MODEL BASED AIRCRAFT CONTROL SYSTEM DESIGN AND SIMULATION

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Abstract

Development of modern aircrafts has become more expensive and time consuming despite enhancement of computer hardware and software technology. In order to minimize the development cost, an improvement of the conceptual design phase is needed. The desired goal of the project is to enhance the functionality of an in house produced framework conducted at the Department of Machine Design, Linköping University, consisting of parametric aircraft models used for conceptual design, where decisions based on uncertain information has an expensively irreversible effect on the outcome of the product. The first part of the work consists of the construction of parametric aircraft control surfaces such as flaps, aileron, rudder and elevator created in CATIA V5. The next part of the work involves designing and simulating a dynamic model in Dymola software. The later part of the work is to create an aerodynamic model in Tornado that can be updated with respect the aircraft model. Parameters can be varied in the interface as per user specification; these values are sent to CATIA, Dymola or Tornado and vice versa. The constructed concept model of control surfaces has been tested for different aircraft shapes and layout. An interface is developed between CATIA, Dymola and Tornado. An optimization case is performed to visualize the automation capability of choosing and actuator from a database for the proposed framework, and enhance the early design phases for aircraft conceptual design.

1 Introduction

The combination of several domains such as structure, aerodynamics, propulsion and electronics is indispensable in the design of complex products in order to acquire a holistic view of the system. Moreover, the product must be treated as a complete system to achieve an optimal design, instead of developing the different subsystems independently. All aspects of the involved domains have to be treated concurrently if the most suitable trade-offs are to be found. Efficient tools and methods for integrated design are needed during the development process in order to efficiently design and develop such products. Different engineering perspectives have dealt with various approaches for integrated design [6], [7], [8], [9] & [10]. These approaches have shown that the use of tools that enable model integration serves to manage the complexity of the products and a new dimension of design studies can be conducted on a system level rather than on a component or subsystem level.

Although a holistic system view has historically accompanied the conceptual design phase of the aircraft industry, the adapted methodology has mainly an empirical nature [12] due to the lack of recourses as described above. A parametric design of control surfaces is proposed in this paper, where the CAD models will cover a large set of different configurations and work as multidisciplinary analysis enablers by providing a common geometric base [11]. A fast, effective and robust framework is ensured by connecting all models to a common parametric geometry, suited for the first stages of design but also allowing for further increase of fidelity throughout the design process [1].

1.1 Outline of the Paper

Nowadays there exist several aircraft design tools which combine geometry models with simulation models such as PrADO [14] and MIDAS [13]. However, the geometry generated from these tools is code based and cannot increase in fidelity without extensive coding for obvious reasons. On the other hand, a wide range of automation capabilities is offered by Modern CAD tools, which pave the way for parametric and associative modeling [15]. This is one of the main reasons why the master geometry of the outlined framework is constructed using a CAE tool.

This paper will start by a description of the separate parts of the framework which have been explicitly worked on, followed by the explanation on how these tools operate and how the integration between them is established. The present work is the extension of the master thesis project presented in June 2009 at Linköping University [3]. An optimization case is shown as a proof of concept to select actuators from a component database.

2 Multidisciplinary Design and Simulation

Multidisciplinary aircraft conceptual design is a suitable workbench to demonstrate the mentioned complexity, as numerous engineering domains must interact to give a clear idea of the whole system. Robust interfaces have to be constructed to provide an automatic interaction between these disciplines.

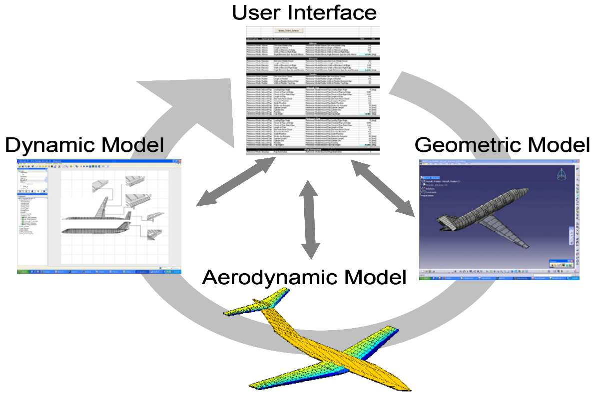
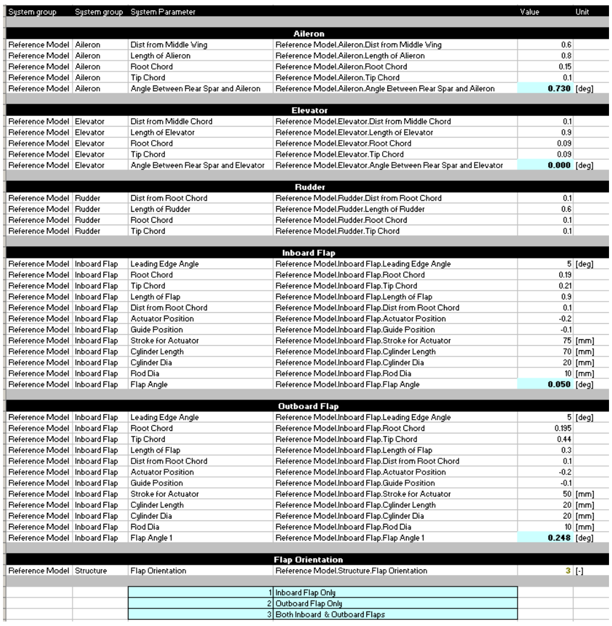


