Multidisciplinary Design Optimization of Flight Control System Parameters in Consideration of Aeroelasticity

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Abstract

In this paper a multidisciplinary design optimization framework is presented which considers the disciplines flight control system design, structural mechanics and aerodynamics. The multidisciplinary design optimization problem is highlighted from both a theoretical and a practical engineering side. The aeroservoelastic optimization framework couples Airbus Defence and Space LAGRANGE for aeroelastic analyses and optimization with an in-house flight control system for a generic, high aspect ratio aircraft configuration. A flight control system parameter which determines a ratio between the aircraft aileron and spoiler deflection is introduced and serves as an optimization design variable, therefore. The initiation of a commanded roll maneuver serves as a static load case. Applying the aeroservoelastic optimization framework leads to a flight control system design that causes minimum elastic energy by minimum compliance in the aircraft structure. The paper explains how to respect the flight control system in a multidisciplinary way during the aircraft design process and highlights the benefits of this approach.

Nomenclature

$\ddot{\Phi}$	Roll acceleration
κ	Angle of spoiler deflection
λ	Ratio between spoiler and aileron deflection
Φ_c	Commanded bank angle
σ	Mechanical stress
ξ	Angle of aileron deflection
f	Objective function
F_i	Nodal forces
g	Constraint function
K	Mechanical stiffness
p	Loads
p_a	Aerodynamic loads
p_s	Structural loads
r	Analysis response function
u	Displacement field
u_i	Nodal displacement
x	Design variable

1 Introduction

In the last years unmanned aerial systems (UAS) or remotely piloted aircraft (RPA) increasingly gained ground in aircraft industries. The terms unmanned combat aircraft systems (UCAS) and unmanned surveillance systems as medium/high altitude long endurance (MALE/HALE) configurations were established. Missions and flight envelopes for RPAs differ from conventional aircraft. Especially for surveillance missions loitering at high altitude is of major importance. For this purpose a high aspect ratio and the resulting increasing importance of aeroelasticity are matters of choice [1]. Usually the mechanical structures of high aspect ratio configurations are noticeably less stiff compared to conventional aircraft. With reduction of structural mass and stiffness, the aircraft structure tends to reach its mechanical limit faster, when experiencing high loads. The influence of the flight control system (FCS) to reduce the danger of flutter, gust or buffeting increases [2, 3]. In this context the problem of controlled loads arises. The term aeroservoelasticity applies when the FCS and aeroelasticity are taken into account simultaneously in the design process [2].

It is state of the art to conceptually design a new aircraft without respecting aeroelasticity in detail. High fidelity methods are usually not applied in this phase [4, 5]. Generating new tools and studying available process chains for the purpose of conceptual model creation is extensively being studied [4, 6, 7]. This early stage focuses on the air vehicle concept, only a first sketch and no detailed numerical values are available from the aircraft. As no actual control system is available, only uncontrolled loads are considered. Very basic assumptions and experience values, must be trusted to respect the influence of control surface loads or aeroelastic phenomena as flutter or gust. The design space for a flight control system is still quite large in conceptual design. In detailed design more emphasis is put on the airframe concept. In detailed FCS design many parameters such as the number and dimensions of the control surfaces or their required effectiveness are fixed or at least limited within certain bounds. Thus, only a small design space is available for the detailed FCS development.

Following these points, it becomes clear that with respect to the flight control system and with controlled loads in the design loop, a wide, methodical gap opens up between conceptual and detailed design. Due to the high number of involved disciplines and the successive improvements of its methods, multidisciplinary design optimization becomes increasingly attractive for today's aircraft design. Especially for aircraft configurations with a high aspect ratio, the interaction of structural elasticity and aerodynamics can be respected best in a multidisciplinary way. Adding FCS requirements in the scope of multidisciplinary design optimization means reducing the gap of respecting both aeroelastic and FCS needs in the conceptual design. However, the focus of the discussions in this paper lies more on detailed design.

The techniques of multidisciplinary design optimization (MDO) were developed to solve problems, where multiple disciplines are involved, various interactions among them occur and solutions must be found, which fit ranges of constraints. Handling the interactions results in a solution of best compromise between the involved disciplines. Thus, MDO is a suitable approach to solve the problem of determining parameters of the FCS. Previous studies, which took aircraft structural models into account, showed the potentials in coupled aeroelastic and FCS analysis [2, 8]. This paper focuses on a process chain, its components and the multidisciplinary interfaces among them. It presents how to simultaneously apply both a detailed FCS and a detailed aeroelastic model in an engineering design process. The aircraft structure will be represented in the optimization objective and constraint functions, its aerodynamics in the application of loads based on potential flow theory and the FCS as the load commanding element.

2 Theoretical aeroservoelastic optimization problem

Basic hints on aeroservoelastic analyses in the scope of optimization will be presented. A brief discussion on designing a FCS using aeroelastic information is followed by an introduction on multidisciplinary optimization with aeroservoelastic background. Understanding the theoretical problem is the base to understand the practical one, discussed hereafter.

