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Knowledge-based Flight Control System and Control Surfaces Integration in RAPID

R. C. Munjulury, I. Escolano Andrés, A. Diaz Puebla and P. Krus

Div. of Fluid and Mechatronic Systems, Dept. of Management and Engineering,
Linköping University, Linköping, 581 83, Sweden (E-mail: *raghu.chaitanya@liu.se)*

Abstract
Nowadays, aircraft design and development process is not only time-consuming but also incur high economic cost. In addition, system integration is highly a multidisciplinary design process, which involves a large number of different discipline teams working at the same time and space. The architecture of the flight control system which is essential for all flight operations has significantly changed throughout the years. The primary objective of this work is to investigate the early design stages to define the flight control system integration. The second part of the work consists of the development of knowledge-based CAD models of different types of flaps and their integration in RAPID. The purpose is to improve the functionality of an in-house produced aircraft conceptual design tool RAPID at the Division of Fluid and Mechatronic Systems, Linköping University.

Keywords
Actuator sizing, Flight control System, Control Surfaces, RAPID, Knowledge-based design.

List of Symbols

l_{Acc}	Accumulator Length
d_{Acc}	Accumulator Diameter
F	Actuator Force
A_{rod}	Rod Area
K_r	Rod Area Constant
p_m	Maximum Allowable Stress
d_{rod}	Rod Diameter
d_{piston}	Piston Diameter
M	Hingemoment
m	Single/Dual Actuator Parameter
p_{maxsys}	Maximum System Pressure
r	Actuator Hinge Arm
ϕ	Swept Angle
A_{piston}	Piston Area
Q_{nom}	Max Flow Rate
V_g	Volumetric Displacement of the Pump
n_{nom}	Nominal Speed of the Motor
tau	Torque of the Motor
$Pmotor$	Power
x^*	Parameter Scaling Ratio
x_{ref}	Reference Parameter
l^*	Length Scaling Ratio
l_{ref}	Reference Length
$V*$	Volume Scaling Ratio
V_{ref}	Reference Volume
V	Volume

l	Length
ρ	Density
ρ^*	Density Scaling Ratio
M^*	Mass Scaling Ratio
F^*	Force Scaling Ratio
T^*	Torque Scaling Ratio
GSD	Generative Shape Design
D_{cyl}	Cylinder Diameter
L_{cyl}	Cylinder Length
D_{ring}	Ring Diameter

Introduction

The process to design an aircraft is highly complex and multidisciplinary. In addition, it is also a time-consuming and costly activity mostly because of inaccuracies. Furthermore, systems integration within this process is one of the best examples of co-working engineering, as different specialized teams coordinate their operations in the same mainframe and with eventual divergent objectives, although the global aim is always shared (Moir & Seabridge 2008, Steinkellner et al. 2010). Consequently, it is a growing trend to consider the aircraft (final product) as a system itself, applying a methodical approach to its complete design. This allows working primarily with the whole coherent product and its entirety added value, leaving to a secondary position the study of the systems by automation under different disciplines perspectives (NASA 2007).

More specifically, flight control system and its linkage to the hydraulics aircraft systems are two of the higher variable sets of components to integrate into an airplane geometry. In turn, their final configuration will highly influence other systems integration. Therefore, it is required to implement a powerful tool to easily manage alternative configurations and provide understanding to focus on the key features, studying them in an interactive way (Haskins et al. 2006). This report proposes a design approach as the central pillar of an efficient systems engineering methodology, enhancing all of the coordinated steps that will lead to a final product definition aiming to improve the systems engineering process (NASA 2007). Currently, CAD tools offer solutions to designers to save time and cost in the first steps of the aircraft definition process. Aerospace is an industry where the systems complexity is always growing, the enhancement of these tools functionality is presented as the next major step forward. Simulation models shall help to have a further understanding of any complex systems and their key requirements, thus more cost-effective decisions and initiatives can be undertaken (Steinkellner et al. 2010).