Fig. 1. Tool Integration framework

The main purpose of the framework shown in Fig. 1 is to supply engineers with a vast design space to browse through with the least amount of effort and re-design of the actual models. A design phase consists of many compromises such as technical and economical factors, hence new methods that enable the achievement of a design at low cost and time have to be developed. In the aircraft industry the recent challenge is to improve the design and lower both the production time and cost.

2.1 User Interface

Integration has been made between CATIA, Tornado and Dymola by a customized framework developed in Excel [25]. Parameters can be varied in the interface as per user specification; these values are sent to the framework and vice versa and this can save time during the design process. The framework is user friendly and powerful, thus the design parameters can be managed easily.



System group	System group	System Parameter		Value	Unit
Aileron					
Reference Model	Aileron	Dist from Middle Wing	Reference Model.Aileron.Dist from Middle Wing	0.6	
Reference Model	Aileron	Length of Aileron	Reference Model.Aileron.Length of Aileron	0.8	
Reference Model	Aileron	Root Chord	Reference Model.Aileron.Root Chord	0.15	
Reference Model	Aileron	Tip Chord	Reference Model.Aileron.Tip Chord	0.1	
Reference Model	Aileron	Angle Between Rear Spar and Aileron	Reference Model.Aileron.Angle Between Rear Spar and Aileron	**0.730**	[deg]
Elevator					
Reference Model	Elevator	Dist from Middle Chord	Reference Model.Elevator.Dist from Middle Chord	0.1	
Reference Model	Elevator	Length of Elevator	Reference Model.Elevator.Length of Elevator	0.9	
Reference Model	Elevator	Root Chord	Reference Model.Elevator.Root Chord	0.09	
Reference Model	Elevator	Tip Chord	Reference Model.Elevator.Tip Chord	0.09	
Reference Model	Elevator	Angle Between Rear Spar and Elevator	Reference Model.Elevator.Angle Between Rear Spar and Elevator	**0.000**	[deg]
Rudder					
Reference Model	Rudder	Dist from Root Chord	Reference Model.Rudder.Dist from Root Chord	0.1	
Reference Model	Rudder	Length of Rudder	Reference Model.Rudder.Length of Rudder	0.6	
Reference Model	Rudder	Root Chord	Reference Model.Rudder.Root Chord	0.1	
Reference Model	Rudder	Tip Chord	Reference Model.Rudder.Tip Chord	0.1	
Inboard Flap					
Reference Model	Inboard Flap	Leading Edge Angle	Reference Model.Inboard Flap.Leading Edge Angle	5	[deg]
Reference Model	Inboard Flap	Root Chord	Reference Model.Inboard Flap.Root Chord	0.19	
Reference Model	Inboard Flap	Tip Chord	Reference Model.Inboard Flap.Tip Chord	0.21	
Reference Model	Inboard Flap	Length of Flap	Reference Model.Inboard Flap.Length of Flap	0.9	
Reference Model	Inboard Flap	Dist from Root Chord	Reference Model.Inboard Flap.Dist from Root Chord	0.1	
Reference Model	Inboard Flap	Actuator Position	Reference Model.Inboard Flap.Actuator Position	-0.2	
Reference Model	Inboard Flap	Guide Position	Reference Model.Inboard Flap.Guide Position	-0.1	
Reference Model	Inboard Flap	Stroke for Actuator	Reference Model.Inboard Flap.Stroke for Actuator	75	[mm]
Reference Model	Inboard Flap	Cylinder Length	Reference Model.Inboard Flap.Cylinder Length	70	[mm]
Reference Model	Inboard Flap	Cylinder Dia	Reference Model.Inboard Flap.Cylinder Dia	20	[mm]
Reference Model	Inboard Flap	Rod Dia	Reference Model.Inboard Flap.Rod Dia	10	[mm]
Reference Model	Inboard Flap	Flap Angle	Reference Model.Inboard Flap.Flap Angle	**0.050**	[deg]
Outboard Flap					
Reference Model	Inboard Flap	Leading Edge Angle	Reference Model.Inboard Flap.Leading Edge Angle	5	[deg]
Reference Model	Inboard Flap	Root Chord	Reference Model.Inboard Flap.Root Chord	0.195	
Reference Model	Inboard Flap	Tip Chord	Reference Model.Inboard Flap.Tip Chord	0.44	
Reference Model	Inboard Flap	Length of Flap	Reference Model.Inboard Flap.Length of Flap	0.3	
Reference Model	Inboard Flap	Dist from Root Chord	Reference Model.Inboard Flap.Dist from Root Chord	0.1	
Reference Model	Inboard Flap	Actuator Position	Reference Model.Inboard Flap.Actuator Position	-0.2	
Reference Model	Inboard Flap	Guide Position	Reference Model.Inboard Flap.Guide Position	-0.1	
Reference Model	Inboard Flap	Stroke for Actuator	Reference Model.Inboard Flap.Stroke for Actuator	50	[mm]
Reference Model	Inboard Flap	Cylinder Length	Reference Model.Inboard Flap.Cylinder Length	20	[mm]
Reference Model	Inboard Flap	Cylinder Dia	Reference Model.Inboard Flap.Cylinder Dia	20	[mm]
Reference Model	Inboard Flap	Rod Dia	Reference Model.Inboard Flap.Rod Dia	10	[mm]
Reference Model	Inboard Flap	Flap Angle 1	Reference Model.Inboard Flap.Flap Angle 1	**0.248**	[deg]
Flap Orientation					
Reference Model	Structure	Flap Orientation	Reference Model.Structure.Flap Orientation	3	[-]
		1	Inboard Flap Only		
		2	Outboard Flap Only		
		3	Both Inboard & Outboard Flaps		