2.1 Flight control system design as aeroservoelastic task

Structural mechanics, aerodynamics and flight mechanics are disciplines which interact with each other and must therefore work closely together in the aircraft design process. Depending on the structural stiffness, it might be necessary to take aeroelastic coupling effects between aerodynamics and structural mechanics into account. From the structural mechanics point of view, stressing criteria need to be analyzed. Stressing criteria merge the requirements of mechanical strength, given by mechanical stresses that remain below a certain allowable value, and of mechanical stability. This applies both locally for single aircraft components and globally for the whole system. Present studies, focus on strength criteria only. Flight dynamic maneuvers, commanded to the aircraft by the flight control system, using flight control system signals, dictate the loading and thus aeroelastic displacements and stresses. In this regard, developing a FCS is a multidisciplinary task.
The described dependencies can be illustrated in an aeroservoelastic triangle, with the FCS containing the flight dynamical system equations:

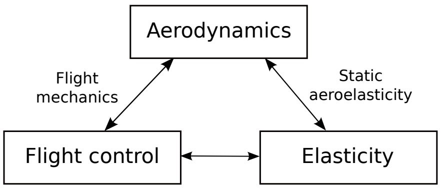

Figure 1: Aeroservoelastic triangle

Based on a coupling of FCS and aeroelastic analysis, structural and flight mechanical parameters can be optimized in an iterative process. With this coupling the engineer is able to determine the influence of interdisciplinary changes. Thicknesses of ribs, bars or stringers of the wing structure and thus structural mass can be reduced, sizes of control surfaces or necessary hinge moments can be optimized. As a first approach this paper takes into account only few degrees of freedom (DOF). Industrial applications will demand a distinctively higher number of DOFs.
An aeroservoelastic analysis as a base for the respective multidisciplinary optimization takes into account the three disciplines aerodynamics, structural mechanics and flight control. A commanded maneuver, given in terms of e.g. a commanded control surface deflection or demanded acceleration is processed in the flight control computer. The calculated control surface deflections are commanded to the actuator which transforms the deflection signal into a physical, actuator force and deflection, thus into mechanical work. As a result the aerodynamic state of the aircraft changes. The so generated aerodynamic forces are applied to the structure, causing its deformation and rigid body movement. As a consequence, mechanical displacements, strains and stresses arise. In order to assess the resulting, mechanical state an appropriate numerical quantity must be chosen.
In aircraft design, aerodynamics are generally presented by potential flow theories, panel methods, advanced euler approaches or even complex Navier-Stokes solvers, so in general by computational fluid dynamics (CFD). Wind tunnel and flight experiments should be named as further aerodynamic methods, here. The present studies use simple panel methods, based on potential flow theories only. From the structural point of view and due to their high development state, finite element methods (FEM) are state of the art.

2.2 Basics of the optimization problem

The general, single objective optimization problem without equality constraints states as

$$min\{f(x_i)|g_j(x_i) \geq 0, x_{l,i} \leq x_i \leq x_{u,i}, i = 1, ..., n, j = 1, ..., p\} \tag{1}$$

The basic ingredients are the design variables x_i , the objective function f and the constraint functions g_j . A set of constraints $g_j \geq 0$ is formulated in order to implicitly limit the range of feasible designs. Gages $x_{l,i}, x_{u,i}$ are given for the set of design variables x_i in order to explicitly restrict the design space in terms of the side constraints $x_{l,i} \leq x_i \leq x_{u,i}$.
A set of equations is necessary to evaluate the objective and constraint functions. In the field of multidisciplinary optimization, they are referred to as system equations. All further evaluations, as e.g. the analysis responses r depend on the solution of the system equations. Numerically r are derived as direct or post-processing results from the system equations. In a structural sense, direct results may be the field of nodal displacements whereas post-processing results could be strains or stresses.
The design variables are given as FCS parameters. They must be properly determined from the design space limited by the various disciplines, to meet further FCS requirements as e.g. demanded control power. FCS parameters could be commanded control surface deflections, FCS requirements could be given by the control surface configuration and may be quantified in terms of control moments or its built up rates. Lower and upper limits of FCS parameters, as the rate of a control surface deflection can be used as gages, which leads to a formulation of FCS side constraints.
A MDO problem follows a certain objective. In case only a single, scalar objective is followed, the term single objective optimization is applied. Otherwise the problem is called a multiobjective optimization problem. A single objective mindset is followed in this paper. Usually f is the structural mass. As FCS parameters, the discussed design variables in this paper do not explicitly affect the mass here. Structural mass remains at its fixed value. In this paper f is chosen as a quantity that represents the mechanical state of the system to be studied. Bending moments or von Mises stresses, due to applied aerodynamic forces resulting from changed aerodynamics following a FCS commanded control surface deflection, might be discussed as well. In that case only a structurally critical location like the wing root would then be focused on. Early phases of aircraft design, as e.g. the conceptual design, are interested in a more global look on the system. Therefore, a quantity representing the mechanical system as a whole is derived from the analysis response data r and will be introduced and used in the next chapters. In aircraft structural design optimization the main objective is minimizing structural mass for stressing constraints as mentioned above, applied to numerous mechanical, finite elements. The classical mass objective function doesn't vary with the flight control system design variables, used in this discussion. However, stress constraints do vary implicitly with these design variables. Generally constraints g are calculated from the analysis responses r. For numerical efficiency of the optimizer, they are formulated in a standardized form. Mechanical stresses σ are constrained by certain allowable values σ_{all}. A mechanical stress constraint usually states as

$$\sigma_{all} \geq \sigma \Leftrightarrow g = 1 - \frac{\sigma}{\sigma_{all}} \geq 0 \tag{2}$$

This constraint formulation will be used, pure FCS constraints will not be applied in the scope of this paper.

3 Practical engineering problem

The theoretical aeroservoelastic optimization problem was discussed in a very general way. A wide range of technical problems can be applied to it. The practical engineering problem is derived from this theoretical problem. It is given by a concrete technical task. The classical, mechanical sizing optimization approach is to reduce structural weight while ensuring that mechanical stresses remain below their critical values by finding a distribution of e.g. material thicknesses, cross section areas, ply angles.

