous modifications of the control system, the control surfaces itself and the aircraft conceptual design. Their optimization of a civil passenger aircraft shows an improved design with respect to performance and handling qualities. In [XK11b] and [Xu12] the influence of a manoeuvre load alleviation system and natural laminar flow is studied for aircraft conceptual design. Based on "low-order, physics-based methods" a reduction of direct operating cost and less fuel consumption is achievable. Furthermore in the PhD thesis [Akm06] an active control for the suppression of flutter effects based on an aeroelastic simulation model is investigated. In [ZY07] a transonic aeroservoelastic model for the purpose of active flutter control is developed. In their technical report [BGW99] M. L. Baker et al. discuss mathematical models for aeroservoelastic

analysis at Boeing. In particular they highlight the importance of including ”structural dynamic and aeroelastic effects” when designing the control law but in addition urge to keep consistency of quantities which are given in frequency or time domain. In his work [Pal11] N. Paletta studies different aspects of the design, effectiveness, benefits and the quantification of manoeuvre load alleviation systems especially for the purpose of enhanced performance and the extension of structural fatigue life expectations. In their work (cf. [Hag12] and [HML12]) S. Haghighat et al. present an aeroservoelastic framework for the simultaneous optimization of the control system, aerodynamic shape and structural properties of a highly flexible UAV for the purpose of performance improvements. Here they use Euler-Bernoulli beam elements in order to model non-linear wing deflections, apply next to a load alleviation function also model predictive control as well as robust controller and make use of a 3-dimensional panel method in order to analyze maneouvre and gust conditions. Comparable analyses are also demonstrated in [SY93], [POK$^+$19] and [WKP$^+$18] where in [POK$^+$19] the authors emphasize a major intention that ”structural weight reduction and high aspect ratio wings play a key role in improving the performance of modern transport aircraft”.
It is stated in [dWASS$^+$07] that the integration of such multidisciplinary approaches into an industrial environment plays an important role such that engineering departments in companies can use these new technologies for commercial analysis and development. Such process integration which indeed enables modularity of disciplines is the subject of the next subsection.

1.2.2 Multidisciplinary simulation frameworks in aeronautics

Different frameworks that involve those major disciplines which are tackled in the frame of this thesis are listed in this subsection. In this sense the analysis environment FAME-W is mentioned (cf. [KG97], [KLG95], [VdVKKM00]) which is an Airbus development for quick weight estimation of the wing during preliminary design phase as a result of parameter studies. As noted in [KLG95] this framework is based on ”an analytical/numerical algorithm based on the classical theory of multicellular shells, beam and structural instability theory”. Indeed, this kind of approach is chosen instead of high fidelity CFD calculations or structural stress analysis based on FEM models in order to enable simulations with less computational resources, too. There is a positive response to this framework especially at the Airbus Future Projects office due to its modularly built structure, the possibility to test new algorithms and available results in a reasonable time frame. Also the impact of an active manoeuvre load alleviation system on the wing bending moment in terms of shear loads and possible wing mass reduction is evaluable including an update of the aerodynamic loads although the calculation of aerodynamic coefficients is based on lifting surface theory.
The optimization framework MBB-Lagrange for structural problems which is developed by the Royal Aerospace Establishment and taken over by Airbus is presented in [BW90] and [Zot92]. The developers of this framework use a FEM model representation of structural components as the central pillar of their optimization approach since detailed structural analysis is more effective using this kind of discretization. In this sense the objective is the minimization of structural weight in which quantities like the element thickness, cross sectional area or the stacking sequence for composite material are used as design variables. It is developed as a modular framework that contains various optimization algorithms and thus makes it possible to connect other software like for the purpose of flutter analysis

and to apply related quantities as boundary conditions. In this way more than only stress boundaries are taken into account. Necessary sensitivity values for the optimization of design variables are obtained analytically due to time reasons but can also be assessed from commercial FEM solvers like MSC Nastran®.

The software ASTROS (cf. [JV88]) is developed for the US Air Force and is supposed to be used during preliminary design for the purpose of time reduction. Also based on a FEM model representation of the aircraft its development is closely based on Nastran notations and file formats. Existing methods for major disciplines are integrated modularly with each module managed and connected using the programming language MAPOL (Matrix Analysis Problem Oriented Language). In this sense the aeroelastic analysis considers steady as well as unsteady aerodynamics and the structural optimization can be performed with the fully stressed design approach or a mathematical optimization including for instance stress, strain or stiffness constraints. Also a static condensation by Guyan is implemented in order to reduce the FEM model for the purpose of modal analysis.