Fig. 2. User interface for Control surfaces

The user interface connecting CATIA control surfaces is as shown in Fig. 2. Parameters such as root chord, tip chord, and length of the control surface can be modified and updated. Inboard flap, Outboard flap and aileron can be updated to both high wing and low wing aircraft, while the elevator can be updated with respect to both T- tail and conventional tail configurations. The values of the above mentioned components can be sent to Tornado to update the aerodynamic model. The Workbook is divided into the following Sheets:

- Design Parameter (DP) sheets for all models connected and used in the proposed framework. The DPs allow users to modify the models without having to enter the tools that are used for their construction.
- Force Parameters sheet contains forces obtained from the Aerodynamic model and are updated in the Dynamic model.
- Mass properties sheet is used to obtain the mass properties from CATIA and update them in the Dynamic model.

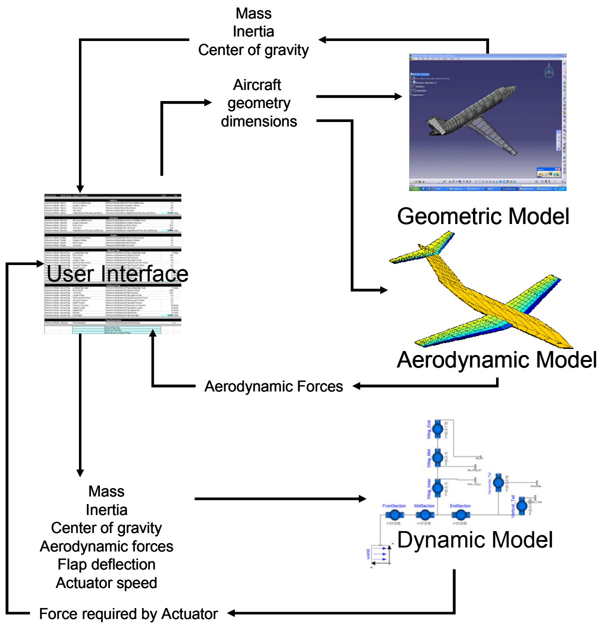


Fig. 3. Connection between CATIA, Dymola, Tornado and Excel

Excel is a tool most users are familiar with and know how to operate, which makes this framework user friendly and at the same time powerful since all necessary design data can be managed through one workbook as shown in Fig. 3.

3 Parametric CAD Modeling

Multidisciplinary parametric and associative design approaches have been feasible due to the emergence of open and hierarchical tree architecture modeling with the introduction of modern CAD tools [1]. Associative modeling serves to describe relations between multiple design objects, allowing top down assembly design where modifications on one component affect the whole system, without requiring manual re-modeling. This introduces new fields of applications for CAD tools. The first layer of Fig. 4. consists of Fixed Models whereas the values of the geometrical object are constant.

