AIRCRAFT PARAMETRIC 3D MODELING AND PANEL CODE ANALYSIS FOR CONCEPTUAL DESIGN

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Abstract

The ever fast growing information technology is enabling a re-definition of the early stages of aircraft design which have been restricted to mostly statistical and empirical approaches because of lengthy and costly simulation times. A novel framework is being developed at Linköping University offering greater comprehension by enabling a holistic view of the aircraft systems with a multidisciplinary analysis approach, involving a centralized easy to use interface. This paper will depict the modules involving an aerodynamic panel code solver integrated to a parametric CAD model. The connection between these tools is made fully automatic, meaning that any modification on the CAD model will with a press of button be aerodynamically analyzed in the panel solver, including re-meshing and re-writing of a input file and finally re-distributing the output file to all other modules involved in the framework.

1 Introduction

Daily advances are taking place from ever growing computer power to better generic physics based analysis tools to more robust CAE tools etc. These improvements combined lead to the evolutionary path of frameworks effectively combining these tools [9] & [11], to achieve multidisciplinary design. In the design of complex products it is essential to be able to combine multiple domains such as structure, aerodynamics, propulsion and electronics in order to obtain a holistic view of the system. Furthermore, to achieve an optimal design the product must be treated as a complete system instead of developing the different subsystems independently which is especially true in the early design phases. All aspects of the involved domains have to be treated concurrently if the most suitable trade-offs are to be found. To efficiently design and develop such products, efficient tools and methods for integrated design are needed throughout the development process. Approaches for integrated design have been discussed and explored from different engineering perspectives [1], [2], [6], [13] & [15] and the previous results show that by using tools that enable model integration, complexity of the products can be managed and a new dimension of design studies can be conducted on a system level rather than on component or subsystem level.

Although the conceptual phase of the aircraft industry historically has had a holistic system view, many would agree that the methodology adapted has mainly an empirical nature [12], developed out of necessity and because of lack of recourses as described above. In present, this industry is on a threshold, a grey zone, whereas the choice between analysis driven and statistical approaches is still debatable. In this paper a parametric design will be proposed whereas the CAD models will cover a large set of different configurations and work as multidisciplinary analysis enablers by providing a common geometric base [11]. By connecting all models to a common parametric geometry, a fast, effective and robust framework is ensured, suited for the early stages of design but also allowing for further increase of fidelity throughout the design process [14].

1.1 Outline of the Paper

Today there exist many aircraft design tools combining geometry models to simulation models such as PrADO [17] and MIDAS [10]. However, the geometry generated from these tools is code based and can for obvious reasons not increase in fidelity without extensive coding. Modern CAD tools on the other hand offer a wide range of automation capabilities and thereby paving way for parametric and associative modeling [8]. This is one main reason for 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 for this paper, and then explain how these tools operate and how the integration between them takes place. As a proof of concept a wind tunnel test of a semi span business jet is benchmarked with a similar configuration analysis made with the proposed framework.

This work has been presented as a master thesis project in early spring of 2007 at Linköping University [16].

2 Multidisciplinary Analysis and Design

At Linköping University a novel framework is being implemented to manage the product complexity during the conceptual design phase, see Figure 1.

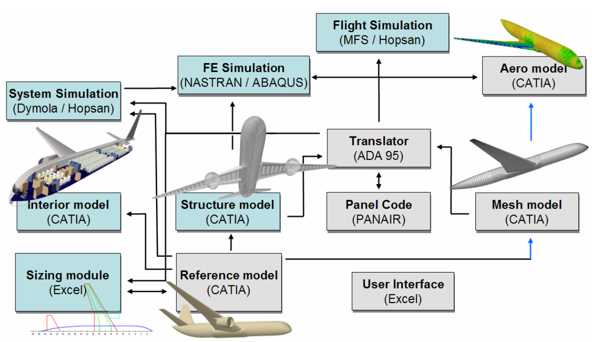


Figure 1. Framework for computational conceptual design showing the relation between different modules and the establishment of information flow. The grey colored blocks will be covered in this paper.

