

AIRCRAFT CONCEPTUAL DESIGN OPTIMIZATION

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Abstract

Aircraft design is an inherently multidisciplinary activity that requires different models and tools for various aspects of the design. At Linköping University a novel design framework is being developed to support the initial conceptual design phase of new aircraft. By linking together various modules via a user-friendly spreadsheet interface, the framework allows multidisciplinary analysis and optimizations to be carried out. The geometrical model created with a high-end CAD system, contains all the available information on the product and thus it plays a central role in the framework. In this work great attention has been paid to techniques that allow creating robust yet highly flexible CAD models. Two different case studies are presented. The first one is a hypothetical wing-box design that is studied with respect to aerodynamic efficiency and loads, and to structural analysis. In this study two approaches were compared. In one case the wing-box design was optimized with a fixed number of structural elements, where only dimensions and position were allowed to change. Then the same wing-box was analyzed allowing also the number of structural elements to vary. Thus only the parts that are required are left and a more efficient design can be obtained. In the second case study a mission simulation is performed on a UAV-type aircraft. Required data for the simulation are gathered from the CAD model and from aerodynamic analysis carried out with PANAIR, a high order panel code. The obtained data are then used as inputs parameters for flight simulation in order to determined hydraulic systems characteristics.

1 Introduction

During the conceptual design phase of a new aircraft designers will evaluate a large number of different concepts, searching for the one that meets the requirements in the best way. This means that they need to iteratively cycle through sketching a concept, analyze it and evaluate and compare its performances. A framework aimed at the automation of this loop is currently being developed at Linköping University [1] [2] [4] [11]. The framework is intended to be a multidisciplinary optimization tool for defining and refining aircraft designs, with respect to its aerodynamics, performance, weight, stability and control. Figure 1 below describes how the complete framework will look like once all modules will be ready and connected.

The conceptual design phase could take advantage of a novel methodology that would not be based on empirical or semi-empirical equations to estimate e.g. weights [5], performances, costs and loads, but rely on analytical models to a greater extent. The presented design framework is thought to meet also requirements of modern complex product development. Many companies are located all over the world and are tightly involved in several global partnerships, where product modules are designed and manufactured at different locations. This is especially true in the aerospace and automotive industry where the end products are more or less assemblies of subsystems from different suppliers. This implies that today's product development is carried out in a distributed, collaborative and competitive fashion and this forms a rather

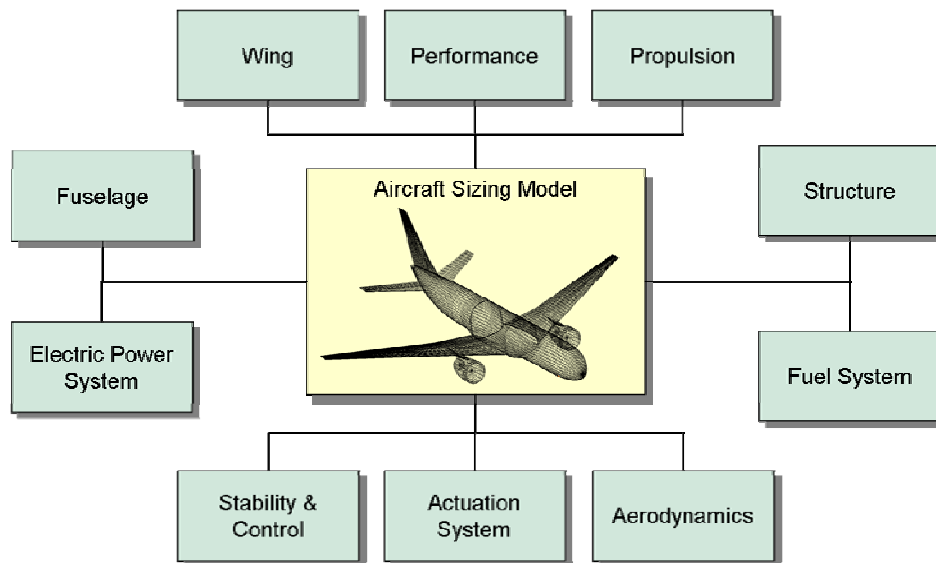


Fig. 1. The complete aircraft design framework

complex environment for the employment of modeling and simulation technology. These aspects must therefore be supported by the modeling and simulation tools.

The goal is to be able to design and optimize the whole aircraft, but at the moment only selected modules are available and are connected to the framework. Different studies have already been carried out for method and framework validation [3] [16] [17]. These studies have been of great help, especially for testing different modeling techniques to ensure the most efficient, robust and flexible CAD model.

