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INVESTIGATING THE PIAGGIO AVANTI DESIGN USING CEASIOM

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Abstract

In early steps of aircraft design the unification of configuration definition is important to avoid user–input errors. Also coupling with each other can strengthen different tools with different specifications simultaneously provided that the geometry definition is transferred with minimum data loss. This is vitally useful especially when geometry data is transferred in order to perform high–fidelity analysis. This paper reports the analysis for the pitch control of a three–lifting–surface aircraft Piaggio Avanti using CEASIOM*, a tool–chain software for aircraft preliminary design, with the baseline configuration coming from the conceptual design code* AAA*, linked by a common name–space* CPACS *for the means of data collaboration.*

1 Introduction

Figure 1 spells out the details in the early steps of aircraft design for the definition of the configuration. The figure illustrates two design loops in the conceptual design phase that follow the first–guess sizing (usually done by a spread–sheet) to obtain the initial layout of the configuration. The first one, the pre–design loop, is aimed at establishing a very quick (time–scale can be from one to a few weeks) yet technically consistent sized configuration with a predicted performance. The second one, the concept–design loop, is a protracted and requires intensive effort involving more advanced first–order trade studies to produce a refinement in defining the minimum goals of a candidate project. At the end of the conceptual design phase all the design layouts will have been analysed, and the "best" one, or possibly two, designs will be down–selected to the preliminary design phase. During the preliminary definition, project design is still undergoing a somewhat fluid process and indeed warrants some element of generalist–type thinking, but the minimum goals of the project have already been established during the conceptual definition phase and the aim is to meet these targets using methods with higher order than those used during the conceptual definition phase. Furthermore, the participants in this working group are mostly genuine specialists in each respective discipline. Figure 1 indicates the way in which data, or information, is passed between specialist groups during the design process. The specialist groups must consider the level of advanced technology to be adopted together with all of the other active constraints on the design. The data flow lines indicate how the technology areas influence the aircraft configuration through its performance. The specialist departments/offices provide the input data to the project designers who then coordinate a systematic search to find the "optimum" configuration and settle disputes between conflicting specialist opinions. There exists today a good deal of inefficiencies in interactions between all these various groups.

This paper shows the application of the high fidelity aircraft design code CEASIOM [1], the Computerised Environment for Aircraft Synthesis and Integrated Optimization Methods for Piaggio Avanti configuration which comes from Advanced Aircraft Analysis AAA [2] by investigating its longitudinal stability and control. The goal is to model the known three–channel control surfaces and to show how the three–lifting–surface for pitch control gives lower trim drag than conventional two–lifting–surface configurations.

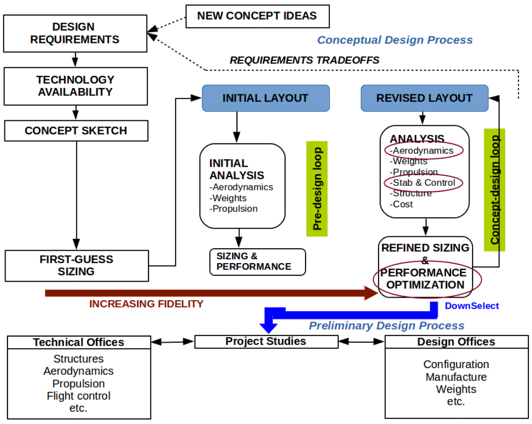

Fig. 1 The two design loops in the *conceptual design phase* process and the *down–select* to project study in *preliminary design*

2 Conceptual Design Tool AAA

Advanced Aircraft Analysis (AAA) provides a powerful framework to support the iterative and non–unique process of aircraft preliminary design. The AAA program allows design engineers and preliminary design engineers to take an aircraft configuration from early weight sizing through open loop and closed loop dynamic stability and sensitivity analysis, while working within regulatory and cost constraints.

The current version of AAA is based on the methods of Airplane Design Parts I–VIII by Jan Roskam, Airplane Flight Dynamics Parts I–II by Jan Roskam, Airplane Aerodynamics and Performance by Jan Roskam and Eddie Lan and methods developed for airplane design by DARcorporation engineers. Since 1991, when DARcorporation acquired the rights for AAA and continued the development as a commercial venture, AAA has been improved and upgraded several times.