In addition, a preliminary design of flight control surfaces and its integration in a parametric model of an aircraft is also addressed in this article. It consists of the development of flexible parametric models of different control surfaces (Aileron, Plain Flap, Double Slotted Flap, Triple Slotted Flap, Fowler Flap, Split Flap, Zap Flap and Slat) that will automatically adapt to any desired wing geometry. Each of the models allows the user to choose the corresponding angle deflection and extended length of the control surface, as well as positioning and sizing it along the wing. In this way, design automation succeeds in bringing the user the possibility to create and analyze any preliminary wing geometry without previous CAD design knowledge. In conclusion, a flexible designing tool will allow recurrent preliminary integration of different flight control systems and wing geometries; for instance, sharply decreasing the conceptual design stage costs. The integration model will lead to faster results, having a positive impact on all the activities of the product life-cycle (Haskins et al. 2006). RAPID (Munjulury et al. 2016, Munjulury 2014) is a knowledge-based aircraft conceptual design tool developed in CATIA ® (CATIA 2016), aiming to enhance CAD modeling in conceptual and knowledge-based design (Munjulury 2014, Byrne et al. 2014) to achieve a more advanced systems engineering approach.

Actuator Sizing

The automatic generation of the flight control system model with a high level of flexibility and adaptability is based on knowledge-based templates created in CATIA ® (CATIA 2016). Components are first designed, along with their driving parameters and instantiated as many times as required. In addition, not all the geometry needs to be instantiated, avoiding too much information included in the model.

Simplifications and Assumptions

- *Systems symmetry:* For simplicity only right hand side is considered based on the symmetry of the airplane, as it is possible to reproduce exactly the same geometry in the corresponding left wing and left horizontal stabilizer.
- *Valves omission:* Valves are not placed in the model, it is considered to be placed inside the reserved space by the routing definition.
- *Flight control system positioning:* Flight Control systems in most commercial aircraft are placed between the front and the rear spars, as the space in-between is used to store aircraft fuel in the corresponding tanks.
- *Default flight control system version:* As the specific configuration of each aircraft depends on a number of factors and the model created has a preliminary design purpose, an aircraft with most of the flight control surfaces which are present in civil airplanes (ailerons, elevators, rudder, flaps, slats and spoilers) has been considered. This allows a higher flexibility for the user, who can select among all of them.
- *Routing considerations:* The model is considered to be a way to assign a concrete space in the aircraft for the integration of the flight control system. In accordance to this philosophy, the routing is a cylindrical guide that integrates tubes for all the redundant systems and the necessary valves.
- *Hydraulic power assembly:* Pump, reservoir, accumulators and the corresponding valves are usually placed really close within the aircraft geometry. In this work, they have not been designed separately. Besides, they are all supposed to be integrated inside the so-called Hydraulic Power Assembly that takes into account the space for the elements mentioned above for further weight calculations.
- *Geometry simplicity:* The purpose of these templates is to symbolize a component, but not to become a manufacturing specification. Relatively simple geometry is represented for the flight control system integration in RAPID.

Electrohydrostatic Actuator (EHA) Sizing

Electrohydrostatic Actuator is an actuator based on an electric motor and driven pump connected to a hydraulic cylinder. In order to be able to size an EHA, the main components are Hydraulic cylinder, Fixed-displacement pump, Electric Motor, Accumulator and Power electronics. It is assumed that the motor and the pump are positioned on the same axis, parallel to the hydraulic cylinder. This criterion is usually used in large aircraft or high power requirements, as shown in fig 1. The accumulator is considered as a cylinder and its size is determined by volume within some limits of l_{Acc}/d_{Acc} ratio, l_{Acc} and d_{Acc} are the length and diameter of the accumulator respectively. Power electronics size is usually determined by its cooling surface, thus the same considerations apply as with the accumulator, but for a cuboid (Frischemeier 1997). As the design is focused on control surface actuators, a sizing method is obtained depending on the main inputs that appear on the control surface. In other words, the desired objective is to obtain a connection between the control surface and the actuator. Hence, in this sizing procedure the actuator force and the control surface hinge moment are used as main inputs. Therefore,