3.1 Discussion on bandwidth optimization for a flexible FCS design

The FCS detailed design ranks among the later phases of aircraft design. Changes in earlier phases as aerodynamics or structural mechanics have strong impact on a FCS. Therefore high flexibility of FCS parameters is a must for a FCS. A FCS designer must so follow another optimization mentality than a structural designer. It is rather sensible to perform a bandwidth optimization than aiming at an "optimal design" of the FCS. Bandwidth optimization means that the results should be given as a range of FCS designs which can be adapted more easily to the changes in e.g. aerodynamics and structural mechanics. From an aerodynamic shape optimization of range, the resulting wing profile defines the design space for later design phases as structural mechanics. Pure structural sizing optimization leads to a thickness distribution within the design space given by e.g. an aerodynamic wing profile and shape. The design space dictated by the preceding design phase, narrows the design space of the consecutive one. Changes in the preceding phase may even define a completely new region for the consecutive one. The solution of an aeroservoelastic optimization problem is especially sensitive to changes in each of the involved disciplines because the FCS is considered so late in the overall design process. Therefore a certain design reserve should always be retained in order to guarantee flexibility. For aeroservoelastic optimization, this means that based on a certain FCS design various flight control systems should still be possible. The solution of an aeroservoelastic optimization problem should therefore be looked at very critical and with a special focus on its flexibility. The bandwidth optimization idea would lead to this flexibility by a range of different FCS designs. With this paragraph, only the criticality of an optimized FCS should be stated. How a sensible range of the designs can be determined is not presented in this paper.

3.2 MDO formulation

The first step to solve an engineering problem is to formulate it in a mathematical, proper way. The theoretical problem from chapter 2 will now be transformed into a more practical application. The focus is now rather on the technical, than on the mathematical nature of the ingredients.

3.2.1 Aeroservoelastic analysis - Components of the system equations

Three disciplines are involved in aeroservoelastic optimization problems. Thus the system equations are influenced by these three disciplines. The framework presented below, uses outputs from one discipline as input for the other and the other way round. A complete presentation of all equations will not be given here in favor of a description of their interfaces.

The flight control system was created in an Airbus Defence and Space in-house model and simulation environment. From the overall control law only the lateral control part was taken into account in order to work with its output for a roll maneuver. For a given maneuver, the FCS delivers the necessary control surface deflection command, which is converted into an actual control surface deflection by the actuator. However, an actuator model was not included in the studies here. Consequently, the commanded control surface deflection is forwarded directly as boundary condition in an aerodynamic panel model. For a roll maneuver, the FCS receives a commanded bank angle Φ_c and calculates the necessary control surface deflections for the aileron ξ and roll spoiler κ to generate the required forces and moments. A further discussion on aileron and roll spoiler will be given later, in a practical application.

The aerodynamic model basically uses a vortex lattice method as basically described in [9]. Drag is introduced as a correction based on aerodynamic derivatives resulting from higher order CFD calculations and represented as a generalized force, only.

$$\frac{\partial C_D}{\partial \alpha} \text{ and } \frac{\partial C_{D,spoil}}{\partial \kappa} \tag{3}$$

The derivatives lead to actual drag forces by dimensionalization through the dynamic pressure and the respective reference area. The drag force acts on the structural model as part of the structural loads p_s . No advanced strategies are applied in this context, this drag representation is very simple. It must be seen as a starting point to properly respect distributed drag in the scope of this paper. Higher order CFD shall not be taken into the optimization loop directly, due to its high computational effort for big models. The commanded control surface deflection from the FCS is applied as a boundary condition to the panel model. This results in an aerodynamic force p_a , which is part of the structural loads p . The aerodynamic loads are interpolated onto the structural mesh, using an infinite plate spline [10].

The mechanical model is given in a finite element way and was created in the structural analysis and optimization tool LAGRANGE by Airbus Defence and Space, which will be briefly presented later. The externally applied loads cause an elastic structural displacement field, that is determined by the aeroelastic analysis solver of LAGRANGE, which also calculates the analysis responses, necessary for further evaluations as e.g. in the optimizer. The above mentioned CFD corrected drag is applied to the structural model as nodal forces and depends on the respective angle of deflection, e.g. κ for the spoiler. As a first step, the angular acceleration $\ddot{\Phi}$ is globally set to the model as static loading condition and so belongs to the structural loading p_s. Within the scope of an unsteady analysis, $\ddot{\Phi}$ will change as $\ddot{\Phi}(t)$ and be derived as an output from the FCS in further studies. The loads p thus consist of an aerodynamic and a structural part:

$$p = p_a + p_s \tag{4}$$

The way from commanded control system input to mechanical response output is now described completely. A functional chain of the dependencies in the aeroservoelastic analysis for the above discussed quantities is given as

$$\Phi_c \xrightarrow{\text{FCS}} \xi, \kappa \xrightarrow{\text{AD}} p_a$$

$$p_a, p_s \xrightarrow{\text{SM}} r$$

With the abbreviations “SM” for structural mechanics and “AD” for aerodynamics.

3.2.2 Design variables

The central variables in an optimization are the design variables x. From the FCS point of view the ratio λ of roll spoiler deflection κ and aileron deflection ξ are taken into account. λ varies within the range of 0 to 1 ($0 \leq \lambda \leq 1$), with $\lambda = 0$ meaning that only the roll spoiler is being used and $\lambda = 1$ meaning that only the aileron is being used in the flight control law.