AAA enables a fully functioning three–dimensional aircraft drafting tool Shark/AP [3]. More information about AAA geometry format and description can be found in [2] or on the website [1].

3 Preliminary Design Toolset CEASIOM

The Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods, CEASIOM, developed within the European 6th Framework Programme SimSAC (Simulating Aircraft Stability And Control Characteristics for Use in Conceptual Design), is a framework tool for conceptual aircraft design that integrates discipline–specific tools like: CAD and mesh generation, computational fluid dynamics (CFD), structures, stability and control analysis, etc., all for the purpose of early preliminary design [1]. It is an *ad hoc* framework that offers possible ways to increase the concurrency and agility of the classical conceptual–preliminary process outlined in Fig. 1. CEASIOMsoftware has four core functions: geometry and mesh generation, CFD, aeroelastic analysis, and stability and control (flight dynamics). Significant features developed and integrated in CEASIOM as modules are:

- Geometry module CPACScreator–`sumo` [4, 5]. A customized geometry construction system coupled to *automated* surface and volume grid generators, resulting model exported to Computer Aided Design (CAD) via Initial Graphics Exchange Specification (IGES) standard.

- Aerodynamic Model Builder AMB–CFD [6]. A complete toolbox of aerodynamic analysis methods ranging from the empirically based DATCOM to physics-based linear and non–linear CFD (Euler & RANS) offering broad choice in fidelity:
  - Digital DATCOM.

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[1] `http://www.darcorp.com/Software/AAA/` [retrieved 14 July, 2014]

  - Steady/unsteady vortex–lattice code (VLM) TORNADO for low–speed (linear) aerodynamics and aeroelasticity.
  - CFD solvers in EDGE code. Euler solver (EDGE code in Euler mode) for inviscid flow cases where total pressure and vorticity fields are too complex to model with isentropic equations e.g. at high speed or swirling flow. Examples of these are shock waves and propeller slipstreams. RANS (Reynolds–Averaged Navier–Stokes) flow simulator (e.g. EDGE CFD code) for high fidelity viscous flow analysis at extreme flight conditions.
- Stability and Control module S & C (e.g. SDSA [7]). A simulation and dynamic stability and control analyser and flying–quality assessor. Includes:
  - Performance prediction.
  - Test flights by six Degrees of Freedom flight simulation.
  - Stability Augmentation System (SAS).
- Aero–elastic module NeoCASS [8]. Quasi–analytical structural analysis methods that support aero–elastic problem formulation and solution.

CEASIOM is intended to support engineers in the conceptual/preliminary design process of the aircraft, with emphasis on the improved prediction of stability and control properties of elastic aircraft achieved by higher–fidelity methods than found in contemporary aircraft design tools. Moreover CEASIOM integrates into one application the main design disciplines, e.g. aerodynamics, structures, and flight dynamics, impacting on the aircraft performance. It is thus a multi–disciplinary analysis toolbox brought to bear on the design of the aero–servo–elastic aircraft [9, 10]. CEASIOM however does not carry out the initial sizing of a baseline configuration, and thus needs to collaborate with a tool like AAA, which was described in Section 2.

4 Interfaces and Wrappers

If an analysis module is not developed to explicitly serve a central data model it is unlikely that the module and the central model share the same parameterization. Hence conversions need to be made. The first step in such a conversion is the filtering of data. By applying mapping rules only the data relevant for the analysis module is transferred. In a second step the tool wrappers do the conversion of the data.

Figure 2 shows that all the related software tools for aircraft concept–design are linked to the central model approach CPACS [11] (visualized via CPACScreator), then the data are sent to the higher order physics-based analysis tools CEASIOM. The baseline geometry studied in this paper is obtained from AAA–CPACS interface [3].

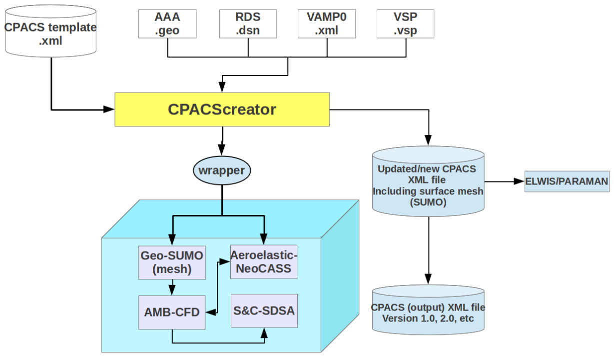

Fig. 2 Different conceptual design tools linked to preliminary design tool–chain CEASIOM by CPACS

5 CEASIOM Down–Select Configuration & Pitch Control Study

Figure 3 shows the AAA 3–view drawing of the final conceptual design for the Piaggio Avanti. This is the configuration that is down–selected from conceptual design and is now ready for preliminary design, as illustrated in Fig. 1.