Even though the framework is intended primarily for the conceptual phase, efforts are being made to increase the detail level of the models involved. Therefore the CAD models of the aircraft not only represent the outer surfaces, but also include an approximated internal structure. The CAD model is built in such a way that during a design optimization study, it does not require the structure to be defined ahead by the designer, since not only the position and size of each structural element, but also the number of elements can be varied. When compared with examples of similar applications that can be found in the literature [19] [24], the presented work shows a much higher grade of design flexibility, i.e. it spans on a much larger design space. In other structure design studies the

designer is usually required to enter a structure layout before the optimization can start. Then the system modifies thicknesses and maybe moves the structural elements from their starting position. This work instead demonstrates that it is possible to design concepts with a much higher degree of freedom. This kind of structural analysis then gets closer to a topological optimization. Thus it can be ensured that the solution obtained will be of a more general character.

A high order panel code solver (PANAIR [8]) analyzes the aerodynamics of the vehicle and the resulting pressure field is used as load case for the structural verification that is operated with a FEM solver.

The framework is controlled through a Microsoft Excel spreadsheet using web-service technology. All parameters and results are sent from the spreadsheet to the framework modules using SOAP messages, as explained by Johansson et al. [11]. This means that any module can be placed on a dedicated computer and connected to all the others through the Internet. VB-scripting is used to access all the needed functions in the adopted CAD system, CATIA V5 r17.

It is interesting to note that the framework comprises many modules that can be run independently or together with others. When running each module alone it is possible to

analyze the properties of one aspect at the time. The other modules will then work as support only; if needed they can be substituted by simpler equations that may be less precise, but faster. In this way the number of parameters to be optimized can be greatly reduced as well as the time required to complete the optimization. This modularity of the framework allows for starting using it even if not all of the modules are completely developed and ready to use. Only once one module is ready and validated it can be added to the framework and used together with all the others.

The framework can be used both for automatic optimization of a particular design as well as for exploring different design alternatives interactively. In the first case the spreadsheet is coupled with an optimization algorithm that acts on one set of input parameters or on all of them. Otherwise the designer is asked to enter by hand the parameter values and to start the analysis.

2 Parametric CAD Modelling

The most important characteristic of the CAD model is to be highly flexible in order to be able to represent a variety of designs as large as possible. Secondly the model must be robust and reliable, since there will not be a specialist manually entering new parameters and supervising the update process. It is fundamental that the model does not produce mathematical errors within its whole allowed design range. In order to guarantee a high degree of flexibility and robustness, the CAD model must be built in a proper way. Figure 2 shows the relational links (hierarchical and associative [1]) between the different elements of the model of a UAV.

The input parameters govern directly the “Datums Model” (MDF) and the “Surfaces Model” (MDS). The MDF-model is a wireframe model where all reference planes and lines, needed to define the aircraft and its structure, are defined. It is important to notice that all the structural components in the CAD model depend on both the MDF-model and MDS-model, that depend instead only on the top level input parameters. The MDS surfaces model

contains all the external surfaces. The structure is obtained by instantiating a general structural element that is designed to adapt itself to a specified context, which is specified in the MDF-model and MDS-model. This general element is used for all the structure parts of the aircraft: frames, ribs and wing spars. The elements’ geometries are governed by individual parameters, allowing for optimization of the structural design, even at a component level.

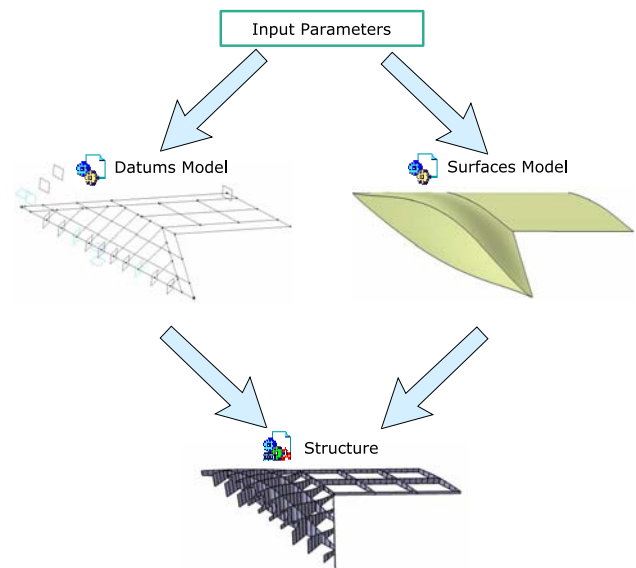


Fig. 2. Relationships between elements in the CAD model

All geometries are created in an automated fashion in CATIA. Through the spreadsheet interface the designer decides the general dimension and shape of the aircraft and the number and position of all structural elements. Then the CAD model is updated to reflect the input in the spreadsheet. To achieve this level of automation the programming possibilities offered by CATIA V5 have been largely taken advantage of. The system allows using several layers of automation and parametrization [1] [15]. With reference to Figure 3, it is worth noting that starting from the lowest level of parametrization and moving to the highest level, the designer is able to increasingly add more knowledge to the model, at same time as the degree of automation and flexibility also increases.