$$A_{rod} = k_r \frac{F}{p_m} \tag{1}$$

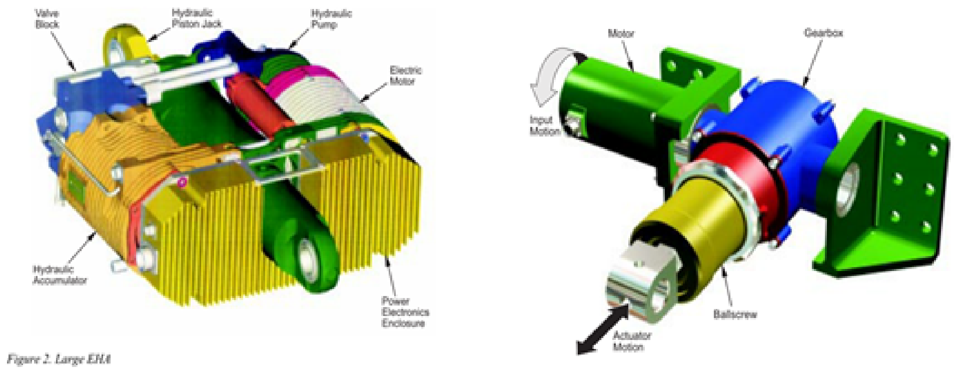

Fig. 1. EHA (left) and EMA (Right) (Botten et al. 2000)

Where F is the actuator force, p_m is the maximum allowable stress in the material and k_r is a constant related to the rod diameter, including a safety factor in order to achieve the structural requirements. The diameter of the rod is given by the following formula:

$$d_{rod}{}^2 = \frac{4}{\pi} A_{rod} \tag{2}$$

d_{rod} the required rod diameter, With the rod diameter as a known parameter and the hinge moment applied to the control surfaces as an input, the diameter of the piston can be calculated through the next equation (Berry 2005):

$$d_{piston} = \sqrt{d_{rod}^2 + \frac{4M}{\pi m p_{MaxSys} r cos\frac{\phi}{2}}} \tag{3}$$

$d_{pistion}$ is the diameter of the actuator piston, M is the hinge moment for a flight control surface, p_{maxsys} is the maximum system pressure, r is the actuator hinge arm and ϕ is the swept angle. The parameter m is a factor describing the type of actuator used: if the actuator is a single actuator m=1 and if it is a tandem actuator m=2 (Berry 2005). The piston area can be finally obtained through the next equation:

$$A_{pistion} = \frac{\pi}{4} d_{rod}{}^2 \tag{4}$$

Once the piston parameters have been obtained, the next step is to calculate the flow parameters: the maximum required flow rate and the volumetric displacement of the pump. To obtain the first parameter:

$$Q_{nom} = V_n A_{pistion} \tag{5}$$

Where Q_{nom} is the maximum required flow rate and V_n is the maximum loaded velocity of the actuator (the required velocity for the correct flight control actuation). With the max flow rate it is possible to obtain the volumetric displacement of the pump with the following formula:

$$V_g = \frac{Q_{nom}}{n_{nom}} \tag{6}$$

Where V_g is the volumetric displacement of the pump and n_{nom} is the nominal speed of the motor. Finally, the motor size can be varied as a function of its nominal torque within some l/d limits. Thus, the torque of the motor must be obtained:

$$\tau = \frac{P_{motor}}{n_{nom}} \tag{7}$$

τ is the nominal torque of the motor and P˙motor the required motor power. Now all the main variables of the main components, piston dimensions, pump volumetric displacement and torque motor are used in a design model of the EHA. The obtained parameters and the Table 2 in (Frischemeier 1997) makes it possible to have sizing of an EHA, depending on the value of several constants ($k_0, k_1, k_2, k_3, k_4 and k_5$). The values of these constants can be obtained with the dimensions of existing EHA's. It is possible to use the dimensions of those EHA's components and extrapolate them to obtain the constant values.

Electromechanical Actuator (EMA) Sizing

An Electromechanical Actuator is an actuator driven by an electric motor connected to the control surface by a mechanical linkage. The major components are a brush-less DC motor (either cylindrical or annular), a mechanical gear reducer, a ball screw and a power off brake (Budinger et al. 2014). The aim of a preliminary sizing is the development of simple yet quite predictive models, with lower levels of detail than the required for specific designs. For this purpose, a good approach is a use of scaling laws. The scaling laws, also known as similarity laws, allow to study the effect of varying representative parameters of a given system (Budinger et al. 2008). Scaling laws make it possible to have a complete estimation of a product range with just one reference component. Their main principle is to establish a valid relation between a component and its parameters, such as dimensions or physical properties, so it is possible to calculate the new values when varying one of the parameters. One of the advantages of the scaling laws, in comparison with other models, is the relatively low complexity of the problem of obtaining the dimensions and physical properties of a component from its primary characteristics, mainly due to two assumptions(Budinger et al. 2012):

- All the material properties are assumed to be identical to those of the component used for reference. All corresponding ratios are thus equal to 1. This means that physical properties such as the density of the material or the Young's modulus will remain constant.
- The ratio of all the lengths of the considered component to all the lengths of the reference component is constant. Therefore, all the dimension variation ratios will be equal to a global dimension variation.