A primary goal of preliminary design is to obtain the final *wing design with optimized performance*: e.g. maximized aerodynamic efficiency

Table 1 Structure of the aerodynamic database constructed in CEASIOM for use in the flight simulation SDSA module.

α	M	β	δ_{ele}	δ_{rud}	δ_{ail}	p	q	r	C_L	C_D	C_m	C_Y	C_ℓ	C_n
x	x	x	–	–	–	–	–	–	x	x	x	x	x	x
x	x	–	x	–	–	–	–	–	x	x	x	x	x	x
x	x	–	–	x	–	–	–	–	x	x	x	x	x	x
x	x	–	–	–	x	–	–	–	x	x	x	x	x	x
x	x	–	–	–	–	x	–	–	x	x	x	x	x	x
x	x	–	–	–	–	–	x	–	x	x	x	x	x	x
x	x	–	–	–	–	–	–	x	x	x	x	x	x	x

or minimized drag coefficient (C_D), usually starting with the cruise point.

The wing aerfoils are chosen by a skilful engineer as the initial design, which may not be optimum, but can be used as a good starting point. Then it should be put in an optimization loop to determine the optimized airfoil shapes (thickness and cambers), twist distributions according to the limits of lift coefficient (C_L), pitching moment coefficient (C_m), bending moment, span loading, fuel tank volumes, etc. for corresponding flight conditions. Take the Piaggio Avanti for example, the aerfoils of the wing are well–designed with cambers and twists to give sufficient lift in order to balance the weight during cruise. Additionally to get a well designed wing a multi–level optimization [12] should be considered, namely, optimizations for cruise, take–off and landing.

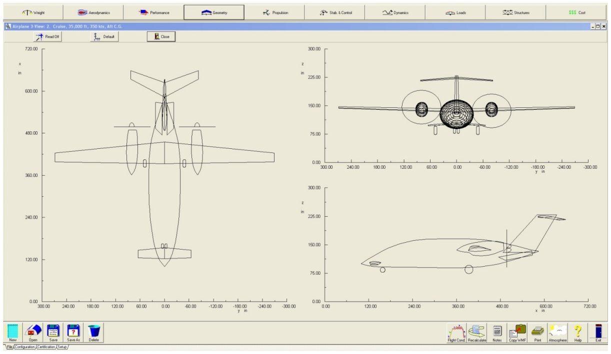

Fig. 3 3–view drawing of Piaggio–Avanti in AAA

Another goal is to determine a *database of aerodynamic forces and moments* that cover sufficiently the flight envelope so that it is appropriate input to a flight simulator for the study of the vehicle performances and handling qualities. Table 1 indicate how the aerodynamic database computed in CEASIOM is organized. It shows the static and quasi–static stability coefficients and the control coefficients. In Table 1 are presented the lift, drag and lateral force coefficients (C_L, C_D, C_Y respectively), pitching, rolling and yawing moment coefficients (C_m, C_ℓ, C_n respectively). The angle of attack is presented as α, M is the Mach number and β the side slip angle while q, p and r are the three rotations in pitch, roll and yaw. The three control surfaces that can be deflected are the elevator (δ_e), the rudder (δ_r) and the aileron (δ_a). The dynamic derivatives $(C_{m_{\dot\alpha}}, C_{Z_{\dot\alpha}}, C_{X_{\dot\alpha}}, C_{Y_{\dot\beta}}, C_{\ell_{\dot\beta}}, C_{n_{\dot\beta}})$ are instead computed only for different Mach numbers.

The coefficients must be obtained for each of these parameters throughout the flight envelope, hence the data is voluminous. In this paper we only focus on longitudinal control analysis in order to validate the advantage of this three–lifting–surface configuration. Thus only the second and sixth rows in Table 1 are filled with CFD Euler computations.