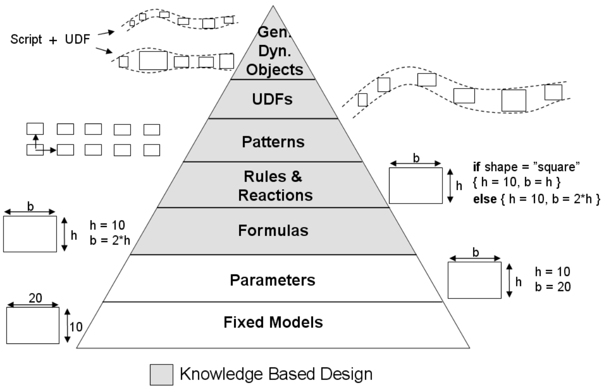


Fig. 4. Levels of parameterization (grey zone) defining Knowledge Based Design.

The values are assigned as parameters and visible directly in the hierarchical tree of the product and can thus be modified directly by the user in the Parameter stage. The third stage of parameterization which represents the first stage of Knowledge Based Design is Formulas, where assigned values are given mathematical relations. Rules & Reactions represents the second stage of knowledge based design (KBD), which allows the management of user triggered objects that are not bound to singular equations and permit simple user written scripts. This allows the construction of case defined components controlled by parametrical changes.

Patterns is the third stage in KBD, which establish the means to dynamically initiate objects following pre-defined directions, with the initiated objects being static copies of the original ones. User Defined Functions (UDFs) is the fourth stage of KBD, which supplies a user defined design approach, where a random object can be initiated in different contexts resulting in unique individuals. UDFs cannot be automatically initiated as the patterns. To create dynamic UDFs, a combination of Reactions and UDFs in the KBD pyramid is needed. This stage is called Generic Dynamic Objects (GDOs) which are dynamically initiated following a generic (user defined) pattern [1].

3.1 Geometric Model

The Structural Model (SM) is shaped by using the master model [1] previously built in CATIA V5 [23] at Linköping University. The initial part of the work consists of the construction of aircraft control surfaces such as ailerons, elevators and rudder parametrically to the above mentioned structural model as shown in Fig. 5.

The fuselage is divided in three sub sections: cockpit, cabin and rear fuselage. The wing is made out of three sub sections: inner, middle and outer wing. These sections are all NACA 4 and NACA 5 profile compatible by the use of the law function in CATIA, which defines a spline according to a mathematical formula. Besides the obvious parameters needed to define the NACA profiles, each wing has the following set of parameters: wing span ratio, chord length, leading edge sweep, twist, profile rotation, dihedral angle, a global parameter defining the total wing span, a parameter for wing placement in X direction and one discrete parameter for high wing and low wing configurations. The horizontal and vertical tails are constructed following the same building methods as the wing, but consist of only one section each.

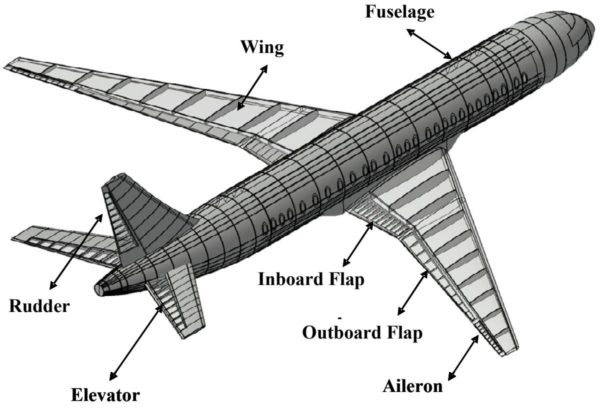


Fig. 5. Aircraft Structure Model

Considering that the wing is made out of three sub divisions, for simplicity, the Inboard flap is constructed in the middle section while the Outboard flap and aileron are constructed in the outer wing section. Rudder and elevator are constructed following the same building method on vertical and horizontal tails respectively.

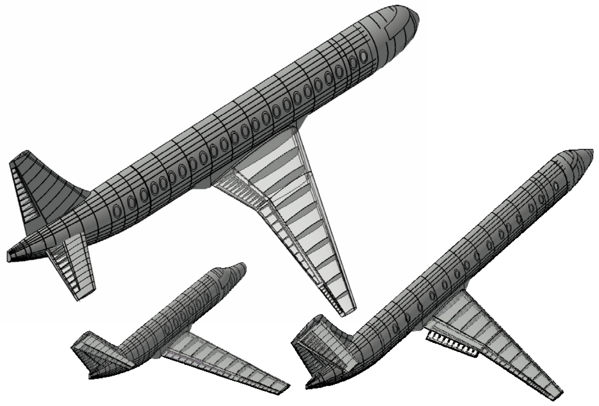


Fig. 6. A range of configurations made on the Structural model

The SM as a stand alone tool is a representation of various aircrafts with design information, more than being a mere visualization tool for rough configuration estimations. The SM is made in such a fashion that in spite of limiting the design space, offers a great deal of design possibilities, ranging from business- to regional- and commercial jet configurations seen in Fig. 6. It is thereby used as an integrator in the outlined framework by providing the same geometry to all analysis models involved. However, as it will be discussed, this geometry is required to undergo translation in some cases.