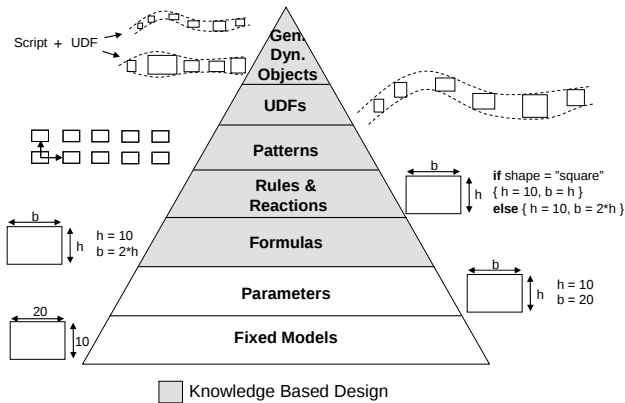


Fig. 3. Different levels of parametrization [1]

4 Panel Code (PANAIR)

At the moment, the aerodynamic analysis tool adopted is a panel code, PANAIR [18] that was developed by The Boeing Company and NASA during the late seventies and early eighties to be able to model and simulate complete vehicle configurations. Panel codes are numerical schemes for solving (the Prandtl-Glauert equation) for linear, inviscid, irrotational flow about aircraft flying at subsonic or supersonic speeds (Erikson [8]). Compared to CFD codes, PANAIR offers advantages in terms of speed and ease of meshing, but lacks in accuracy. On the other hand, during the conceptual design phase, uncertainties are large so that it can be reasonable to sacrifice accuracy of results for computing time required. The panel code is used mainly to compare the effectiveness of different concepts with each other, rather than to gather exact and absolute figures of their aerodynamic efficiency. Nevertheless, when more powerful and faster computers should be available or if higher accuracy was required, PANAIR could be substituted with other solvers, thanks to the modular nature of the framework.

5 Aerodynamic modelling

The Parametric Dynamic Aerodynamic Model (PDAM) that has been used for the mission simulation example, is based on the suction analogy method developed by Polhamus [23] and extended by Traub [26]. In order to include dynamic effects and angle of attack in

the post-stall region, state-space variables, representing the flow behaviour over the wing, are introduced. Goman and Khrabov [10] introduced state-space variables for delta wing characteristics under pitching motions. PDAM is largely discussed and presented in Jouannet [12]. PDAM does not account for Mach number or Reynolds number effects. For aerodynamic predictions over slender delta wings the Reynolds number can be ignored, since slender delta wings with a sharp leading edge are almost Reynolds-insensitive [20].

6 Excel Interface

The design parameters are input through a user-friendly MS Excel spreadsheet interface. There are different areas where selected aspects of the wing design are governed. There is an area where to input the parameters that control the plan-form of each wing section and the parameters that specify the shape of the wing profiles; in another one are the parameters that control type, size, number and placement of the structural element; finally, in a third part, the results from the different modules are displayed. Figure 4 shows a view of the user interface.

Fig. 4. The MS Excel user interface.

As well as all other modules, also the CATIA V5 model is completely controlled by the spreadsheet interface. Therefore the user is not required of any specific knowledge to operate the CAD system or any other software. It is nevertheless important to have a general understanding of the engineering problem so that the results can be screened and evaluated. It is fundamental to remember that design optimization can never substitute the designer, but should be thought as a tool to help screen and explore large portions of the design space in a relatively short time.

7 Test Cases

To test and validate the functionalities of the framework two different problems have been studied as test cases. In the first one a wing-box structure was optimized, given the air loads and a predefined shape. In the second test case a mission simulation was performed on a UAV-type of aircraft. All inputs required for the simulation were gathered from the CAD model and from the aerodynamic analysis performed with PANAIR.