6 Piaggio Avanti

Piaggio Avanti is a three–lifting–surface twin–engine turboprop aircraft that has a small forward wing (canard) to produce extra lift and a T–tail for longitudinal and lateral control. It is claimed that it can save up to around 30% fuel compared with similar aircraft due to the non–traditional configuration. The main wing is designed to have laminar flow over a very high percentage of the wing chord, and the fixed canard is designed to stall before the main wing, resulting in a nose–down effect improving the airplane good performance at high angles of attack. The Piaggio Avanti is designed to cruise at Mach number of 0.62 at an altitude of 39,000 ft (economy cruise). More about the cruise speed and altitude can be referred in [13] and summarized in Table 2 according to Instrument Flight Rules IFR Range & Payload graph.

Table 2 Cruise speed at maximum cruise power [13]

Description	Speed [kts]	Altitude [ft]
Service ceiling at OEI	–	24,000
Maximum speed[2]	395	30,000
Cruise	370	37,000
*Economy cruise	356	39,000
Service ceiling	320	41,000

The typical mid–cruise weight is estimated by:

$$W = \text{Operating weight} + 4\text{PAX} + 1/2\text{Full fuel} \tag{1}$$

at ISA condition and IFR reserves. The lift is produced to balance the weight, which is around 450 kN estimated by taking maximum payload and half full fuel [13]. The CFD solvers operate inside CEASIOM and then all the data are sent to Stability and Control Analysis module SDSA in CEASIOM to model/simulate the pitch controls.

Figure 4 shows its 3–channel standard control surfaces illustrated on the 3–view drawing. The canard is a fixed lifting surface, and elevators on the horizontal tail control the pitch.

Tornado VLM and Edge Euler computations are carried out at Mach number 0.62 (economy cruise 356 kts) in order to build a complete aero–database to verify the advertised the superior flight qualities. The VLM method is fast but with lower fidelity. It is used to quickly generate a complete data–set as Table 1 is shown that is sent into SDSA for stability and control analysis.

At the next higher level of detail, the graphical surface modelling tool `sumo` can be used to define a more detailed geometry based on a moderate number (often less than 30) spline surfaces. This description is used to generate input for CFD solutions based on the Euler equations. Horizontal trim is studied for both full and canard off configurations.

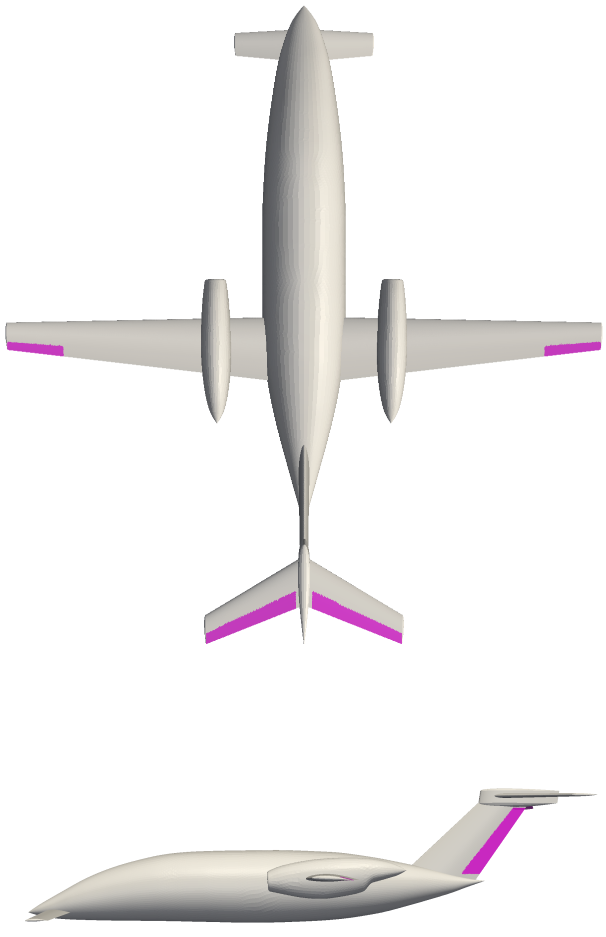

Fig. 4 Control surface illustrated on 3–view drawing [13]

6.1 Aerodynamics using Vortex Lattice Method

In VLM method the compressibility Prandtl–Glauert correction was applied for high subsonic Mach number (0.62). Figure 5 are the VLM mesh and solution for economy cruise at Mach number of 0.62.