Consequently, using scaling laws significantly reduces the number of inputs and simplifies the model to obtain all the main parameters as a function of one specific parameter, called as the *Definition Parameter* (Budinger et al. 2012). The first step is to define the scaling ratio of a given parameter, being used the notation proposed (Jufer 1996) for scaling laws calculation:

$$x^* = \frac{x}{x_{ref}} \tag{8}$$

x is the studied parameter, x_{ref} is the parameter of the component taken as reference and x^* is the scaling ratio of x. Geometric proportions are kept when using scaling laws, being able to link geometric dimensions through a geometric similarity. All the dimensions variations will be equal to a generic length variation l^*. The variation of a cylinder radius r or volume V can be thus expressed as:

$$r^* = l^* \tag{9}$$

$$V^* = \frac{V}{V_{ref}} = \frac{\pi r^2 l}{\pi r_{ref}^2 l_{ref}} \tag{10}$$

The previous result remains valid for any other geometry. Using the same procedure it is possible to obtain the variation of other parameters, as mass M as function of l^*:

$$M = \int \rho \partial V \Rightarrow M^* = V^* = l^{*3} (\rho^* = 1) \tag{11}$$

For mechanical components based on the design on a fixed constraint σ_{max} allows to link the variation of efforts to the variation of length l^* (Budinger et al. 2008):

$$F^* = l^{*3} \tag{12}$$

Where F^* is the transmitted force scaling ratio. Therefore, the nominal torque ratio T^* of a mechanical component can be estimated as:

$$T^* = l^2 \tag{13}$$

Estimations models can now be applied individually to each of the components of an EMA. The aim of the models is to minimize the entry parameters required to have a complete definition of the component. For mechanical components, particularly bearings and ball and roller screws (See fig 2), a model as the one showed in Table 3 in (Budinger et al. 2012) is applied. For the others mechanical and electro-mechanical components, speed reducers and brush-less motors, similar models are used, as shown in the Table 5 and Table 6 in (Budinger et al. 2012). The typical operational area of the motor will depend on its type. With all the relations it is possible to use the estimation models to create a preliminary sizing of an EMA using existing actuator components as references. The validity of the equations is applied to a single component performance. Nevertheless, before applying those formulas the scaling laws used must be validated by comparison with manufacturer data.

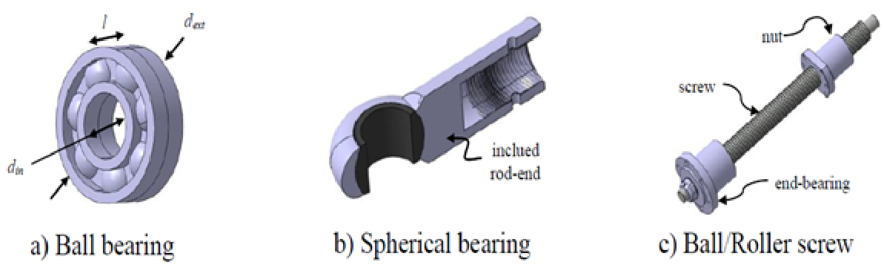

Fig. 2. General Program Diagram (Budinger et al. 2012)

Hydraulic Actuator Sizing

An actuator with a lever arm is responsible for holding the flight control surface and deflecting it as a response to the pilot's input. Taking that into account and sizing the actuator piston for the most demanding case (high speed flight at ground level); actuator piston diameter is defined by formula mentioned below (Berry 2005).

$$M = c_h S_{ref} q_{max} \overline{c} \tag{14}$$

$$d_{piston} = \sqrt{d_{rod}^2 + \frac{4M}{\pi m p_{MaxSys} r cos \frac{\phi}{2}}} \tag{15}$$

m is a factor adding information about the type of actuator which is being sized; m = 1 in case it is a single actuator and m = 2 whether it is a tandem actuator.Furthermore, the weight of the actuator can is also calculated (Berry 2005).