7.1 Wing-Box Design Optimization

This first test case was intended to demonstrate the advantages related to the use of increasing flexibility level of the models involved. In the study a wing-box structure was tailored to a given wing shape. The structure was made of two spars for carrying the bending loads, a number of ribs distributed between the two spars and skin sheets on the upper and lower surfaces. To reduce problem complexity and the number of design variables, the skins were not dressed with any stringers. Figure 5 shows schematically the arrangement of the wing structure. Each rib requires three parameters to be completely defined:

- starting point coefficient that defines where on the front spar the rib should be located;
- end point coefficient that defines where on the rear spar the rib should end;
- thickness.

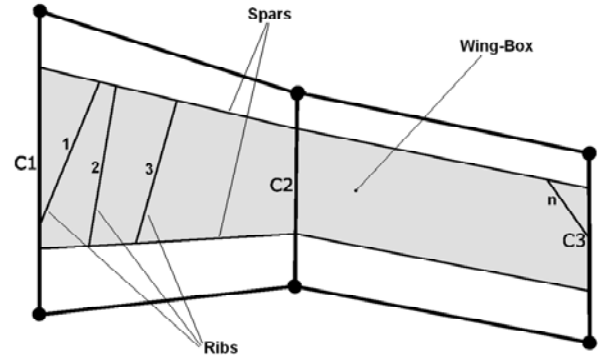


Fig. 5. Wing structure arrangement.

To ensure that the same structural configuration could not be described by different parameter combinations, the two spars were divided into a number of segments equal to the number of ribs to distribute and then the start and end coefficients were allowed to vary between 0 and 1 within to each segment.

The loads considered were the airloads obtained from PANAIR during a hypothetical 3g pull up maneuver. Stress relieves from both an engine mounted on a wing pylon and from the structure weight itself were also taken into account.

The optimization problem to solve was formulated as following:

$$\begin{aligned} \min(W_w) \\ \text{s.t.: } \sigma_{MAX} \leq \sigma_{Allowed} \end{aligned} \quad (1)$$

W_w is the total wing weight, while σ_{MAX} and $\sigma_{Allowed}$ are – respectively - the maximum stress value measured in the structure and the maximum allowed stress set by the designer. The constraint was formulated as a soft constraint, so that a penalty function aggravates the objective function value when the maximum stress exceeds the highest allowed value, according to the following equation:

$$P_\sigma = K \cdot \left(\frac{\sigma_{MAX}}{\sigma_{Allowed}} \right)^\alpha \quad (2)$$

In equation (2) K and α are factors used to balance the effect of the penalty function P_σ .

The design problem was approached using two strategies. First the number of ribs in the

wing was selected and fixed to ten. That means that in this case, in addition to the skin and spar thickness, only rib positions and thicknesses were changed. In the second attempt instead, the number of ribs was allowed to vary between 5 and 15. By doing so the system is not bound to the tentative solution initially entered by the designer and is free to explore a significantly larger portion of the design space.

For the optimization a genetic algorithm was adopted. The population size was set to 40 individuals, and the system was allowed to evolve for 1000 trials before stopping and comparing results.

7.1.1 Results

The results from the design optimization runs show that after 1000 trials the genetic algorithm is not fully converged yet. Figure 6a and 6b illustrates how the objective function values have evolved, in case the number of ribs is fixed (a) or variable (b). The best solution is plotted with a red line, while the average solution in the current population is represented by the black line.

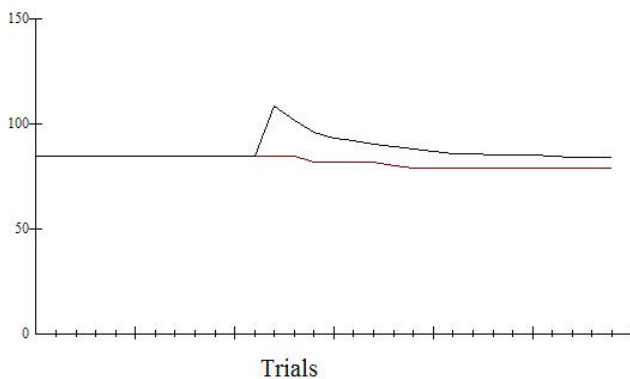


Fig.6a. Objective function value evolution when the rib number is fixed.