The tool NeoCASS (Next generation Conceptual Aero-Structural Sizing Suite) as described in [CRR09] and [BCDR$^+$08] is based on low and medium fidelity models and especially used for the aircraft conceptual design. It is built in a modular way and combines weight estimation, structural sizing and optimization as well as aeroelastic analysis. The developers put much focus on a reliable weight estimation in early stages including next to the primary structure also the non-structural mass. The process starts with an initial weight estimation based on statistical methods as well as databases and then a regression analysis after the structural sizing is applied in order to update the first estimation. On the other hand no FEM model representation is used for the structural analysis but rather analytical formulas with simplifying assumptions on the structural model. The aeroelastic analysis relies on a beam stick model and aerodynamic panel methods using generalized equations of motion.

P. Piperni et al. from Bombardier Aerospace describe in [PAK04] the integration of in-house developments and other existing tools of various disciplines into a multidisciplinary analysis platform for the purpose of simultaneous optimization of the wing shape and cross sectional properties. Aiming at a reduction of development time during conceptual design phase CFD analysis of different fidelity is implemented and combined with a wing structural analysis as well as weight estimation code. Their idea is to start the optimization with low fidelity models in order to be able to analyze a high number of load cases and then to refine the model in a further step using higher order models. In this sense the software VADOR is used especially for data management and the package EPOGY contains different optimization algorithms. TWSAP is developed in-house in order to generate a wing beam stick model for aeroelastic analysis and in addition to design the wing box which is the basis for their weight estimation module.

In [Gar18] the industrial way of working at Dassault Aviation is described. The major focus of the author lies on the description of the approaches in the field of aeroelastic, aeroservoelastic and aerostructural analysis. The key enablers for these types of FEM model based multidisciplinary studies are the platform ELFINI®, which is used for data management and additionally allows the use of different solvers, and the software CATIA® which is used for pre- and post-processing steps. In standard processes a beam stick model with an accurate stiffness and mass distribution of the aircraft is used in order to be able to calculate thousands of load conditions. Additionally, more sophisticated approaches are developed like the replacement of aerodynamic panel methods and databases for correction by linearized CFD analysis. Central part of the aerostructural analysis is the global FEM model of the aircraft which is used for internal loads calculation and thus is a basis for the assessment of strength and stability criteria. In terms of aeroservoelastic analysis the author of [Gar18] points out that more research is planned to investigate the use of active load alleviation systems in early development phases in order to achieve mass reductions.

Different frameworks are developed at several institutes of the German Aerospace Center - DLR. For instance A. Schuster et al. from the Institute of Composite Structures and Adaptive Systems present in [SSF+16] their developments regarding the sizing of a civil passenger aircraft focusing mainly on metallic/composite fuselage and wing components. For this purpose they develop a sequential process that covers aeroelastic, aerodynamic and structural analysis. Hereby the generation of simulation models and especially of the global FEM is based on their developed CPACS (Common Parametric Aircraft Configuration Schema) which contains all needed pieces of information like the aircraft mass, center of gravity, position of stringers, frames, ribs, spars and more. The internal loads of the beam stick model after the calculation of load conditions are given in form of Shear, Moment and Torque curves. These values are applied to the global wing and fuselage FEM models in form of discrete forces using rigid body elements without stiffness whose master nodes are placed along the reference axis. The sizing of the fuselage is based on analytical methods first and then followed by numerical simulations. The global FEM static analysis of both fuselage and wing is performed with the ANSYS® solver whereas the sizing is done based on a fully stressed design algorithm using reserve factor values of different sizing criteria until mass convergence.