Knowledge-based Implementation

The flight control system and flight control surfaces are created for RAPID using knowledge-based engineering language in CATIA® (CATIA 2016). The implementation of the modeling work and different characteristics are going to be briefly explained in this chapter.

Flight Control System Integration

A parametric CAD model of EHA, EMA and hydraulic actuator were developed. The aim was to have a basic 3D model through parametric design so it was possible to change its dimensions and position it in a quick and simple way.

Hydraulic Circuit Basic Components		
NAME	QUANTITY	FUNCTION
Hydraulic Pump	2/system	It generates the hydraulic pressure which will power the actuators in the control surfaces.
Hydraulic Tank (Reservoir)	1/system	It stores the hydraulic fluid which transmits power within the circuit.
Regulating valve of the pump	2/system	It regulates the hydraulic fluid flow.
Hydraulic Accumulator	1/system	It storages hydraulic fluid which will be used in case of emergencies and peak performance.
Hydraulic conductors	N/A	They transfer the hydraulic fluid between the components of the circuit.
APU	1	It generates the hydraulic pressure which will power the actuators in the control surfaces.
Power and Control Units		
NAME	QUANTITY	FUNCTION
ARTCU	3	Deflection control unit.
Power Unit	1/actuators path	It powers a set of actuators.
Actuator Drive Assembly	1/actuator	It controls a specific actuator.
Electric Drive Unit	1	It powers slats rotary actuator.
Hydraulic Actuators		
NAME	QUANTITY	FUNCTION
Slats	1/surface	Rotary actuator which extends slats in the leading edge.
Ailerons	1/surface	It deflects ailerons’ control surface.
Elevators	1/surface	It deflects elevators’ control surface.
Rudder	1/surface	It deflects rudder’s control surface.
Flaps	1/surface	It extends flaps’ control surface.
Spoilers	1/surface	It deflects spoilers’ control,surface.

EHA Model

The model had to be flexible and cover a wide range of different measures of the components. The result is shown in fig 3, with all the components specified. It has been tried to achieve a similar model to the ones shown in fig 1.Through parametric design it is possible to vary its dimensions by changing the values of the corresponding parameters. fig 3 show possible configurations of the EHA through the variation of the parameters.