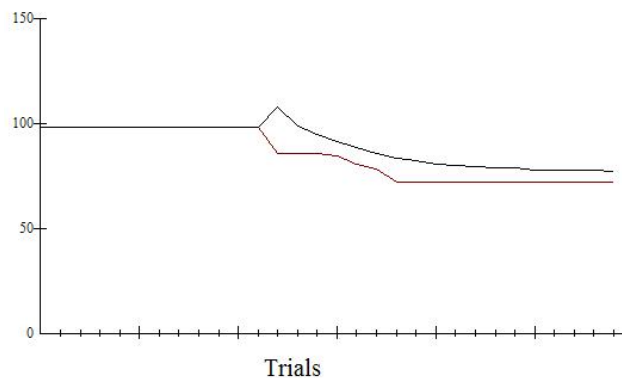


Fig.6b. Objective function value evolution when the rib number is not fixed.

The best objective function value achieved with a fix number of ribs was 79,1 which corresponds to a wing weighting 1511,5 kg and a maximum stress value of 455 MPa; in case of a variable number of ribs the objective function value was lowered to 71,8 which equals to a wing weight of 1500 kg and a maximum stress value of 403 MPa.

Besides these shear numbers, it is much more interesting to have a look at how the two resulting wings look (Fig. 7a and 7b respectively). It is very clear that despite the similar results in terms of weights and stresses the configurations are very different. The pictures show that the ribs tend to be placed at such an angle that they can help carrying the bending loads. The outer two ribs in Fig. 7b are not following this trend, but that could be due to the fact that, since bending loads on the outer part of the wing are small, the influence of those ribs on the objective function value is limited.

Off course, since the problem was initially simplified neglecting the influence of buckling or installation constraints, the resulting models have extremely limited practical validity. Nevertheless it has been showed that granting the optimization a higher degree of freedom resulted in a very different solution, with fewer parts but with similar performances.

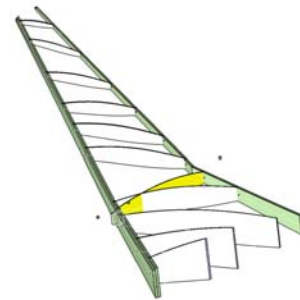


Fig.7a. Resulting wing when the rib number is fixed.

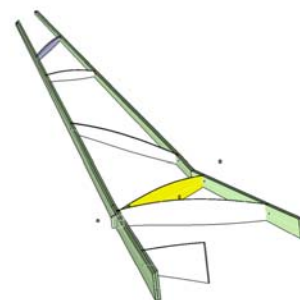


Fig.7b. Resulting wing when the rib number is not fixed.

The study showed that much can be gained from the extra flexibility granted to the model. To achieve such flexibility requires the model to be designed taking advantage of all the powerful automation features that are included in CATIA V5. Clearly the final result will then be closer to a global optimum solution than in case the number of structural elements would have been fixed from the start.

7.2 Simulation Based Optimization

The rapid development in simulation methods and the general increase in hardware performance imply that design methods based on different kinds of numerical optimization for system design, are becoming much more important. Numerical optimization methods require that the object function is evaluated (using simulation) a large number of times, but they are very attractive since they can optimise complete non-linear systems and do not rely on grossly simplified models as more analytical methods do. Work in this area has shown that optimization can be used both for parameter optimization and for component sizing [13]. If a system model in the form of a simulation model is defined, it is possible to use optimization based on simulation. Using this method, the system is simulated using different sets of system parameters. From each system evaluation a set of system characteristics are obtained and using these, the objective function is formulated. In general the simulation is used to obtain the performance characteristics of the system. In this second test case simulation is used to optimize an actuator system and the configuration of an aircraft in conceptual design.

The simulation-based optimization loop is illustrated in Fig.8. Optimization based on simulation puts very high demands on the numerical efficiency and robustness of the simulation. Since a high number of simulations need to be run, typically ranging from a few hundred to tens of thousands, short simulation time is of course very important. Another thing is that, in simulation-based optimization, parameters can vary substantially especially in the initial stages. This could result in very long

simulation times, which would be wasted on solutions that are usually far from the optimum anyway. Therefore, it can be concluded that simulation-based optimization benefits strongly from the deterministic simulation times obtained using fixed time steps [14].

7.2.1. Explicit design relations

In this study there are many explicit design relations that can be used to reduce the number of optimization variables. The most obvious one is the symmetry relations. Due to the symmetry requirement there is a left-right symmetry in the control system which means that many of the design variables are transformed into two system variables. Another useful mechanism for parameter reduction that also falls into this category is the use of scaling. A component such as a servo valve has many design parameters but the driving requirements for a servo valve are usually only flow capacity and bandwidth (speed). This means that it can be assumed that most real valves can be described by only two performance parameters and in this case only size is used (representative of the weight). The pistons are also only described by one parameter, which is the piston area.