Aircraft conceptual design is a great workbench to demonstrate the mentioned complexity since numerous engineering domains have to interact to give a clear overview of the whole product. To be able to have an automatic interaction between these disciplines, robust interfaces have to be constructed. The interface which will be illustrated in this paper is between the panel code solver and the geometrical master model. The main scope of our framework and this paper is to supply engineers with a vast design space to browse through with least amount of effort and re-designing of the actual models. To fulfill this aim, the following points had to be realized:

- Defining the design space needed during the conceptual design space, see Figure 2.
- Choosing robust and reliable tools which can provide the mentioned design space.
- Constructing robust and flexible models in the tools mentioned, covering the sought after design space, see Figure 3.
- Constructing translator tools which enable integration between the models.
- Integrating the models with a common user interface containing all design variables, see Figure 3.

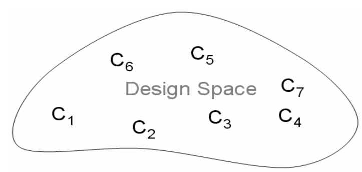


Figure 2. Definition of the design space with a finite number of allowable configurations (C_x).

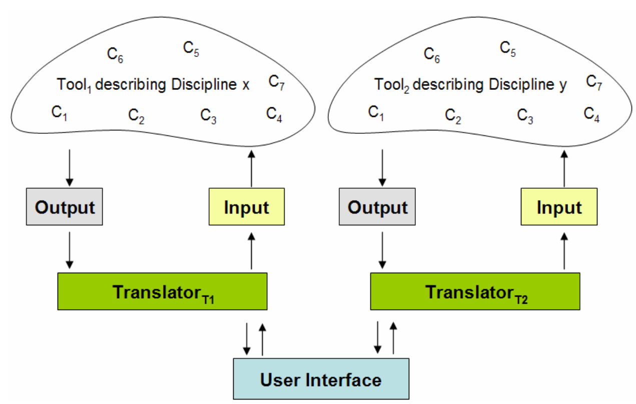
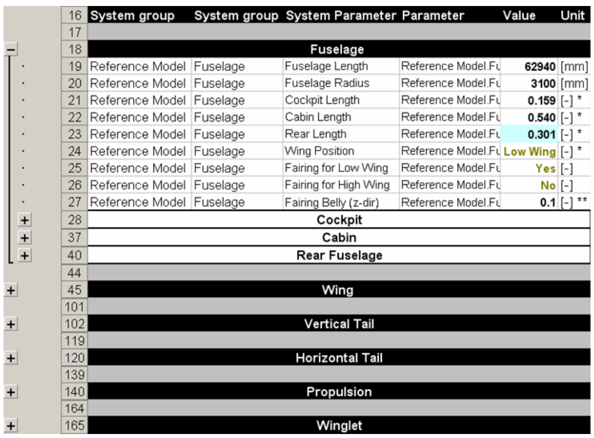


Figure 3. Models containing pre defined design space, linked to a common user interface after undergoing specific data translation.

2.1 User Interface

There exist commercial frameworks for tool integration in the design process such as iSIGHT [20], ModelCenter [22] and modeFRONTIER [23]. However, for the work presented here, a customized framework was developed which integrates the involved modules, developed in MS Excel [21], see Figure 4.



	System group	System group	System Parameter	Parameter	Value	Unit
16	System group	System group	System Parameter	Parameter	Value	Unit
17						
18	Fuselage					
19	Reference Model	Fuselage	Fuselage Length	Reference Model.Fu	62940	[mm]
20	Reference Model	Fuselage	Fuselage Radius	Reference Model.Fu	3100	[mm]
21	Reference Model	Fuselage	Cockpit Length	Reference Model.Fu	0.159	[-] *
22	Reference Model	Fuselage	Cabin Length	Reference Model.Fu	0.540	[-] *
23	Reference Model	Fuselage	Rear Length	Reference Model.Fu	0.301	[-] *
24	Reference Model	Fuselage	Wing Position	Reference Model.Fu	Low Wing	[-] *
25	Reference Model	Fuselage	Fairing for Low Wing	Reference Model.Fu	Yes	[-]
26	Reference Model	Fuselage	Fairing for High Wing	Reference Model.Fu	No	[-]
27	Reference Model	Fuselage	Fairing Belly (z-dir)	Reference Model.Fu	0.1	[-] **
28	Cockpit					
37	Cabin					
40	Rear Fuselage					
44						
45	Wing					
101						
102	Vertical Tail					
119						
120	Horizontal Tail					
139						
140	Propulsion					
164						
165	Winglet					

Figure 4. Screenshot of the User interface.