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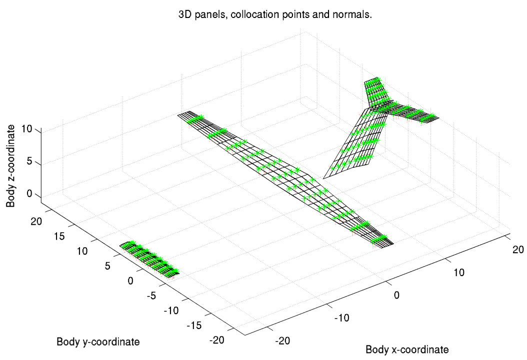
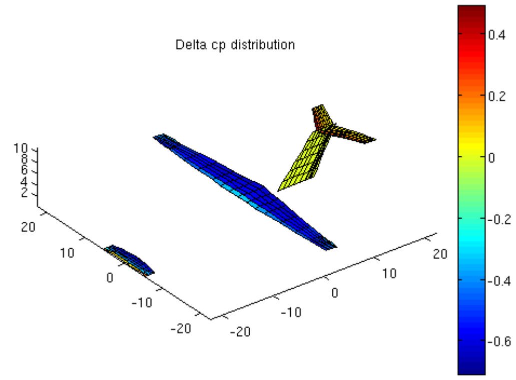
[2] At ISA conditions



(a) Tornado VLM panels

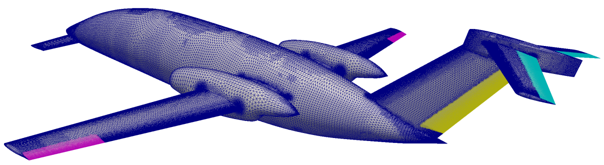


(b) Tornado VLM pressure coefficient distribution for steady flight at M=0.62 and C_L=0.65

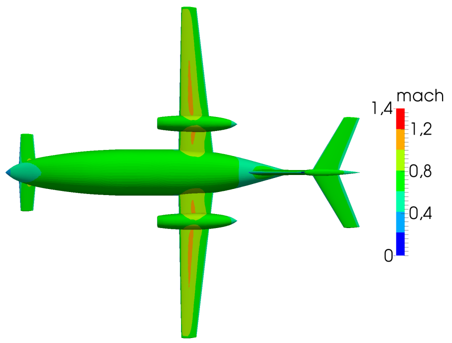
Fig. 5 Tornado VLM solutions from CEASIOM

6.2 Euler solutions

Figure 6(a) shows an Euler mesh used in this paper generated in `sumo` with 9.4 million nodes. The results for movable control surfaces are computed not by physically deflected, but by transpiration boundary condition in Edge. Figure 6(b) shows the Mach contour on the same condition predicted by CEASIOM Euler solver. We see that a weak shock is formed at the mid–chord of the wing due to high lift. Note that the VLM model only includes lifting surfaces such as wing, vertical tail and stabilizer, while the `sumo` geometrical representation also includes aerfoil thickness and non–lifting surfaces such as the fuselage. Again the VLM only treats the flow fields around the lifting surfaces linearly, which has poor fidelity on non–linear aerodynamics such as the wing in transonic flow. All of these above motivate us to turn to Euler solver to get more accurate solutions.



(a) Euler mesh generated by `sumo` and TetGen [14]