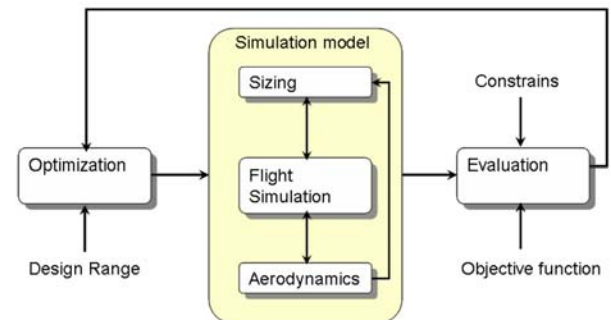


Fig. 8. Simulation based optimization.

7.2.2. Aircraft Model

The model will be used for a pure delta wing configuration, similar to the X-47 Pegasus configuration in size but not in wing loading (the present case uses a higher wing loading). The present configuration characteristics are illustrated in Fig. 9. The control surfaces consist of four ailerons located at the trailing edge of the delta wing. The aircraft's geometrical layout is illustrated in Fig. 9. The main layout is very similar to recent UCAV configurations such as

NEURON or X-45C. The aerodynamic coefficients are approximated to the one of an equivalent slender delta wing defined by PDAM. Two different aerodynamic models are used, one including angular rate dependency, the other only using static aerodynamic.

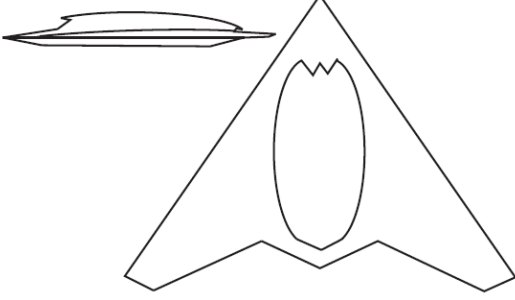


Fig. 9. Geometrical layout.

7.2.3. Flight Mechanics

The flight mechanics model is based on Stevens and Lewis [25] and Etkin et al. [7]. The nonlinear aircraft model is the base for the present work. The flat-Earth vector equation will be used, and when these are expanded, the standard six degree of freedom equations are used.

7.2.4. Systems

Also a model of the hydraulic flight control actuation system has been created, together with a flight control unit. This could either represent an actual flight control unit or just a system needed to represent a pilot flying the aircraft through the simulation. Even if the purpose of this optimization is not the design of a flight control system, it is necessary to be included in the optimization since different controllers may be needed for different actuation system parameters. There is also a simple engine model to represent the two engines in the aircraft. There are ten design parameters used for the optimization in this example. They are:

- Size of the aileron pistons
- Size of the elevator pistons
- Size of the aileron valves
- Size of the elevator valves
- Gain of the aileron servos
- Gain of the elevator servos
- FCU gain in pitch

- FCU gain in roll
- FCU gain in yaw
- FCU coupling gain between yaw and roll.

In order to be more efficient it is often useful to let the optimization algorithm operate on the logarithm of the design parameters. This is especially useful when the design parameter space spans several orders of magnitude. The design space for all these parameters was at least one order of magnitude.

7.2.5. Objective function

The main objective is to produce an actuation system that can turn the aircraft as fast as possible while being as light as possible. This means that the components should have as small size as possible. In addition the pressure variations in the actuators are something that should be limited in order to promote stable systems. In this example there are no constraints except in the explicit design relations. The objective function can be written as following:

$$f_{obj} = - \left(\frac{Ie_{\varphi}}{Ie_{\varphi 0}} + \frac{Ie_{\theta}}{Ie_{\theta 0}} + \frac{Ip}{Ip_0} + (\phi - \phi_{ref}) + \frac{g}{g_{nom}} \right) \quad (3)$$

Here Ie_{φ} is the integrated error in yaw angle, Ie_{θ} is the integrated error in tip. Ip is the sum of integrated pressure variations in all the actuators (high pass filtered to remove the DC component), ϕ defines the turn angle, g is the g -load and g_{nom} is the maximum allowed g -load. The optimization algorithm is set up for finding maximum, hence the negative sign in front of the expression.

The other objective was to examine the influences of different aerodynamic models.

7.2.6. Results

The main objective was to perform a 90 degree turn within the g -loads limits and minimize the weight of the actuators. Please note that minimizing the actuators weight is similar to reducing the maximum pressure in the system.