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 of which they are constructed in.
- ➢ Component database sheet for propulsions lavatories, galleys etc.

Excel is a tool most 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.

3 Parametric CAD Modeling

It was concluded in [14] that since the introduction of modern CAD tools it has been practicable to perform modeling in open and hierarchal tree architecture, which truly enables multi disciplinary parametric and associative design approaches see Figure 5. With associative modeling it is possible to describe relations between multiple design objects, allowing top down assembly design where modifications on one component affects the whole product, without requiring manual re-modeling. This paves way for new fields of applications for CAD tools.

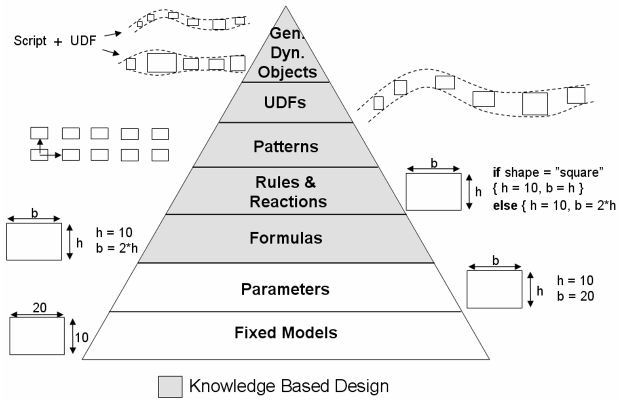


Figure 5. Levels of parameterization (grey zone) defining Knowledge Based Design.

The first layer of Figure 5 consists of Fixed Models whereas the values of the geometrical object are static. The Parameter stage is approached when the values are assigned as parameters and visible directly in the hierarchal tree of the product and can therefore be modified directly by the user. The third stage of parameterization which represents the first stage of Knowledge Based Design is Formulas, where values assigned are given mathematical relations. The second stage of knowledge based design (KBD), Rules & Reactions, manage user triggered objects not bound to singular equations and allow simple user written scripts. This allows construction of case defined components controlled by parametrical changes. The third stage in KBD is Patterns which provides the means to dynamically initiate object following pre-defined directions, with the initiated objects being static copies of the original object. The forth stage of KBD is User Defined Functions (UDFs) and as the name suggest provides a user defined design approach, whereas an arbitrary object can be initiated in different contexts resulting in unique individuals. However unlike patterns, UDFs are not dynamic and cannot be automatically initiated. To create dynamic UDFs, a combination of the second step namely Reactions and forth step namely 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.

3.1 Geometric Reference Model

The master model, also referred as Reference Model (RM) is constructed in CATIA [19] following the levels of parameterization methodology earlier discussed and described in detail in [14]. This model is able to parametrically change into different aircraft configurations ranging from business jets to wide body passenger aircraft.

The RM is divided in several sections namely Fuselage, Wing, Horizontal Tail, Vertical Tail, Propulsion and Winglet. A brief description of some of the components follows to give an overview of the construction methodology adapted.

The fuselage is divided in three main sub sections namely cockpit, cabin and rear fuselage. The wing is made out of three sub sections, namely 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. Beside 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.

The propulsion component is made out of 4 placement configurations; two wing mounted propulsions, one fuselage mounted and one tail mounted and are all activated and deactivated automatically. The propulsion on the RM consists only of the outer shape of the nacelles. The user selects these discreetly from the user interface, which is linked to the component library in the same workbook containing pre-set products. The body which connects the propulsion to the fuselage or wing, i.e. the pylon, is included in the propulsion component, and its geometry is automatically generated depending on the position of the propulsion.

The winglet built, is by general standards considered as a wingtip device, with the main geometric characteristic being the visually normal angle relation it has in respect to the wing. However the parametric winglet constructed for the RM has a variable cant angle which enables the design of raked wingtips as well.

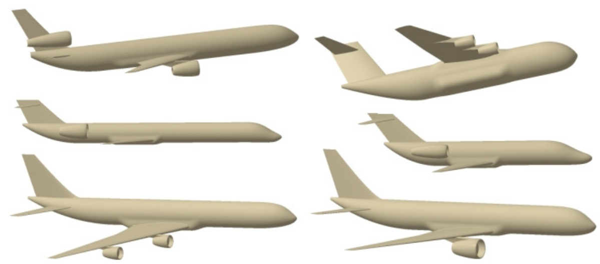


Figure 6. A range of configurations made on the Reference model.