The physics of spoiler and aileron are too extensive to be discussed here in detail. However, to understand λ, some remarks on using spoilers and ailerons for roll maneuvers shall be made. A roll spoiler basically serves the purpose of initiating turns or correcting high frequency rolls in turbulent flows. The aileron is applied in the main phases of a turn and for trimming roll maneuvers. Roll control could be performed by each of the control surface itself and independently of the other. Thus it is possible to design a version for the roll control system where only the spoiler or where only the aileron controls the roll movement. The targeted distribution between these two extreme cases will make use of the advantages of both systems, i.e. fast lift changes by the roll spoiler and small drag from the aileron. At the same time the distribution aims at reducing the elastic energy introduced into the structure. It has to be kept in mind that the solution of the aeroservoelastic optimization problem is aircraft specific.

λ directly influences the control surface deflections ξ and κ. As explained, ξ and κ then affect p_a:

$$\lambda \xrightarrow{\text{FCS}} \xi, \kappa \xrightarrow{\text{AD}} p_a$$

As a consequence, the functional chain from above must be enhanced by λ:

$$\Rightarrow \Phi_c, \lambda \xrightarrow{\text{FCS}} \xi, \kappa \xrightarrow{\text{AD}} p_a$$

$$p_a, p_s \xrightarrow{\text{SM}} r$$

Next to Φ_c, λ affects the responses r now. The design variable λ can be seen as a design suggestion of the optimizer to the FCS. Within the opimizer the objective function, the constraints and their gradients with respect to the design variable are evaluated. Based on these values the optimizer suggests a new FCS design by a different λ. The new FCS design will be better in terms of the objective function and the constraints, based on its gradient information. This design suggestion is then commited to the FCS, which evaluates it and delivers the new control surface deflections for the aeroelastic optimization process.

3.2.3 Objective function

The objective function represents the main task of the optimization problem. For the aeroservoelastic approach followed here, a quantity representing the elastic state of the system is needed. Originating from topology optimization, the compliance is used here. It is can be seen as a quantity representing the systems strain energy. Compliance as an objective function was implemented in Airbus Defence and Space LAGRANGE and was successfully tested for various topology optimization problems. Compliance poses a sensible objective function as it measures the elastic state of the aeroservoelastic system in one scalar value. Minimum compliance means maximum global stiffness [11]. Here it is used only to measure the inner elastic energy in the system.

$$f = \frac{1}{2} \int_\Omega C_{ijkl} \sigma_{ij} \sigma_{kl} d\Omega \tag{5}$$

Making use of the principle of virtual work, it can be obtained from the external work as well. At the time the compliance is calculated in the optimization process, the elastic equation is already solved. Discrete nodal displacements u_i and nodal forces F_i are thus available from a finite element approach. So the compliance can numerically be determined from the discrete displacement field and the nodal forces as well:

$$f = \sum_i F_i u_i \tag{6}$$

3.2.4 Constraints

Control surface deflections, commanded by the FCS change the aerodynamic loads on an aircraft and thus lead to mechanical stresses in the structure, which must not exceed certain allowable values σ_{all}
As stated in chapter 2, the MDO constraints are formulated as stress constraints:

$$\sigma_{all} \geq \sigma \Rightarrow g = 1 - \frac{\sigma}{\sigma_{all}} \geq 0$$

Physically, stresses must be seen as multidimensional quantities and are usually given in tensor form. Historically, various comparison stresses were defined and discussed in order to compare certain components with each other. The von Mises stress is well known from basic courses on structural mechanics and suits the materials studied here. With respect to the computational effort for the constraint evaluation it is numerically not sensible to constrain all elements of a model. Therefore only critical areas shall be respected in the constraint formulation. Engineering knowledge helps to select these regions. Especially the wing roots are prone to high mechanical stresses, whereas wide parts of the fuselage or the wing tips will experience only low stress values.

So far no FCS constraints were discussed. In the context of this paper, it is not sensible to formulate a flight maneuver in form of a classical inequality constraint. In the scope of the aeroservoelastic studies discussed here, a maneuver cannot be stated as e.g. "95% successfully flyable". A commanded bank angle Φ_c is used here as an input for the FCS. Based on this input the necessary control surface deflection commands are calculated. The idea of using agility requirements was not followed, here. However, FCS inequality constraints in terms of e.g. stability or robustness could be formulated and used by the optimizer as well.

3.2.5 Mathematical representation

With all ingredients being discussed, the practical, engineering, aeroservoelastic optimization problem can now be formulated. In a mathematical form the problem is given as

$$min\{f(x_i)|g_j(x_i) \geq 0, x_{l,i} \leq x_i \leq x_{u,i}, i = 1, ..., n, j = 1, ..., p\} \tag{7}$$

with the system equations resulting from the aeroservoelastic analysis as described above, the design variables x being chosen as ratio of spoiler to aileron deflection λ, the objective function f being given as the compliance function of the mechanical system

$$f = \frac{1}{2} \int_\Omega C_{ijkl} \sigma_{ij} \sigma_{kl} d\Omega$$

and the constraints g being formulated based on mechanical stresses:

$$g = 1 - \frac{\sigma}{\sigma_{all}} \geq 0$$

4 Integrated numerical solution of the aeroservoelastic optimization problem

4.1 Aeroelastic solver LAGRANGE

For aeroservoelastic problems, the department for multidisciplinary optimization of Airbus Defence and Space uses and developes the program LAGRANGE. It enables the solution of both multidisciplinary analyses and optimization tasks [12]. Static structural analyses, modal analyses, gust and flutter or static aeroelastic analyses are possible, to name but a few. With the analyses as a base, respective optimization tasks can be treated. Analytical, numerical and semi-analytical gradients are available for various disciplines. Structural models are discretized and partitioned using the finite element method. In the last decades, interfaces to aerodynamic methods have been generated. Simple two-dimensional panel methods, as vortex or double lattice methods can be taken into consideration as well as the three-dimensional HISSS-method, a higher order subsonic and supersonic panel method. The panel methods have in common that they implicitely deliver aerodynamic loads via matrices of aerodynamic influence coefficients. An aeroelastic representation arises when aerodynamic loads are applied to elastic finite element models and the elastic displacements are then applied to the aerodynamic model again.