3.1 Flap Mechanism

‘Single slotted fowler flap’ mechanism is built both for Inboard and Outboard. The actuator is fixed to the rear spar of the wing.

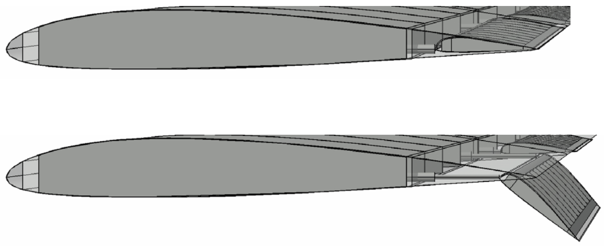


Fig. 7. Retracted and extended flaps

The flap extends and retracts when the stroke of the piston is changed. Wing area and chord increases as the flap extends and decreases as the flap retracts. Fig. 7. shows the extended and retracted flaps. This mechanism can be modified to suit the different aircraft configurations.

4 Aerodynamic Model

Tornado [26] is a Vortex Lattice Method for linear aerodynamic wing design applications in conceptual aircraft design, implemented in Matlab. It considers all the lifting surfaces as thin plates, and as it has a very high computational speed, the feedback is obtained straight away [26]. Wings are built up of quadrilateral partitions in Tornado, with characters such as sweep, dihedral, twist, taper, camber, trailing edge control surfaces and NACA 4-digits defining the geometry of the aircraft.

The Aerodynamic Model of the aircraft identifies all surfaces as wings. The number of wings is chosen, and each wing is divided into sections, and each section is divided into panels. The number of panels required in X-coordinates and Y-coordinates can be selected. The root Chord of the wing is specified along with the Taper Ratio.

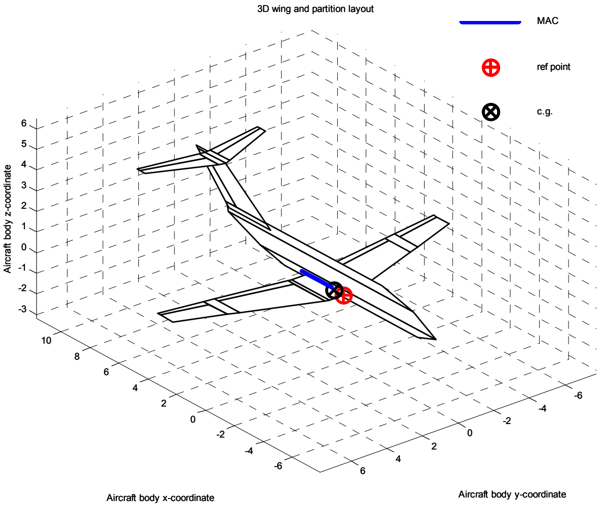


Fig. 8. Aerodynamic model of Cessna Citation CJ4

The Wing is divided into five sections; the flap is placed in the third section and the aileron in the fifth. The root chord of any control surface is given as the ratio of the length of the chord of the wing to the root chord of the control surface. The length of the flap is the full length of the section. After performing aerodynamic analysis, the force distribution is updated in the dynamic model. A 3D view of the aerodynamic model can be seen in Fig. 8. The state variables such as angle of attack, yaw angle, roll angle air speed etc., are defined. The geometry is then meshed with quadrilateral partitions and aerodynamic analysis is performed. The pressure distribution of configuration resembling Cessna citation CJ4 can be seen in Fig. 9. The force distribution on the flap is sent to the Dynamic model to obtain the force required to extend the flap.

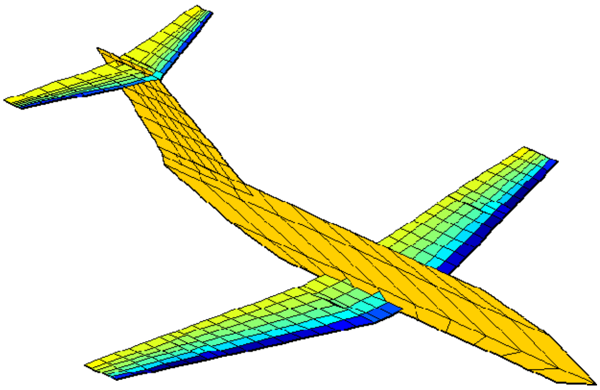


Fig. 9. Aerodynamic model pressure distribution

5 Dynamic Simulation and Modelica Model

Apart from the geometric models mentioned in section 3, models to predict dynamic properties of the system are also needed. These sorts of models typically rely on differential and algebraic equations. In the particular case of aircrafts they can serve to predict properties such as motion and force of the control surfaces, speed and torque of the actuator, etc.