The RM as a stand alone tool is merely a rubber representation of various aircraft with no design information more than being a mere visualization tool for rough configuration estimations. However it is as the name suggests useful for reference purposes for other domains, such as aerodynamic and structure models. The RM is made in a fashion which although limits the design space still offers a great deal of design possibilities, ranging from business- to regional- and commercial jet configurations seen in Figure 6. It is thereby used as an integrator in the outlined framework by providing the same geometry to all analysis models involved. However as will be discussed, this geometry is in some cases required to undergo translation.

3.2 Mesh model

To be able to perform aerodynamic simulation on the panel solver the surfaces of the RM have to be translated into points. Hence the choice of constructing a mesh model in CATIA, see Figure 7.

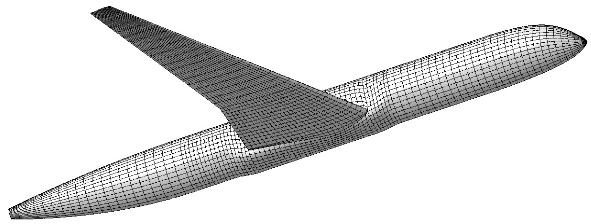
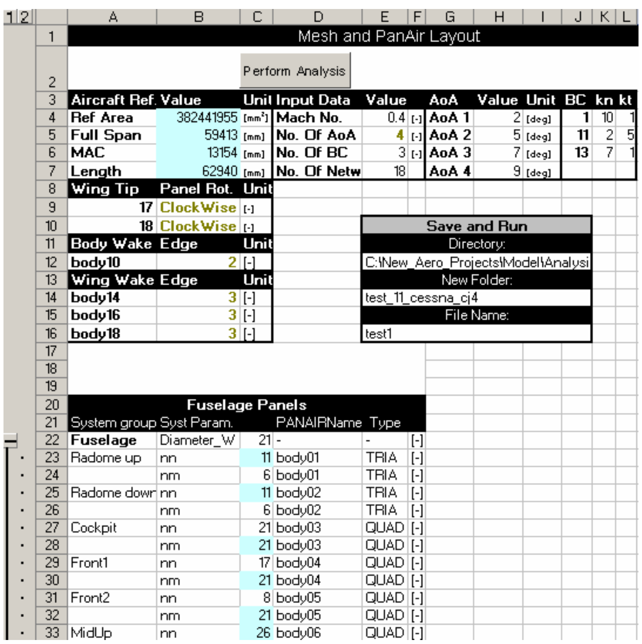


Figure 7. Screenshot of the mesh model.

The surfaces of the RM are published and meshed as quadrilateral or triangular panels. The mesh is made parametric, meaning that the grid intensity of the mesh model can be monitored and modified from the excel user interface seen in Figure 8.



	A	B	C	D	E	F	G	H	I	J	K	L
1	Mesh and PanAir Layout											
2			Perform Analysis									
3	Aircraft Ref.	Value	Unit	Input Data	Value		AoA	Value	Unit	BC	kn	kt
4	Ref Area	382441955	[mm²]	Mach No.	0.4	[-]	AoA 1	2	[deg]	1	10	1
5	Full Span	59413	[mm]	No. Of AoA	4	[-]	AoA 2	5	[deg]	11	2	5
6	MAC	13154	[mm]	No. Of BC	3	[-]	AoA 3	7	[deg]	13	7	1
7	Length	62940	[mm]	No. Of Netw	18		AoA 4	9	[deg]			
8	Wing Tip	Panel Rot.	Unit									
9	17	ClockWise	[-]									
10	18	ClockWise	[-]		Save and Run							
11	Body Wake	Edge	Unit		Directory:							
12	body10	2	[-]		C:\New_Aero_Projects\Model\Analysi							
13	Wing Wake	Edge	Unit		New Folder:							
14	body14	3	[-]		test_11_cessna_cj4							
15	body16	3	[-]		File Name:							
16	body18	3	[-]		test1							
17												
18												
19												
20	Fuselage Panels											
21	System group	Syst Param.		PANAIRName	Type							
22	Fuselage	Diameter_W	21	-	-	[-]						
23	Radome up	nn	11	body01	TRIA	[-]						
24		nm	6	body01	TRIA	[-]						
25	Radome dowr	nn	11	body02	TRIA	[-]						
26		nm	6	body02	TRIA	[-]						
27	Cockpit	nn	21	body03	QUAD	[-]						
28		nm	21	body03	QUAD	[-]						
29	Front1	nn	17	body04	QUAD	[-]						
30		nm	21	body04	QUAD	[-]						
31	Front2	nn	8	body05	QUAD	[-]						
32		nm	21	body05	QUAD	[-]						
33	MidUp	nn	26	body06	QUAD	[-]						