4.2 Aeroservoelastic interface

Depending on the physical nature of the analysis, an optimization problem can be formulated and solved with the LAGRANGE multidisciplinary optimization capabilities. The choice of the proper optimization algorithm is important as not all optimizers treat the problem specific design variables, objective functions and constraints in the same way. A linear optimization method might be more suitable for a linear physical problem, than a quadratic one.

LAGRANGE can be used as a library, offering its subroutines and functions to other programs. An optimization problem can be formulated and controlled in python, using the LAGRANGE analysis capability of the structural system and its optimization capabilities seperately. With

respect to aeroservoelastic optimization, python will serve as manager, which controls the parameter flow between aeroelastic analysis and flight control system evaluations.
The aeroservoelastic analysis takes into account various disciplines. The critical point within this analysis doesn't lie in the respective disciplines themselves, but rather in their interfaces. It must be cleared in which way the disciplines interact with each other and how they can work together. A managing script was therefore set up in python. To initialize the aeroelastic model, a first design is must be created. All geometrical, structural and aerodynamic data are loaded from an input file and processed with the LAGRANGE library. In a next step the FCS variables are declared and initialized. Necessary gains, derivatives, fixed parameters and other quantities from possible higher control system instances must be set correctly as input-variables. With the aeroelastic and the flight control model being initialized, the optimization process is entered. The current FCS given by λ^i ($i = 0$ after the initialization) delivers control surface deflections, which are applied to the aeroelastic model. LAGRANGE performes an aeroelastic analysis, followed by the determination of the respective gradients of the objective and the constraints and an update λ^{i+1} from λ^i of the design variable. The update is based on the gradient information, so that the best compromise between objective and constraint functions can be achieved. Thus, the optimizer suggestes a FCS design, namely a FCS input for the next optimization iteration, which leads to better values of the objective and the constraints. With this new input, the iterative process is re-entered and quit only, when the exit conditions of the optimization are met. Usually a combination of maximum iteration number and a convergence criterion as a predefined smallest change in design variable, constraint or gradient values, is used therefore. A schematic flow chart of the above described process explains the occurring interfaces:

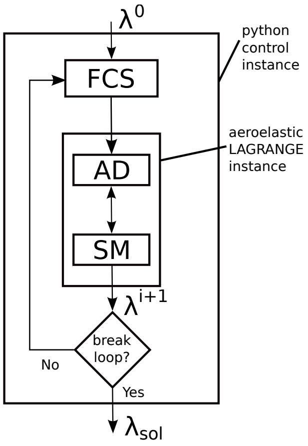

Figure 2: Schematic flowchart of aeroservoelastic optimization with LAGRANGE

4.3 Gradients in the framework

Unlike stochastic algorithms as e.g. evolutionary strategies their deterministic counterpart, the gradient based optimization methods explicitly require the computation of gradients with respect to the design variables x. Basically, the gradients can be calculated in a numerical or an analytical way. While numerical gradients are easy to formulate, they require multiple evaluations of the objective f and constraint functions g_j. The numerical effort for analytical gradients is significantly lower, but they require the detailed, analytical representation of f and g_j.
The formulation of gradients shall be explained in the scope of the aeroservoelastic analysis. The design variables are flight control system variables. No structural sizing, shape or other design variables will be applied.

The basic system equations for stationary, linear elastic structures are given in matrix form as

$$Ku(x) = p(x) \tag{8}$$

with the mechanical stiffness matrix K, the structural loading p, the displacement field u and the design variable of the optimization problem x. In a structural scope, design variables usually are physical sizing or shape properties. Here, K exclusively depends on geometrical and structural properties and is not affected by FCS design variables. p is given by the aerodynamic forces, resulting from the panel model, which are splined to the structural model on the one hand and structural loads like drag and roll acceleration, as described previously, on the other hand. The displacement field is a result of the system equations, and thus depends on the FCS design variables as well. The system responses r basically depend on the displacement field u, and therefore implicitly are influenced by the design variables x as well:

$$r = r(u(x)) \tag{9}$$

Both the objective function f, formulated as the system compliance, and the constraints g, given by structural stresses, depend on the responses r:

$$f = f(r) \text{ and } g_j = g_j(r) \tag{10}$$

The quantities of interest are the gradients of f and g with respect to x

$$\frac{\partial f}{\partial x} \text{ and } \frac{\partial g}{\partial x}$$

4.3.1 Numerical Gradients

Numerical gradients can be obtained using finite difference approaches

$$\frac{\partial f}{\partial x} \approx \frac{\Delta f}{\Delta x} \overset{\text{finite differences}}{=} \frac{f^{i+1} - f^i}{x^{i+1} - x^i} \tag{11}$$

$$\frac{\partial g_j}{\partial x} \approx \frac{\Delta g_j}{\Delta x} \overset{\text{finite differences}}{=} \frac{g_j^{i+1} - g_j^i}{x^{i+1} - x^i} \tag{12}$$