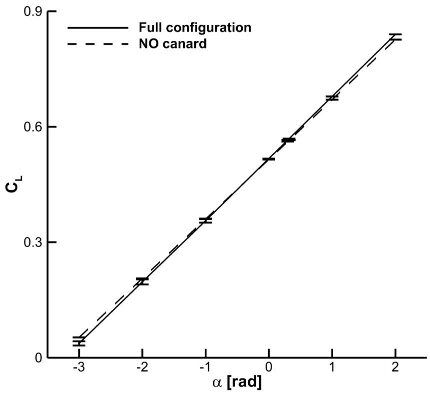


(b) Euler computation for cruise at $C_L = 0.565$ and Mach=0.62 at 39,000 ft

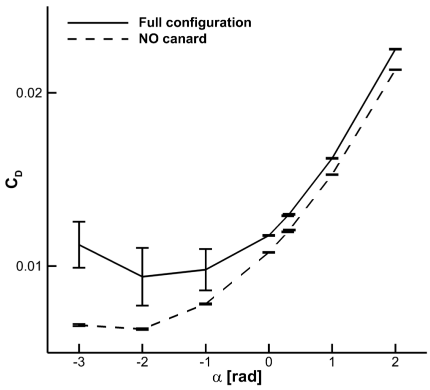
Fig. 6 Euler solutions from CEASIOM

Figure 7 shows the forces and moments predicted for both the full and the canard–off configurations from Euler solver in CEASIOM. The canard is very small that only produces slight lift, so the total lift from both configurations are quite close. We see significant differences on C_D and C_m for both configurations. Note that the error bars showing maximum deviations of the last 500 iterations indicated very poor convergence for steady flow computed for drag coefficient and pitching moment for negative angles of attack. Hence, the simulations below zero degree angle of attack is computed in unsteady model. This means that the deviation bars for the results of negative angle of attack cases indicates the actual unsteadiness predicted by simulation.

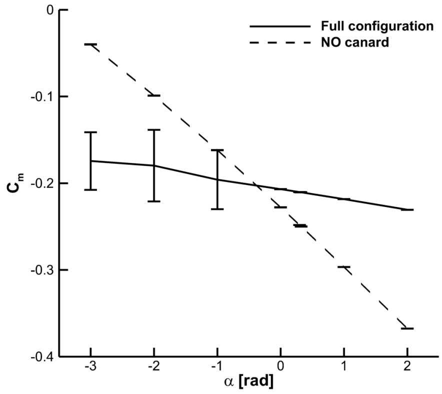
Figure 9 shows the pressure distributions C_p from Euler solutions at trimmed flight conditions for both full & canard–off configurations. For the



(a) Lift coefficient



(b) Drag coefficient



(c) Pitching moment coefficient, reference point at 7.41m from the nose

Fig. 7 Euler solutions at Mach number of 0.62, canard ON & OFF cases; error bars represent maximum deviations during the last 500 CFD iterations

full configuration, the horizontal trim is achieved by deflecting the elevator up (negative) 3.33 deg at α=0.56 deg to maintain the desired lift. For the alternative geometry without canard, the horizontal trim can be achieved at α=0.62 deg with elevator deflection at δ_e=-4.25 deg. The elevator deflection angles are small for both configurations at trimmed flight, however the canard–off aircraft is too stable compared with its fully configured counterpart. During the presented study the center of gravity position was assumed unchanged between canard ON & OFF cases at 23.41 ft from the nose. As figure 7(c) shows, the static margin for the full configuration is around 7.5% MAC, while for the canard–off one is around 42% MAC. Adding the canard moves the aerodynamic center forward that reduces the static margin accordingly.

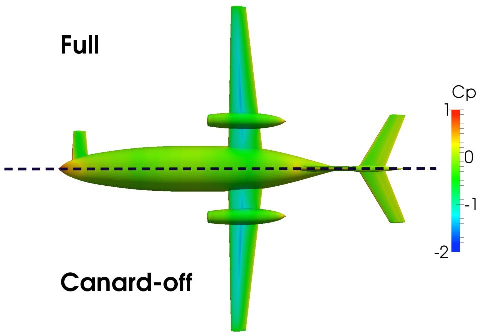
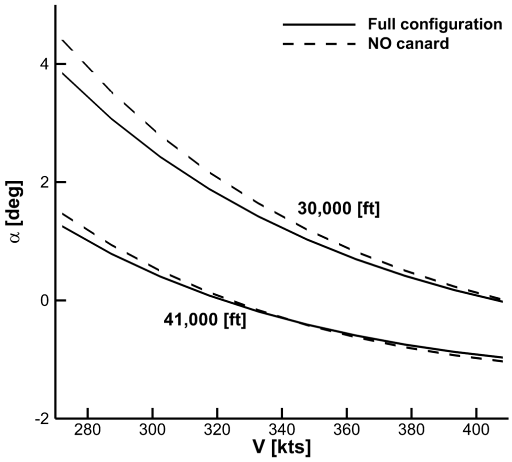
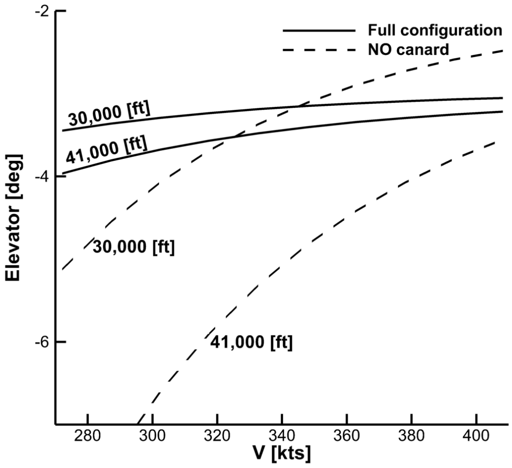