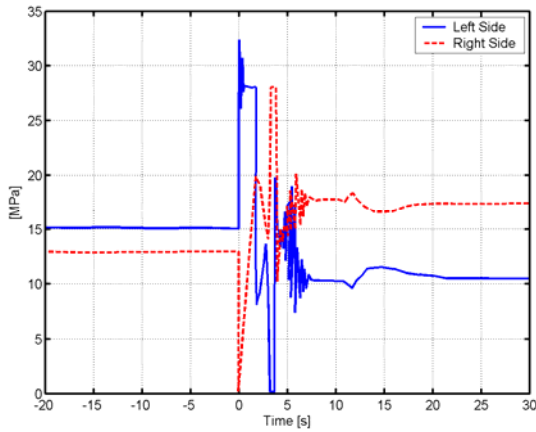


Fig. 10. Pressure in the system for unsteady aerodynamic model.

From the pressure in Fig. 10, it can be seen that the system behavior is satisfactory and the maximum pressure to perform the maneuver has been reduced.

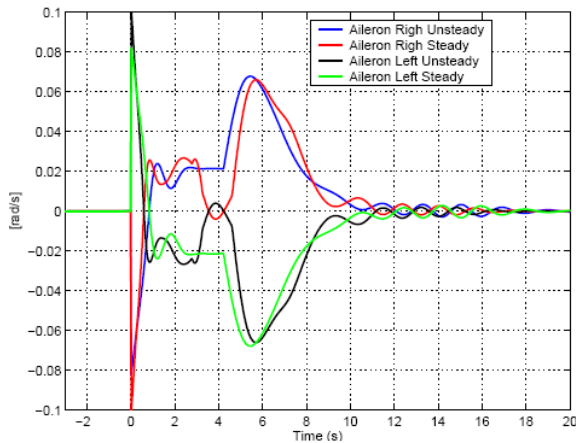


Fig. 11. Elevators angular rates.

The Elevator response is coherent with the angular results presented in Fig. 11, with a damping of the elevator until the aircraft finish the turn.

The two different aerodynamic models produce similar results with small variations. As expected, the simulation with the dynamic dependency model produces a slightly better performance. This is mainly seen in the flight path from above (Fig. 13), where the simulation with the unsteady model performs the turn faster than the other model. This can also be seen in Fig.12, where the unsteady model angular response is slightly faster.

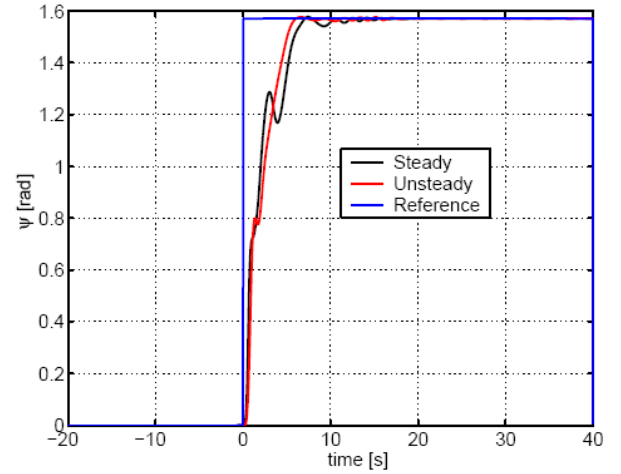


Fig. 12. Turn response from the aircraft.

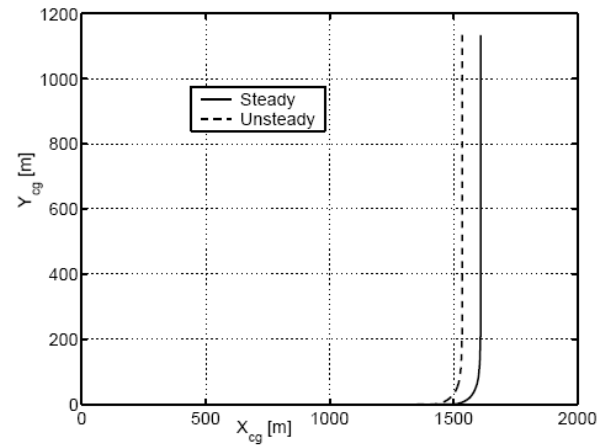


Fig.13. Flight path from above.

Optimization techniques are the core of computational engineering design and in this case it has been demonstrated that direct-search optimization methods can be used on full-scale simulation models for system optimization. And the relevance of the different aerodynamic model used in the simulation has been shown.

8 Discussion

Rationalization of the design process and introduction of multidisciplinary optimization are no novel topics in aircraft design. In the literature there are examples that can be tracked back to the early seventies [9], emphasizing how the need and the benefits have been known for a very long time.