Figure 8. Excel User interface where the users can easily set up the mesh intensity and analysis case by modifying the cells.

The user is thereby able to modify the grid intensity of each surface i.e. Front1 as seen in Figure 8 and Figure 9.

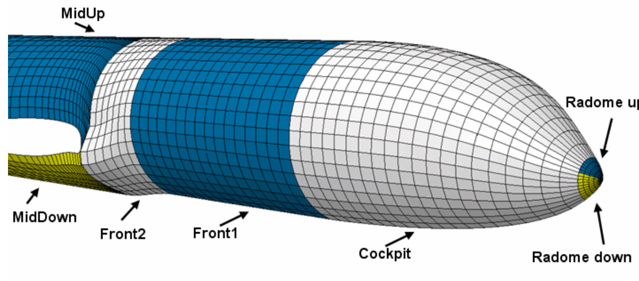


Figure 9. Mesh model consisting of several mesh surfaces.

After each mesh update a textual image on the mesh is generated and saved as a txt file and the information is eventually processed in aerodynamic panel solver.

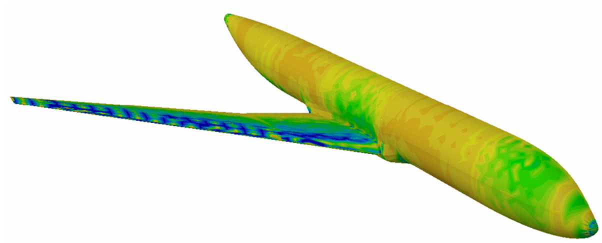


Figure 10. Mesh model visualizing the pressure distribution.

After the performed aerodynamic analysis the force distribution is sent back and updated in the mesh model, see Figure 10.

4 Aerodynamic Panel Code Solvers

Panel method codes have been used for aerodynamic analysis in the aeronautical industry for several decades. One main reason being is that it is a simple and inexpensive way to predict the aerodynamic characteristics of an aircraft [4]. In today's industry, and research field for aeronautics, Computer Fluid Dynamics has improved immensely thanks to the new and more sophisticated computers that are available. However computational power comes with a high price and a basic aerodynamic analysis performed on any geometry, such as that of a complete aircraft is still relatively time consuming. Therefore the use of panel code solvers in our framework has been preferred.

A panel code solver relies on the Prandtl-Glauert equation for linear, inviscid, irrotational flow at subsonic or supersonic free-stream Mach numbers [4]. The Prandtl-Glauert equation is a linear equation and it is the simplest form of the fluid-flow equations that contain compressibility effects. These equations are obtained from a more general approach to the Navier-Stokes equations. This general approach implies that the effects of viscosity and heat transfer are neglected, as well as, non linear terms. After eliminating these terms the equation for subsonic and supersonic flow are:

$$\tilde{\nabla}^2\phi = \left(1 - M_\infty^2\right)\phi_{xx} + \phi_{yy} + \phi_{zz} = 0$$

Equation for Subsonic flow

$$-\tilde{\nabla}^2\phi = \left(M_\infty^2 - 1\right)\phi_{xx} - \phi_{yy} - \phi_{zz} = 0$$

Equation for Supersonic flow

Where M_∞ is the free stream Mach number and ϕ is the perturbation velocity potential. The perturbation velocity potential is the approximated solution for the velocity potential of the flow. Panel methods rely on surface distributions of sources, doublets, and vorticity.

During the long time that panel method solvers have been in the aeronautical industry one can find several different codes on the market, i.e. MCAERO, PANAIR, Quadpan, VSAERO and ZONAIR [4].

4.1 PANAIR

Developed at Boeing during early 80's, PANAIR [7] & [24] is a higher-order panel method solver chosen to perform the aerodynamic analysis. The term "higher-order" comes to reference of the approached used by the programmers to solve the Prandtl-Glauert equation.