In their conference paper [KK16] W. R. Krüger and T. Klimmek summarize the developments in the frame of the iLOADS (integrated LOADS analysis at DLR) project by the Institute of Aeroelasticity, Institute of Aerodynamics and Flow Technology, Institute of Structures and Design as well as some other institutes of the German Aerospace Center - DLR. Here the focus is on the loads calculation process and mainly on the aerodynamic analysis as well as on the calculation of manoeuvre and gust loads. The process consists of a definition step of the considered load conditions (e.g. mass, CG, flight points), the loads calculation itself and a post processing in which the resulting Shear, Moment and Torque values are interpreted for load case selection. The model definition and data management is kept in the DLR CPACS, too. Indeed, a number of different DLR developments are used for dedicated tasks. For instance the tool MONA is used for the purpose of creating a parametric FEM model and performing optimization using MSC Nastran®. Another example is the tool VarLoads (which is based on panel methods, a beam stick model and generalized equations of motion) which is used for the loads calculation. The structural sizing is realized with S-BOT or commercial software like HyperSizer® by Collier Research Corporation. Indeed, in the frame of the iLOADS project also different methods for the calculation of aerodynamic loads are investigated like the lifting line theory, 3-dimensional panel methods or Navier-Stokes equations. The resulting loads distribution is applied to the fuselage structure for the purpose of structural analysis (static strength, stability and structural fatigue life). The same approach for structural analysis is also shown in [SSF+16]. Indeed, the authors of [KK16] point out that applying the loads along the fuselage reference axis only might not be accurate enough for sizing purposes. Further studies based on partially the same tool sets are presented in [KDDB+16] in the frame of aeroelastic and aeroservoelastic tailoring of adaptive wing structures and in [DNG12] in the frame of wing mass estimation, including also parts of the secondary structure, using a physical approach.

Different tools for structural optimization are developed at Airbus that can be included into in-house multidisciplinary analysis frameworks. In this sense in [Gri17] the tools PRESTO, ISAMI, ACO and AMO are presented which are all based on a global FEM model of the analyzed components. Essential for this set of tools is the extraction of internal loads and/or sensitivities using the MSC Nastran® solver. PRESTO as a rapid sizing tool is based on a database of discrete internal loads and material properties associated to their related structural reserves. It is developed with the intention to support engineers during early design phases for the purpose of parameter studies. On the other hand ACO and AMO are developed for detailed structural analysis of composite and metallic components applying mathematical optimization. ISAMI is developed to be the official sizing tool at Airbus including a large set of failure criteria. Another development at Airbus regarding the optimization of stiffened fuselage panels is presented in [GSM+09].
The simulation framework PrADO is developed at the Institute of Aircraft Design and Lightweight Structures of the Technische Universität Braunschweig especially for the purpose of aircraft conceptual design studies. Its modularly built structure allows to run different disciplines like aerodynamic or structural analysis in an independent way. Developments on PrADO are coupled with research projects and related PhD thesis. In this sense in [Öst06] the improvement of the framework with a "physical representation of the aircraft configuration" is shown with special attention paid on weight estimation methods and FEM model based analysis. In [Han09] and [HHH08] the extension of the framework to the analysis of a Blended Wing Body configuration is shown. In his thesis [Rie13] the author analyzes composite materials and thus makes use of aeroelastic tailoring. More developments on the framework PrADO are described also in [ÖHH01] and [ÖHH00].
It is worth mentioning that different frameworks are developed by various companies for the purpose of model and tool integration. Examples are given with AML (Adaptive Modeling Language) by Technosoft, CAFFE (Collaborative Application Framework For Engineering), FIDO (Framework for Interdisciplinary Design Optimization) which are developed by the NASA, Isight by Dassault Systems and ModelCenter by Phoenix Integration.

1.3 Objectives and thesis overview

This PhD thesis is the result of a collaboration between the Institute of Aircraft Design and Lightweight Structures of the Technische Universität Braunschweig and the Flight Physics department at Airbus in Hamburg. Its objective is the development of a modular multidisciplinary analysis and optimization framework using a distributed architecture that is directly placed on the Airbus computing infrastructure. A big effort of this thesis is the computational implementation of in-house Airbus tools as well as self-developed algorithms and program code into one framework and thus bring them together as a whole. The process needs to run sequentially with each discipline integrated as a module which means that high fidelity coupled aerostructural or aeroservoelastic analysis are not covered. In addition, parametrization is a core aspect since the framework has to be capable of parameter studies cross disciplines and to assess the impact on multiple aircraft components. Appropriate means, like parallel computing and simulation models of different fidelity, shall be used in order to keep the computation time for a complete analysis loop with hundreds of load conditions reasonable. Furthermore a multi-level decomposition approach for the wing box structural property optimization has to be used in order to implement a fully stressed design algorithm based on static sizing criteria. The idea is to accomplish a first demonstrator based on the latest infrastructure, simulation models and software to lay the foundation for a future standardization of multidisciplinary analysis in a less time consuming aircraft development process.