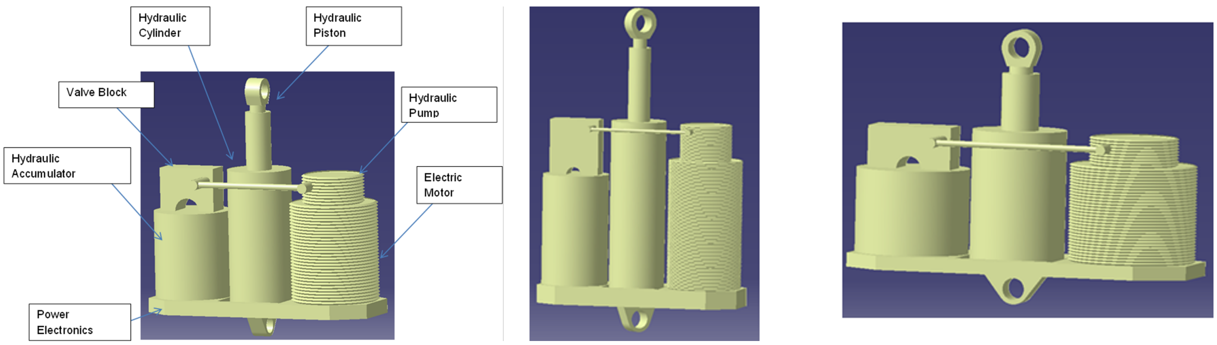

Fig. 3. EHA components and different configurations

EMA Model

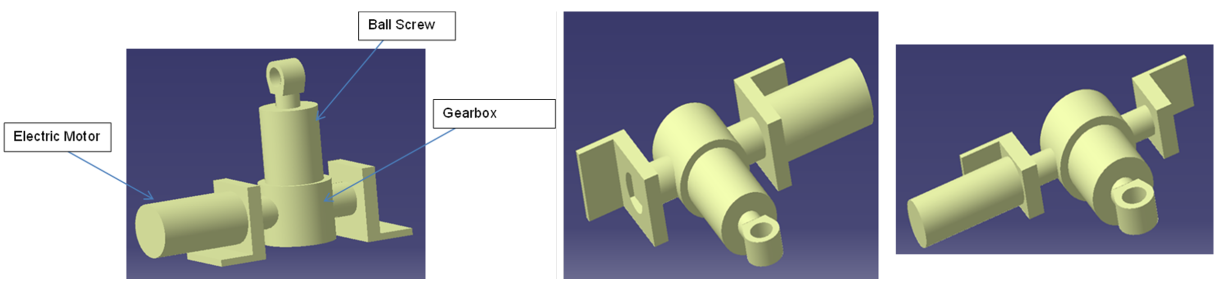

Fig. 4. EMA components and different configurations

The main components of an electro-mechanical actuator are Electric motor, Gearbox reducer, Ball screw. The most sought in the model is the flexibility to cover a wide range of measures. The result of the EMA model is shown in fig 4, where it can be appreciated that for the electric motor it has been chosen a cylindrical one. fig 4 shows possible combinations using different components.

Hydraulic Actuator

A key point in this geometry is two variations, the reason for this is a preliminary design of a new actuator which is flexible to be translated in the aircraft absolute Z axis; in this work it has been only placed in the horizontal tail, but a further development of this work would need to repeat this process to both the wing and vertical tail.

Control surfaces Integration

One of the objectives as mentioned before is the development of different types of CAD models for control surfaces design automation and integration in RAPID. The majority of those control surfaces are different types of flaps.

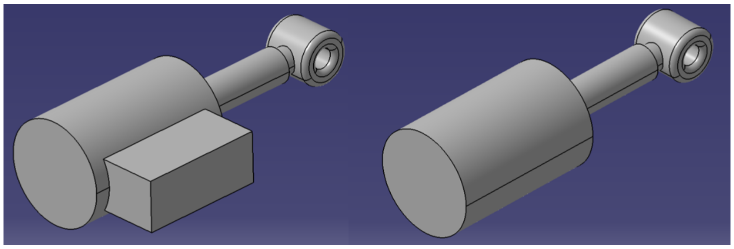

Fig. 5. Hydraulic actuator and tandem hydraulic actuator

For the control surfaces integration references have been taken from it, as it will be further explained in this section.Each of the models allows the user to choose the corresponding angle deflection and extended length of the control surface, as well as positioning and sizing it along the wing, among other parameters. It is also possible to combine each of the control surfaces along with slats. The following control surfaces have been developed; Aileron, Plain Flap, Double Slotted Flap, Triple Slotted Flap, Fowler Flap, Split Flap, Zap Flap, Slat.

Positioning and Sizing

As all the models can be positioned and their span can be chosen, in the same way, this section also provides information of the positioning and span sizing implementation. The control surface span starts on what it is going to be named Left Airfoil and finishes in the Right Airfoil. These airfoils are going to be considered the first and the last control surfaces airfoils, respectively. fig 6 shows all the elements involved to help the following procedure description.

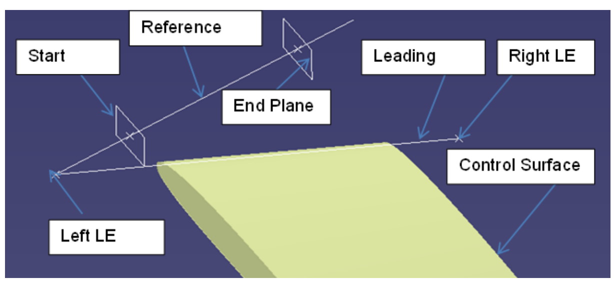

Fig. 6. Positioning and Span Sizing of the Control Surface

The Leading Edge Points are the most forward points of the airfoils, and all of them set up the Leading Edge (LE). The Leading Edge starts on the Left Airfoil and ends in the Right Airfoil. A Reference Line is then created with the wing span (transverse axis) direction. Reference line goes from Left Airfoil to the plane that contains Right Airfoil. In that line, two planes are created: Start Plane and End Plane. These planes define where between the Left Airfoil and the Right Airfoil the control surface starts and ends. Two parameters control the position of both planes.

Aileron,Plain Flap and Double Slotted Flap

The similarities between these control surfaces make it possible to integrate both surfaces in the same model. Actually, even the single slotted flap can be included by just adding a slot to the control surface as going to be later explained. The CAD model is as shown in fig 7. Double slotted flap as shown in fig 7 is similar to the plain flap with ana addded second slot.