PANAIR can perform the analysis within the region of subsonic or supersonic velocities, although a limitation that it is encountered at exactly Mach 1.

The geometry is inputted as panels. These panels are normally flat quadrilateral. When constructing a complex geometry like a wing that has a curved leading edge or the union between a wing and a fuselage, there are bound to be gaps between the panels. It is traditionally the job of the user to minimize the number and size of the gaps so when the analysis is run the results are as accurate as possible.

In subsonic flow, the gaps cause little numerical error, but in supersonic flow the cumulative effect of the gaps becomes a serious source of error, not because of "leakage" of flow through the gaps, but because the doublet strength jumps abruptly from a non-zero value to zero at a panels edge, which does not exactly meet the adjacent edge [3].

PANAIR can be considered to be an analytical wind tunnel or a "virtual" wind tunnel. The information that can be extracted from PANAIR will allow the design team to experiment at different angles of attack to observe the aerodynamic capability of any given geometry. This virtual wind tunnel has the ability to handle asymmetric configurations as well as geometries with one or two planes of symmetry. This is also true for symmetric configurations in either symmetric or asymmetric flow.

The main results obtained with the PANAIR analysis run is summarized in the output file, this summary gives the induce drag coefficient, CD_i, lift coefficient, C_L, forces and moments around the three axes (X, Y, Z) and the pressure coefficient, C_p, both globally and locally in each panel.

It is important to remember that PANAIR solves for irrotational and inviscid flow and other assumptions about the flow effects on the real flow will not be predicted, such as flow separation, skin-friction drag and transonic shocks.

4.2 Translator

This module is a compiled program written entirely in ADA 95 [18]. One main task of the translator is to translate the geometry of the RM to the proper form required of the tools used outside the CAE tool i.e. PANAIR.

Writing an input file is an error-prone process, also it is difficult to prepare a case for any panel code, by defining the surface geometry as a set of quadrilateral panels. Therefore for this to be done automatically ultimately saves a considerable amount of time.

The route of how the data is translated is visualized in Figure 11. When the user has defined the geometry of the aircraft in the RM, the mesh model will be automatically updated and saved as a text file in a pre defined folder. The translator tool sorts this file and re-orders it in the required PANAIR input format, also other necessary data is extracted from the user interface. These are saved down into three text files:

1. The first text file will describe the case which will be simulated in PANAIR, i.e. Mach number, angle of attack and boundary condition for each surface.
2. The second file contains number of networks in the mesh model and number of points in each network.
3. The third and final file describes which networks are joined in the mesh model. This information will be used by the translator to better join these surfaces in the PANAIR input file.

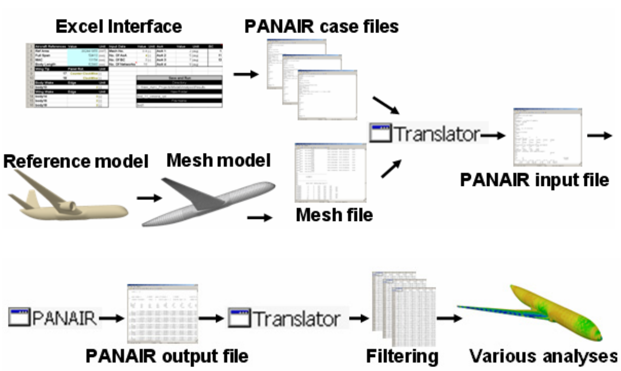


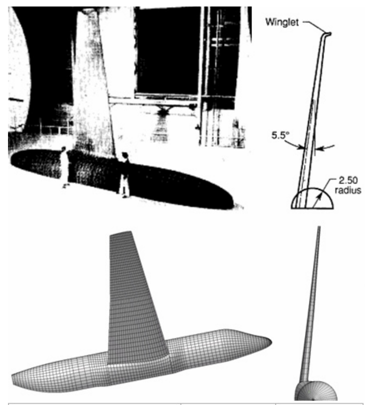
Figure 11. The block diagram shows the route of how the PANAIR input file is generated and the results of the simulation are distributed for various analyses.