The evaluation of these equations requires high computational effort, but is rather simple to implement. The determination of gradients by this numerical way requires some analyses, which deliver the respective responses, followed by the objective and the constraint values f^{i+1}, f^i, g_j^{i+1} and g_j^i. A straight forward calculation of simple fractions then leads to the numerical gradient values. To reach a high accuracy of the numerical gradients, the designs evaluated (x^{i+1} and x^i) must lie close to each other. Then the finite, difference quotient approaches the infinite, differential quotient, which can be recalled from basic calculus:

$$\frac{\partial f}{\partial x} = \lim_{\Delta x \to 0} \frac{\Delta f}{\Delta x} \tag{13}$$

For aeroelastic models with a high number of panel- or FEM-degrees of freedom, the calculation of the finite differences takes a lot of time. Thus analytical gradients should be used whenever possible. In the present studies, the potentials of analytical gradients were not followed, as further, detailed information on the flight control system were necessary. Here, the FCS is only considered as a black box. Detailed information on its inner structure, necessary for deriving analytical gradients, are not available. However, a brief discussion on analytical gradients and semi-analytical gradients shall be given.

4.3.2 Discussion on analytical and semi-analytical Gradients

For the analysis of big industrial models, analytical gradients will be necessary. They result from the application of the chain rule of differentiation to the respective governing equations. They are an important component of the scientific field, especially when structural sizing or shape variables are included to the optimization problem. Using the constraint function g_j with respect to a design variable x_i as an example, the gradient states as

$$\frac{\partial g_j(r(u(x)))}{\partial x_i} = \frac{\partial g_j}{\partial r}\frac{\partial r}{\partial u}\frac{\partial u}{\partial x_i} \tag{14}$$

The numerically most critical part is given in the last factor $\frac{\partial u}{\partial x}$. It has the highest effect on the computational effort. The reason for this can be seen at its analytical representation. Following the system equation as given above, it can be derived as

$$\frac{\partial u}{\partial x} = K^{-1}[-\frac{\partial K}{\partial x}u + \frac{\partial p}{\partial x}] \tag{15}$$

The inverse of the structural stiffness matrix is needed. During the analysis a complete decomposition of K was already made. For the gradient computation only the forward-backward-substitution must be done, therefore. Using the advantages of both the pure numerical and the pure analytical approach, semi-analytical gradients can be formulated. Instead of directly calculating $\frac{\partial f}{\partial x_i}$ and $\frac{\partial g_j}{\partial x_i}$ in a numerical way, the analytical decomposition from equation (14) is used. Only $\frac{\partial K}{\partial x_i}$ and $\frac{\partial p}{\partial x_i}$ are determined numerically, then. Hereafter, they are substituted into equation (15) which leads to the required constraint gradients.

4.4 Choice of the optimization algorithm

Numerically, the solution of an optimization problem may depend on the applied optimization algorithm and its parameter settings. Thus, a sensible selection of the optimizer means better solutions of the FCS optimization problem.

Different gradient based optimization algorithms are available in LAGRANGE. Recursive quadratic programming (RQP) by Schittkowski, also known as sequential quadratic programming (SQP) and sequential linear programming (SLP) shall be named. For the problem here, the NLPQL algorithm by Schittkowski [13] proved itself the most suitable in various numerical studies. It is based on RQP but uses an advanced, non-monotone line search for function and gradient evaluations. Internal restarts guarantee a better stabilization during the optimization process. RQP has a second order convergence property. The implementation in LAGRANGE makes use of an internal assessment of active constraints to decide which gradients are taken into account within one iteration.

5 Application to a generic MALE RPA

A generic twin-jet medium altitude long endurance remotely piloted aircraft (MALE RPA) in roll serves for further studies concerning the scalar FCS parameter λ, the ratio between spoiler and aileron deflection. The aircraft is a high aspect ratio configuration. From a flight mechanical point of view, both the spoiler and the aileron can be deflected to generate a roll moment on the aircraft. The mechanical engineer is interested in how to choose λ to achieve a minimal compliance value for a roll maneuver given by a respective roll command Φ_c and the resulting roll acceleration $\ddot{\Phi}_c$. From the flight mechanical point of view, the roll acceleration actually is a function of λ. Here, only the initiation of the maneuver will be observed as a static load case with a predefined roll acceleration.

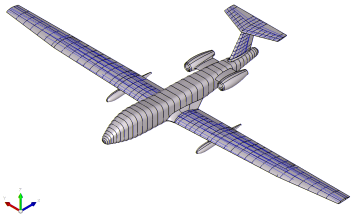

Figure 3: Configuration of the model

5.1 Model description

The FCS of the RPA was set up with a model-based development environment and is linked dynamically to the aeroelastic model as a library. Only the lateral control law of a complex flight control law was considered. It determines commanded control surface deflections for a given commanded bank angle Φ_c. The bank angle command serves as an input for the lateral control law and its intrinsic, but in the scope of optimization variable, parameter λ. As an output, a commanded aileron deflection ξ_c and a commanded roll spoiler deflection κ_c follow, which is applied to the static aeroelastic model.

The aerodynamic model consists of over 90 panels, with in total about 3000 boxes. The two engine nacelles are fuselage mounted and are given, both as structural and aerodynamic model. The FCS enables the determination of drag coefficients resulting from spoiler deflections. As the applied panel method is not able to deliver drag values, drag coefficients from higher order methods were used to apply a drag force to the structural model. The flight state is given by a Mach number of $Ma = 0.2$ and a dynamic pressure of $p_{dyn} = 2.837 \cdot 10^3 Pa$.