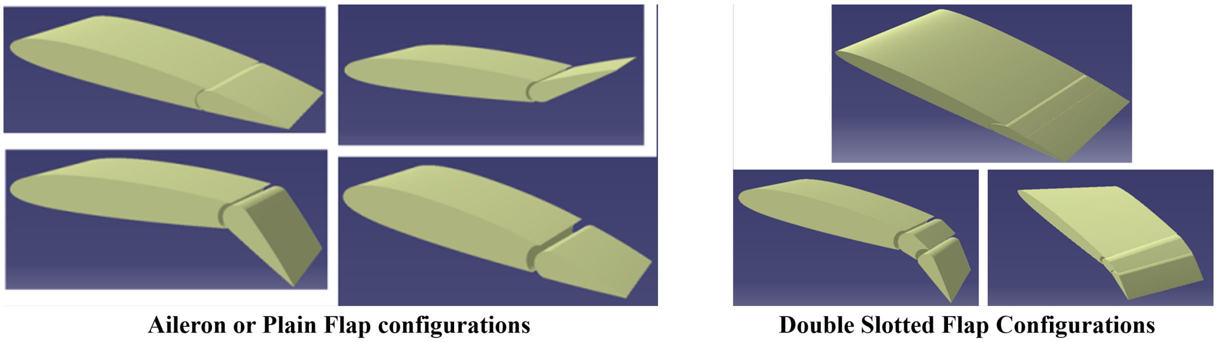

Fig. 7. Aileron or Plain Flap and Double Slotted Flap

Triple Slotted Flap and Fowler Flap

The triple slotted flap has an added slot to the double slotted flap is as shown in fig 8 and The Fowler Flap model is shown in the fig 8

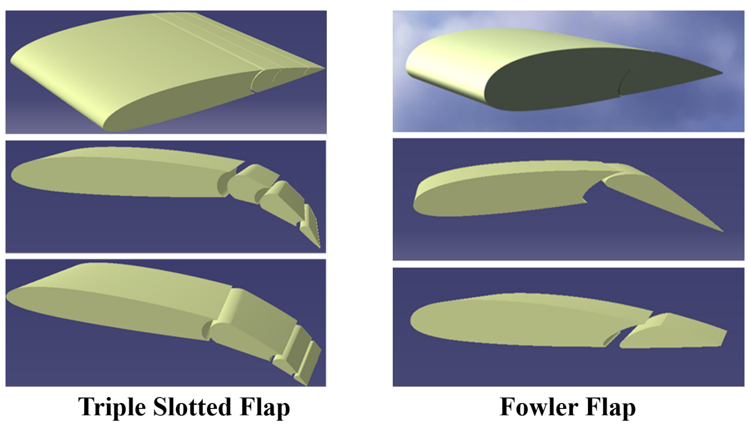

Fig. 8. Triple Slotted Flap and Fowler Flap

Split, Zap Flap and Slat

The similarities between these control surfaces make it possible to integrate both surfaces in the same model. The Zap Flap is like the split flap with the added feature of the translation of the control surface. fig 9 shows a screen shot of this CAD model. A slat model has also been developed to make possible a closer configuration of a real wing. This CAD model is shown in fig 9.

Results and Flexibility of the Model

The work presented is considered as first step into a full new line of work carrying out flexible para metrical integration of the necessary functional systems in RAPID. A first milestone is attained in this work, as it has been investigated and proved the possibility to define a flight control system model that represents different integration

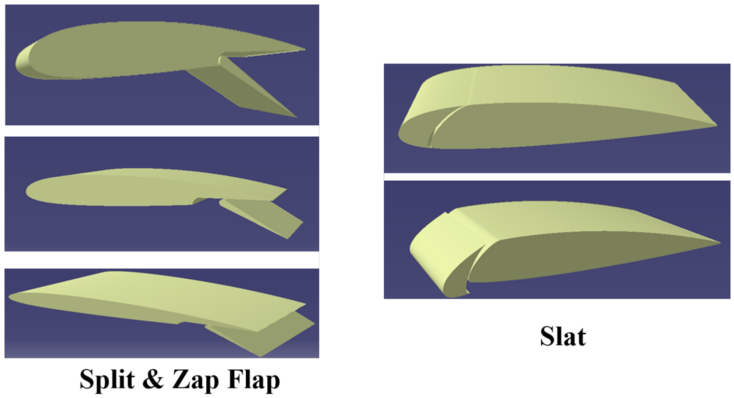

Fig. 9. Split & Zap Flap and Slat

solutions in a relatively easy and fast way for the user. Moreover, the work has been automated to save time for future developers and users, avoiding carrying out the first stages of recurrent work in templates and model definition.