Modelica is a general modeling language that the Modelica Association developed in an international effort [16]. The Modelica Association counts with members from both industry and academia that share a common interest in creating an effectively standard for modeling and simulation of complex systems from different engineering domains [4]. The Modelica language is equipped with several features for the implementation of concepts of so-called object-oriented modeling. These concepts support model integration and model evolution during the design process.

The Modelica language is a high-level modeling language and in order to simulate the models, the code must be compiled into executable code. Dymola, MathModelica System Designer, MOSILAB and SimulationX are tools programmed on commercial Modelica simulation environment. DynasimAB developed Dymola, which is the first tool that fully supports Modelica language [4]. A thorough understanding of the Modelica language is outside the scope of this paper, see the documentation for Modelica Association [16] for further reading.

5.1 Modelica Model of Aircraft

The Inverse dynamic simulation model of the aircraft control surfaces is developed in Dymola using Modelica language. This part of the work involves designing and simulating a dynamic model of the control surfaces in Dymola software [9]. The connection diagram in Fig. 10 shows an example of the dynamic model, including the control surfaces.

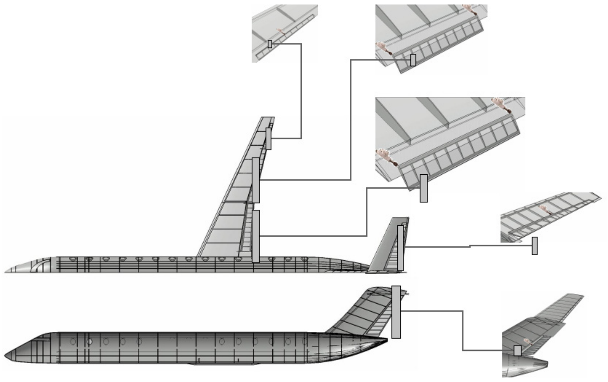


Fig. 10. Parametric connection between aircraft of the geometric and dynamic models.

In the aspiration of having cleaner systems, Electro-mechanical actuators (EMA) are considered in the dynamic model. The need of more electric aircraft (MEA) concept is to run not only the high power electric actuation systems but also the flight control surfaces such as rudder, ailerons and spoilers. This technology has merits in compactness and weight optimization [5]. It is built by a power convertor and an electrical motor. The electrical motor is connected to a roller screw and the screw is connected to the actuator. This is adapted in the design of actuators for the control surfaces in the dynamic model. A hydraulic actuator can be used in the place of EMA, but this is out of the scope of the present work.

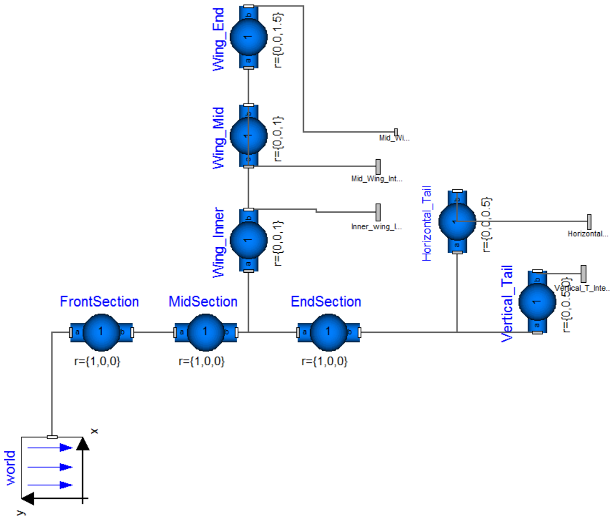


Fig. 11. Dynamic model in Dymola.

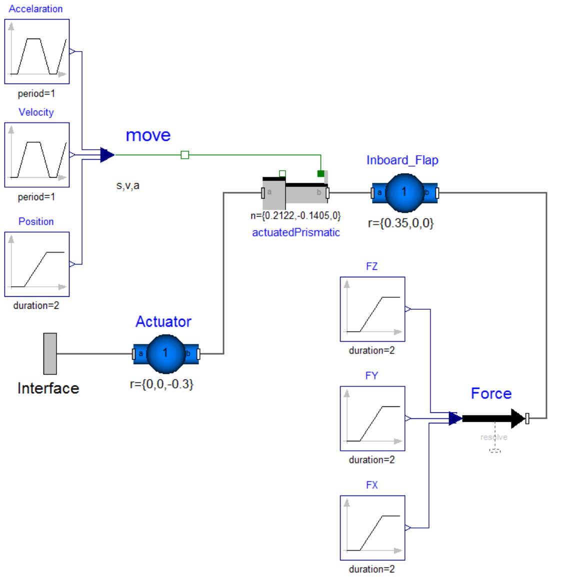


Fig. 12. Dynamic model of both Inboard and Outboard flap with Aerodynamic force.