The structural model of the RPM and its geometrical design are given as a FEM model in LAGRANGE. The wingspan is approximately $28m$, the fuselage length counts about $14m$. The aircraft is designed with a T-tail. The detailed, structural model contains e.g. ribs, stringers, bars and spars distributed in the wings, fuselage or the control surfaces. The configuration can be seen in figure 3. It was created with the Airbus Defence and Space in-house tool DESCARTES [7]. To avoid misunderstandings in the following, it is to be noted that the coordinate system in figure 3 is a structural coordinate system and not a flight mechanical one.

The static load case for the analyses is given as a combination of

1. a scalar roll acceleration, applied to all structural nodes
2. aileron and spoiler deflections, applied to the panel model
3. the approximation of drag due to the spoiler deflection as a force acting on the structural model

The commanded control surface deflections ξ_c and κ_c are applied to the aeroelastic model, following the flight mechanical standards, given by DIN 9300. It should be recalled that the aeroelastic model doesn't contain an actuator. The commanded values are applied to the aeroelastic model directly. A positive roll, i.e. a roll about the x_g axis requires a negative aileron command $\xi_c < 0$. The aileron of the right wing is deflected in a negative way (upwards), while the left aileron is deflected in a positive way (downwards) to generate the required roll forces and moments. The spoiler was set up following this logic. A negative spoiler command $\kappa_c < 0$ means a deflection of the spoilers on the right wing, while a positive spoiler command $\kappa_c > 0$ deflects the left wing spoilers. Thus the aircraft rolls to the side which the spoiler is deflected on, due to the loss of lift on the respective wing.

5.2 Aeroservoelastic studies and optimization

The FCS delivers control surface deflections for a given maneuver input, e.g. a commanded bank angle, following the overall control law. Only its lateral control law is used in the studies, here. A bank to bank maneuver from +30° to −30° can be seen in figure 4 for the overall control law. The bank angle follows its commanded value, the roll acceleration and the aileron and spoiler deflections are set accordingly. The commanded aileron and spoiler deflections are not shown here.

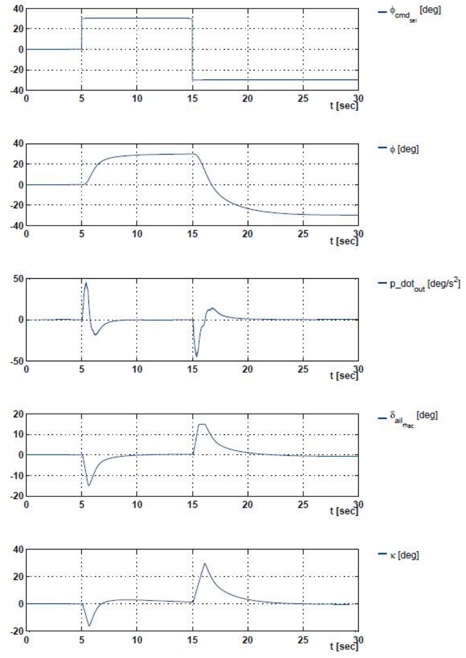

Figure 4: Responses of the overall control law

Before applying an optimization method to the problem, some basic thoughts shall be discussed. The compliance will not have a minimum, when the FCS is not in the optimization loop and λ is varied for a fixed aileron and varying spoiler or a fixed spoiler and varying aileron deflection. Increasing control surface deflections will result in higher compliance values, when aileron and spoiler are not coupled by a FCS. Only the opposing trend between κ and ξ given by the control law may define a compliance optimum to the problem.

Using different λ-values in the control law leads to different, commanded aileron and spoiler deflections ξ_c and κ_c. In the range $\lambda \in [0, 1]$ the deflections normalized with their respective maximum value (maximum ξ_c for $\lambda = 1$, maximum κ_c for $\lambda = 0$) vary linearly as show in figure 5. These trends, generated from parameter studies with the lateral FCS, represent the control surface dependencies which are applied to the aeroelastic model.

First optimizations for the given model lead to an optimal λ-value of 0.92. The resulting compliance value, given by nodal displacements and forces, was minimal compared to neighboring designs. This result shows a tendency towards using the aileron rather than the roll spoiler for the commanded bank angle given by the maximum value of its transient behavior in figure 4 and applied as a rotational acceleration load. It must be kept in mind that only a static load case was analyzed here. Taking into account the overall roll maneuver, its transient effects or an improved drag distribution will result in different λ-values. However, the result shows the possibilities of an aeroservoelastic optimization approach. The connection of the disciplines of structural mechanics, aerodynamics and flight control system lead to a FCS design, which generates only small elastic energy values.