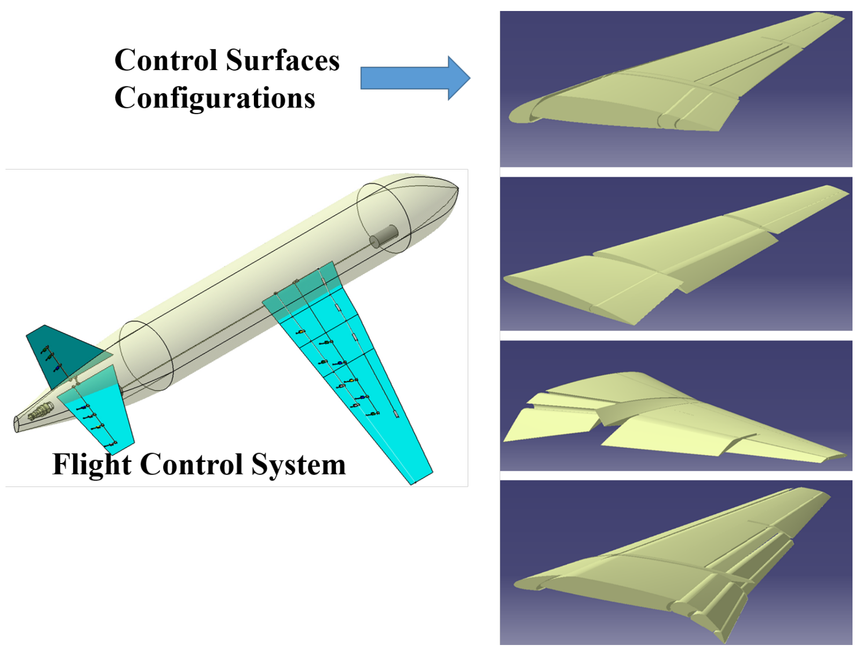

Fig. 10. Flight Cntrol System and Control Surfaces Configurations

The flap integration in RAPID guarantee the flexibility of the instantiated models. Through the parametric design, the user is able to modify each of the control surface parameters as well as the wing parameters- and observe how each of them affects the whole model and the different configurations that can be achieved.The possibility of choosing the position and the span length of the control surfaces through the two positioning parameters makes the model quite flexible and allows the user to define precisely the placement of the control surface, adapting the model to the needed requirements. Moreover, the possibility of changing the root and the tip chord length of the control surfaces provides the models with multiple configurations.

Nevertheless, although the individual parameters of the models already make them quite flexible, that is not all the flexibility the model can achieve. A great part of the flexibility resides in the automatic adaptation to the wing geometry modifications. The main possible modifications that the wing can present are, Wing Span, Airfoils Chord, Dihedral Angle, and Twist Angle. If any of the above parameters is modified, the model will automatically adapt to the changes. Furthermore, special mention should be made of the two last elements of the above list: the dihedral and twist angle, due to the difficulties had to make possible the model adaptation to these two parameters.

fig 10 shows flight control system and different wing control surfaces configurations through the variation of both individual and wing parameters. It is obviously impossible to observe some of the configurations in real airplanes, with different values of twist and dihedral angles in each of the four input airfoils, but it has just been shown to prove the flexibility of the model.

Discussion and Conclusion

Flexible flight control system integration in RAPID has been developed, proving the usefulness of Knowledge-based design to enhanced conceptual aircraft systems design. The work carried out in the actuator sizing was to provide a general overview of the new actuators that are currently being implemented. These actuators are powered by an electric motor, due to the present tendency of the development of MEA concept. It can be considered a first step into a preliminary sizing model of EHAs and EMAs, although at this point more research is needed. It is necessary for the utilization of the model or of any other model based on scaling laws- to have an updated and detailed actuator data table with dimensions and parameter values of existing flight control surface actuators. It would be also necessary a more detailed model of the sizing of both types of actuators in order to achieve a closest solution to real values beyond preliminary design models.

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