Bearing in mind that the geometric model is divided into sections, a very similar idea is adapted in the Dynamic model that is shown in Fig. 11. The fuselage is divided into three sub sections: front, middle and end section. The wing is made out of three sub sections: inner, middle and end wing. The horizontal and vertical tails consist of only one section each. Each control surface consists of an EMA. The parameters for the actuator such as mass, volume, stroke length, diameter and speed are taken from the actuator database. The dynamic model of the Inboard and Outboard flaps is shown in Fig. 12 and that of aileron, elevator and rudder is shown in Fig. 13.

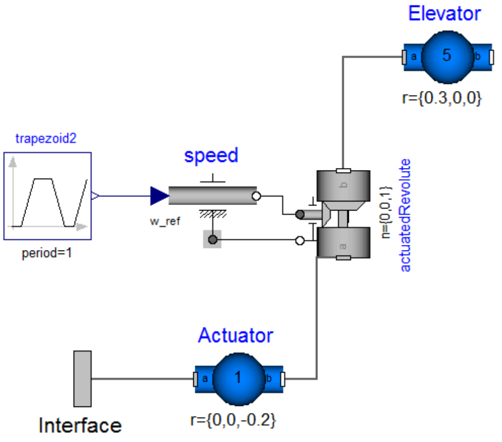


Fig. 13. Dynamic model of aileron, elevator and rudder.

After calculating the aerodynamic forces of the aircraft, the forces on the flap are sent to the dynamic model. The dynamic model computes the force required to retract the flap and provides it for the optimization.

6 Optimization

The characterization of optimization methods can be based on the order of the derivatives used in solving the problem, i.e. zero, first or second order methods, where zero order methods do not use derivatives. This later class of methods has a broad application since they do not rely on assumptions on the properties of the objective function such as differentiability, continuity, etc, but they imply more cost in terms of computational time than derivative methods. In this paper a non-gradient method has been used, explicitly genetic algorithm (GA) [10] and [17].

6.1 Genetic algorithm

Genetic algorithm is based on the mechanics of natural selection [18]. Each optimization variable is coded into a gene, which can be for instance a real number or a string of bits. A chromosome that describes each individual is formed by the corresponding genes of all parameters. The nature of a chromosome depends on the specific problem, and can vary from an array of real numbers to a binary string or a list of components in a database. Each individual carries a potential solution, and a set of individuals form a population. The fittest individuals among a population have the highest probability of being selected for mating. Mating is the combination of genes from different parents to give birth to a child, called a crossover. A mutation is also likely to occur at this stage. Finally a new generation is created by inserting the children into the population.

In this application, a chromosome is used including one integer variable per each actuator. The crossover operator is uniformed crossover where each gene of the mother is crossed with the corresponding gene of the father using blend crossover, and integer values are obtained by rounding them after crossover.

6.2 Optimization Framework

The application studied in this paper is the choice of an actuator for a specific flap configuration. This section will outline the computational process for the dynamic design optimization once a flap dimension is determined. The overall computational process including the integration of different computational tools is shown in Fig. 14.

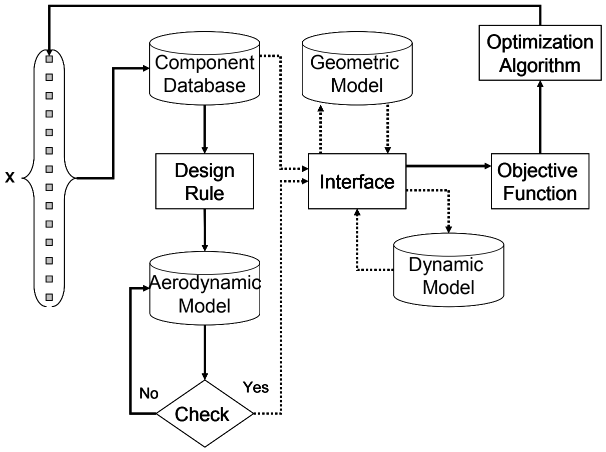


Fig. 14. Computational Process

The flow in the optimization model is illustrated in Fig. 14 and explained in the following points:

- The first part of the design vector defines the actuator choices.
- The geometric properties of the chosen actuator are sent from the component database to a block containing the design rules in which the geometry of the actuator is defined, e.g. the size of the flap is modified to fit the particular actuator.
- The information of the actuator choices is sent to the geometric model through the geometry interface, and the flap geometry is sent to both aerodynamic model and geometric model.
- The aerodynamic model calculates the forces on the control surfaces. The check function ensures that the required coefficient of lift is obtained; otherwise the flap is deflected and calculated again until the required coefficient of lift is reached and the output is stored in the interface.
- The geometric model will take shape according to the parameters from the interface and the outputs are sent to be stored in the user interface.
- The aerodynamic forces on the control surfaces and the mass properties from the interface are sent to the dynamic model and the output is sent back to the interface.
- The obtained outputs from aerodynamic, geometric and dynamic models are used in the Objective function.