Compliance showcase studies for λ-values in the region of $\lambda = 0.92$ help to get a better insight in the design space. The latter could have been scanned before the application of the optimization

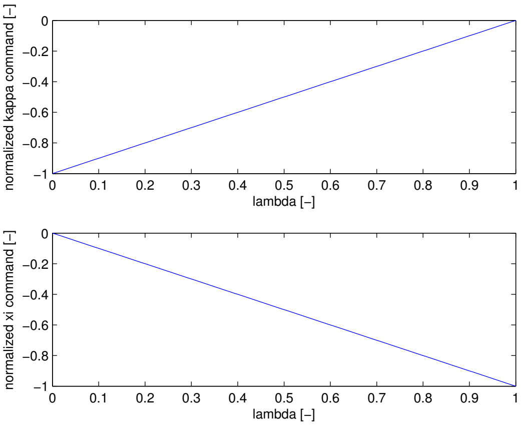

Figure 5: Normalized ξ_c and κ_c for different control systems given by λ

as well, but due to the high computational effort of single analyses the optimization approach was followed first. Thus a good starting point for such parameter studies is given by the solution of the aeroservoelastic optimization. Table 1 shows normalized compliance values nc for FCS designs given by λ, which were planned for the lateral control law in the FCS design phase, together with $\lambda = 0.92$. The reference for the normalization is given by the solution $\lambda = 0.92$ itself:

$$nc = \frac{\text{compliance}}{\text{compliance}(\lambda = 0.92)} \tag{16}$$

λ [-]	0.7929	0.8359	0.8807	**0.9200**	1.000
nc [-]	2.5699	1.6959	1.1569	**1**	1.5884

Table 1: Normalized compliance values for different FCS designs λ

The solution of the optimization problem given by $\lambda = 0.92$ represents one FCS design only. According to the discussion in chapter 3.1, it eliminated the flexibility of the FCS for changes in the structural and aerodynamic model. Further studies must be taken out, keeping this important point in mind. A set of FCS designs should be generated, following the idea of bandwidth optimization. Additionally, overall, aeroservoelastic analyses respecting time-dependent phenomena as a changing roll acceleration instead of a static one, will give further ideas on an optimal roll spoiler to aileron distribution.

6 Conclusion

In this work an approach for coupling the disciplines aeroelasticity and flight control system in a multidisciplinary design optimization process was formulated. Flight control system design was presented from an aeroservoelastic point of view, the aeroservoelastic optimization problem was introduced in a theoretical way. In this scope it was explained why the term of an "optimal" control system must be treated with caution and rather a bandwidths optimization should be followed in further studies. The special nature of FCS design variables within the optimization process was clarified. The engineering problem was discussed by partitioning it to its components. Optimization ideas from other disciplines, as using a compliance objective function, were introduced to the problem of aeroservoelasticity. A possible solution idea, using a tool chain of industrial programs was presented. The numerical interface and its components were explained. Some notes on aeroservoelastic gradients were given and a sensible optimization algorithm for the underlying problem was chosen. To test the tool chain, an asymmetric roll maneuver was used as a static load case. Roll acceleration and drag forces resulting from a spoiler deflection were applied to the model in a simple way. The respective flight mechanical logics were explained briefly, therefore. Numerical results were interpreted to gain insights into the aeroservoelastic analysis. The focus of the studies was put on mechanical quantities. Aerodynamic, flight control system related or performance demands could be integrated in the presented tool chain in a next step. A first example showed that the aeroservoelastic optimization using a FCS design variable can reduce elastic energy in the system, while respecting mechanical stressing constraints. Time-dependent analyses and optimizations will be studied in the future based on the tool-framework introduced in this paper.

References

[1] D.H. Hodges and G.A. Pierce. *Introduction to Structural Dynamics and Aeroelasticity.* Cambridge Aerospace Series. Cambridge University Press, 2002.

[2] W. Luber and J. Becker. An Integrated Design Procedure for Aircraft Structure Including the Influence of Flight Control System on Aircraft Flutter. Technical report, NATO Research and Technology Organisation, 1999.

[3] C. Ballauf. *Dämpfung aeroelastischer Strukturen mit modelladaptiver Regelung.* Dissertation, Lehrstuhl für Leichtbau Technische Universität München, 2008.

[4] T. Kier and J. Hofstee. VarLoads - Eine Simulationsumgebung zur Lastenberechnung eines voll flexiblen, freifliegenden Flugzeugs. In *Deutscher Luft- und Raumfahrtkongress*, 2004.

[5] A. Hamann, A. Köthe, and R. Luckner. Automatische Auslegung von Flugregelungsfunktionen für den Flugzeugvorentwurf. In *Deutscher Luft- und Raumfahrtkongress, Augsburg*, 2014.

[6] M. Marquard. *Erweiterte Prozesskette zur Erstellung integraler Modelle und Aeroelastikregelung flexibler Transportflugzeuge im transsonischen Machzahlbereich.* PhD thesis, Fakultät Luft- und Raumfahrttechnik und Geodäsie der Universität Stuttgart, Holzgartenstr. 16, 70174 Stuttgart, 2008.

[7] R. Maierl, Ö. Petersson, F. Daoud, and K.-U. Bletzinger. Automatically generated aeroelastic analysis models including physics based control surface representation. In *In 4th Aircraft Structural Design Conference*, 2014.

[8] S. Haghighat, J. R. R. A. Martins, and H. H. T. Liu. Aeroservoelastic design optimization of a flexible wing. *Journal of Aircraft*, 49(2):432–443, Mar 2012.

[9] J. Katz and A. Plotkin. *Low-Speed Aerodynamics.* Cambridge Aerospace Series. Cambridge University Press, 2001.

[10] R. L. Harder and R. N. Desmarais. Interpolation using surface splines. *Journal of Aircraft*, 9(2):189–191, 1972.

[11] M.P. Bendsoe and O. Sigmund. *Topology Optimization: Theory, Methods and Applications.* Engineering online library. Springer, 2003.

[12] J. Krammer. Practical architecture of design optmisation software for aircraft structures taking the mbb-lagrange code as an example. *AGARD-Lecture Series No. 186*, 1992.

[13] K. Schittkowski. Nlpql: A fortran subroutine solving constrained nonlinear programming problems. *Annals of Operations Research*, 5(2):485–500, 1986.