A physically based approach is applied using global FEM representations of industry standard generic long range aircraft components with proper discretization to yield high accuracy in terms of internal loads distribution and overall stiffness. Only the primary structure of the wing and fuselage are studied and related mass changes assessed as delta values accordingly. Indeed, structural property changes of the wing and subsequent modal analysis with related mass and stiffness variations are taken into account but flutter phenomena, which are studied by many other researchers, are not included.

As a first major use case for this Airbus in-house developed prototype an active load alleviation system as one possible way of mass reduction has to be studied. In this sense the very first target user is the chief engineer after preliminary design who can use the framework as a supporting tool for decision making. With respect to *incremental innovation* the outcome of this PhD thesis has to be a means of quantifying and judging on load alleviation parameter changes regarding their impact on the wing box covers and fuselage stiffened skin panels. Thus the decision of the chief engineer concerning the scale of possible design modifications can be supported quantitatively by results of this simulation framework.

It is worth mentioning that many multidisciplinary analysis and optimization frameworks are developed by different companies or research institutes. However most of them use simplifications in some form, like for instance in the make up of the structural model, apply a small number of load cases, consider a few structural failure criteria, choose a rough discretization of the FEM model or do not use a flight control system. Accordingly many frameworks are used for conceptual studies or preliminary design. Hence the focus of this PhD thesis is to develop a fast approach to achieve reliable and accurate results for a high number of load conditions in a reduced time frame but still under real industrial circumstances. Thus taking into account the major disciplines of aircraft development and combining them in a single framework on high performance servers lays the foundation for more niche use cases like the investigation of incidents during in-service or the analysis of flight test validated loads.

In this sense *chapter 2* contains a description of the developed multidisciplinary analysis and optimization framework. A short explanation of each integrated major module is given with some more exemplary use cases. It follows an overview of the way how the framework is computationally implemented. Some useful post processing routines originated in the frame of this thesis and hence are listed, too.

In *chapter 3* the loads calculation process is described. Here the scope of computed vertical manoeuvres and continuous turbulence conditions with associated mass cases and flight points is outlined. Special attention is paid to the loads calculation model whose accuracy of results, which are provided in form of discrete shear loads over evaluation stations, influences the outcome of the subsequent structural property optimization. The distinct parts of the loads calculation model are listed and detailed, e.g. the applied 3-dimensional aerodynamic panel methods for steady/unsteady calculations, the structural dynamic model which consists of the beam stick model, the mass distribution and the EFCS (Electronic Flight Control System) model. Accordingly the purpose and general aspects of the EFCS are explained with special focus on the manoeuvre load alleviation system and the ways of optimizing its parameters.

In *chapter 4* the structural property optimization and mass penalty estimation are described. This chapter starts with a description of considered material properties as well as modeling aspects of the global FEM representation and its purpose of providing an accurate internal loads flow. Other frameworks, that also make use of the global FEM internal loads, apply the external discrete forces along the loads reference axis of the fuselage only. Contrary to this a *unitary load case* approach is implemented in the frame of this thesis in which the discrete forces and moments are applied along the fuselage according to the physical mass distribution of the secondary structure. The wing box is loaded along the reference axis as it is done in common practice. The results of the linear static analysis are used for both the multi-level wing box property optimization, for which a stress value and reserve factor based fully stressed design approach is implemented, and fuselage mass penalty estimation, that is based on internal loads exceedance values.

The implemented feedback loop in order to pass the updated wing box structural properties back to the loads calculation model is described in *chapter 5*. Here an *equivalent beam* approach is used after the static condensation of the wing box in order to overcome discrepancies in the discretization of both the global FEM *model for strength assessment* and *model for dynamic analysis* which are mandatory used at Airbus. The assessment of delta mass values after the structural property optimization is based on the calculation of concentrated masses with the *Grid Point Weight Generator* whose resulting values are evaluated in the implemented global convergence criteria, too.

Chapter 6 contains the results of the performed design studies. The whole PhD thesis is summarized in *chapter 7* together with a discussion of the applied methods and results. Additional material can be found in the *appendices*.