6.3 Problem formulation

An actuator database is formed for the optimization by taking actuators data from leading actuator manufacturers [20], [21] and [22]. The actuators are chosen from the actuator database of 176 different number of EMA, which can produce the required force, needed to operate the flap, for the particular wing, for example configuration resembling CJ4 Cessna. The optimization variable depends on the particular actuator. In the characteristic problem formulation, the objectives are to minimize the volume (VA) and weight of the actuator (WA), keeping in mind the force of the actuator (FA), weight of the flap (WF), and the force obtained from the dynamic simulation (FD). Actuator weight, force and volume are obtained from the database and the flap dimensions are calculated. The weight of the flap is obtained from the geometric model; the force is obtained from the dynamic model.

The problem could be formulated as:

$$\begin{aligned} f(\mathbf{x}) &= \lambda_1 WF(\mathbf{x}) + \lambda_2 FD(\mathbf{x}) \\ &\quad - \lambda_3 FA(\mathbf{x}) + \lambda_4 WA(\mathbf{x}) + \lambda_5 VA(\mathbf{x}) \qquad (1) \\ x_i &\in \{1, 2, \ldots, n_{actuators}\}, i = 1, 2, 3 \end{aligned}$$

6.4 Optimization results

The optimization problem stated above has been solved using GA. The GA is generally more robust in identifying the global optimum, but it does require more function evaluations compared to gradient based methods in order to converge.

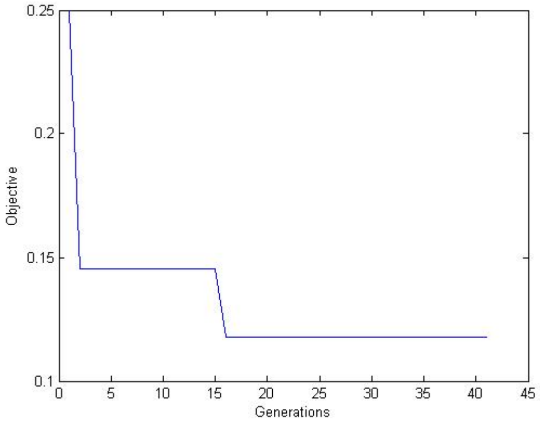


Fig. 15. Convergence of the Objective function.

All together the GA requires 10 hours on a standard PC to converge for 15 individuals and 40 generations. The time take to converge is high since GA is computationally expensive as it takes more number of function evaluations to converge at the final point. The modification of geometry, aerodynamic and dynamic model for every iteration also accounts to some extra time.

The convergence of the optimization process is visualized in Fig. 15. The optimal point is x = 4; this implies that the actuator 4 is chosen after the completion of optimization.

The convergence of EMA selection can be seen in Fig. 16

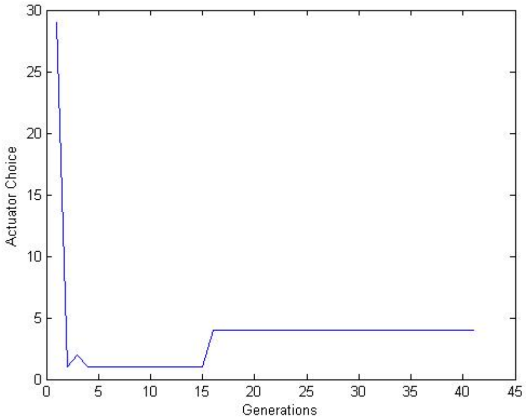


Fig. 16. Convergence of the EMA choice

7 Discussion and Model validation

In this paper, an approach to enable the integration of multiple analysis tools, for design and optimization has been presented, which facilitates concurrent engineering. The main components in this approach are the following:

- A highly flexible geometrical model that is able to accurately represent a wide range of variants parametrically.
- A parametric dynamic simulation model that maps to the CAD model.
- An aerodynamic model that replicates the CAD model.
- A framework for integration of the models and execution of the design process through one user interface.
- An optimization framework that enables design automation.

Different types of aircraft are tested to emphasize on the robustness of the framework. The aerodynamic forces can be varied and new results can be obtained with less cost. The control surfaces can be adapted for a wide range of aircraft configurations resembling Cessna CJ4, Embraer 145 and Boeing 777 etc., [19] refer to Fig. 6.

The framework can be suited when drastic layout changes are performed to the wing, then the optimization can be made to obtain the required actuator for the flap. If a library of different systems layout is built, i.e. aircraft actuators, this framework would acquire more capability for the optimization, as the output would give results for real systems in aircraft applications. Further work can be conducted by adding different flap configurations, slats and spoilers can be developed for the wing and trim tabs for the primary control surfaces. An optimization case can also be performed to choose an actuator for all the above newly added elements.

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