What has been proposed in this paper is a framework architecture that focuses on its flexibility of application. To avoid continuing

using semi-empirical or statistical equation during the conceptual phase of aircraft design, it has been suggested to make a larger use of analytical tools. For the aerodynamics a high order panel code – PANAIR – has been successfully employed.

It has been researched how to proficiently include a high-end CAD system – CATIA V5 – during the initial geometry generation of the three-dimensional aircraft model. This is achieved by making a large use of the automation features that CATIA offers, mostly the User Defined Features (UDFs) together with scripts. UDFs ensures the context dependence of the automatically instantiated features, while scripts stand for the dynamic behavior of the whole system.

Two very different studies have been presented as test cases to validate the use of the framework.

In the design optimization of a wing-box structure, two strategies have been adopted. First deciding ahead the number of ribs and then allowing the system to change the number freely. The results showed two very interesting aspects:

- the models involved in the design study and the framework itself were able to carry out the design optimization with a varying number of elements;
- the increased flexibility allowed the system to suggest design solutions very different from the initial design. This supports the idea that, in this kind of design studies, a larger effort should be spent on not over-constraining the solution as it is too often done.

In the second test case a flight simulation was used to optimize the actuator system. It has been demonstrated that simulation based optimization can be used on a wide range of problems in aircraft conceptual design. The inclusion of time and pitch dependency into the aerodynamic modelling has shown significant influences.

Two different uses of the framework have been presented with encouraging results. Even though the nature of the problem presented and

the tools required to solve them were different, the framework was successfully adopted to link together the models, to gather data, regulate the information flow and to carry out analysis, simulations and design optimizations.

9 Future Work

In order to get more accurate and detailed results from the structure design problem, a more precise finite element model will be developed. So far the models have been kept relatively simple so that computing time would remain acceptable. Plans are now to examine and compare an in-house solution with different software for model integration, such as iSIGHT by Phoenix Integration [22], MODELCENTER by Engineous Software [6] or Optimus by Noesis Solutions [21]. The main goal is to be able to distribute computing on several machines through parallelization, thus being able to cope with much more complex problems without time penalties.

Then it will be possible to carry out broader design optimizations, where the outer shape of a body will not be decided and fixed ahead. The optimization variables will then be both the ones controlling the structural layout and those governing the outer shape of the vehicle (plan-form, airfoils, twisting...). The data flow in such a problem will be as shown in Fig.14 below, where the interaction between aerodynamics and structural efficiency can be captured in the internal loop pictured.

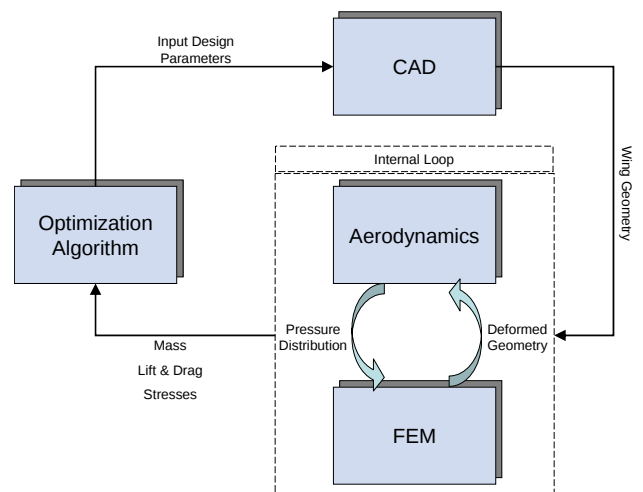


Fig. 14. Data flow within the framework in the two loops needed to account for aeroelasticity.

Another important part of the work to come will be to link together the two presented cases in order to include the flight requirements onto the shape and structural optimization. By doing so, the knowledge in the conceptual design stage will further increase, in order to provide better confidence in the decisions to be taken.

10 Conclusions

In this paper a framework architecture that focuses on flexibility of application, has been outlined. To avoid continuing using semi-empirical or statistical equation during the conceptual phase of aircraft design it has been suggested to make a larger use of analytical tools. For the aerodynamics, a high order panel code – PANAIR – has been employed. PANAIR may not represent the most advanced tool for aerodynamic analysis, but it served the purpose of illustrating the process. Clearly any other panel code or CFD software could equally be used instead.

A CAD model has also been included as one module in the framework, where geometric calculations, as well as structural analysis are performed.

Furthermore, a flight simulation model was used to optimize the actuator system of a UAV-type of aircraft, and it has demonstrated that simulation based optimization can be used on a large scale problem in aircraft conceptual design.

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