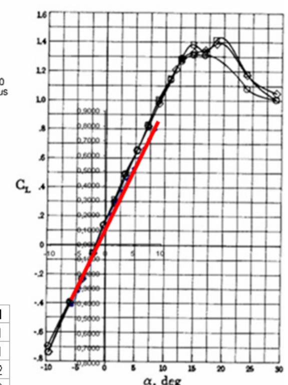
Following the PANAIR simulation, an output file will be generated from PANAIR which will be processed immediately by the translator tool. The information is filtered and translated to the proper form and sent to all modules requesting the information for further analyses i.e. structural analysis. All the information exchange described is monitored and triggered by the user interface.

5 Framework Validation

To validate the connection between PANAIR and CATIA it was decided to input the value of design parameters of the RM to resemble that of a full-scale semi span test of a business jet performed at Langley Research Center by NASA [5], see Figure 12. The flight and boundary conditions where set in the user interface and an analysis was performed. As can be observed in Figure 12 some deviations existed in the analyzed model, namely the lack of a winglet and a slightly different wing profile, but with the exact same wing thickness.

The C_L curve of the models at a specific mach number has been compared, as can be seen in Figure 12. The C_L curve of the wind tunnel model is colored black and the curve of our model is colored red.





	Langley test	CAD model
Semi span [m]	6,81	6,81
Semis pan ref. area [m²]	11,61	11,61
Root chord [m]	2,52	2,52
Tip chord [m]	0,89	0,89
Mean aerodyn. Chord [m]	1,87	1,87
Dihedral angle [deg]	5,50	5,50
LE sweep [deg]	4,15	4,15
Airfoil	HSNLF 0213	NACA 2413
Fuselage Length [m]	10,69	10,69
Fuselage Radius [m]	0,76	0,76

Figure 12. A Comparison on the CL to alpha curve of a wind tunnel test made at Langley Research Center with an analysis made on the outlined framework.

Another test which was performed, was a simple FEM analysis made on the structure model seen in Figure 1. The forces extracted from PANAIR were imported after being filtered and translated and could therefore easily be analyzed on an aircraft structure Figure 13.

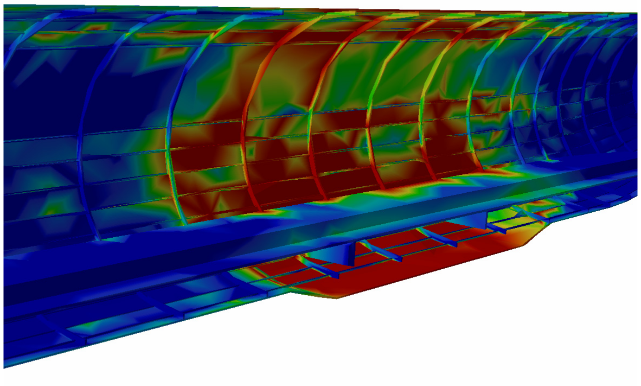


Figure 13. Screenshots of the FE simulation made on the structure model in the CATIA GSA module.

Conclusions

We have in this paper showed that it is possible to connect a modern CAD tool with aerodynamic panel solvers to ultimately provide designers with a tool one step closer to a more non statistical holistic approach for aircraft conceptual design. Instant and fast information on the aerodynamics behavior of the aircraft is thereby possible following a parametric modification on the geometric model.

To demonstrate the capabilities of the framework a benchmarking was performed using results of a wind tunnel test made on a full-scale semi span business jet. The deviation on the C_L curves seen in Figure 12 can depend on many different factors. The most obvious ones are the fact that the model tested in this framework didn't include any winglets and the wing profile was slightly different. The wing on the wing tunnel model was actually built with purpose of providing better aerodynamic qualities, which could partly explain why its C_L curve has a sharper angle in increasing angles of attack. Another reason is that PANAIR as mentioned earlier does not take into consideration factors such as flow separation though the equations that govern the panel solver do not take viscosity effects into account.

The FEM analysis made on the structure model promises exciting new research. Whereas a robust parametric and correctly set up Finite Element model could give designers fast and valuable information following a geometric modification on the aircraft. The analysis presented in this paper doesn't raise a claim of accuracy; however it does show that other more accurately set up analysis can be performed using the same force distribution extracted from PANAIR.

For future work we recommend to increase the functionality of the proposed framework by introducing similar models as presented in this paper for other engineering disciplines. We will also include the presented work in future multidisciplinary optimization test cases.

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