Fig. 8 C_p from Euler solutions for trimmed flight at Mach number of 0.62 (U = 356 kts at 39,000 ft), full & canard–off configurations

Then we would like to ask why both configurations have very close trim angles. If we go back to figure 7(c), we could see that, round $\alpha = 0$ (computed cruise lift coefficient $C_L \approx 0.56$), the pitching moments C_m for both configurations are quite close. This means to get the pitching moments balanced for both configurations require similar efforts, namely, similar nose–up moments provided from the horizontal stabilizer. However, if we expand the speed and altitude from the economy cruise point according to Table 2, we found that although the differences of the trimmed angles of attack between the full and canard–off configurations are within 0.5 deg for concerned speeds and altitudes, the elevator deflections vary significantly for both configurations. From figures 9 and 10 we can see the full canard configuration superiors in the horizontal trim flight: the elevator deflected angles are almost kept constantly at small negative values; while for the canard–off one the behavior is on a common level, the elevator deflects less (in absolute value) as the speed increases.

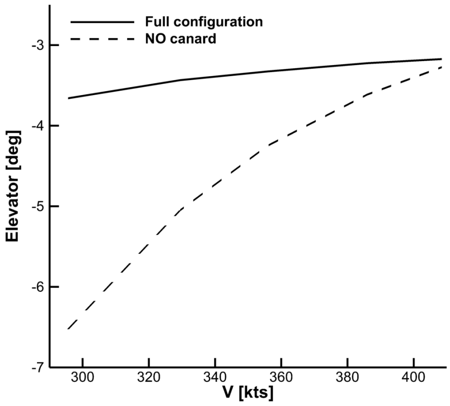


(a) Trim angle of attack

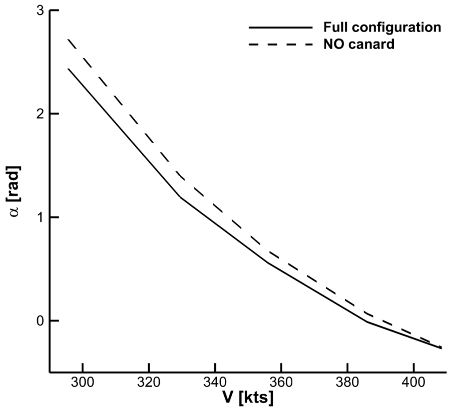


(b) Trim elevator deflection

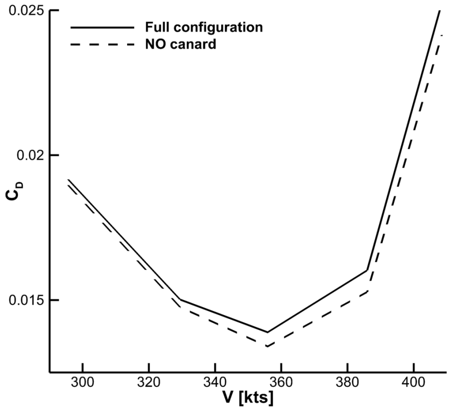
Fig. 9 Longitudinal trim calculated and interpolated/extrapolated from Euler solutions for full (solid line) & canard–off (dashed line) configurations



(a) Trim elevator deflection



(b) Trim angle of attack



(c) Trim drag

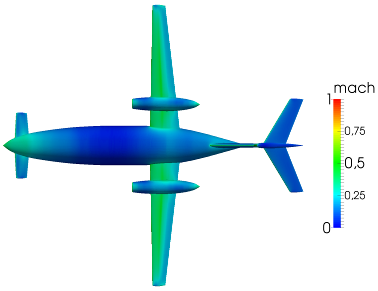
Fig. 10 Economy cruise trimmed conditions at altitude of 39,000 ft, calculated from CEASIOM–Euler

6.2.1 *Innovative design*

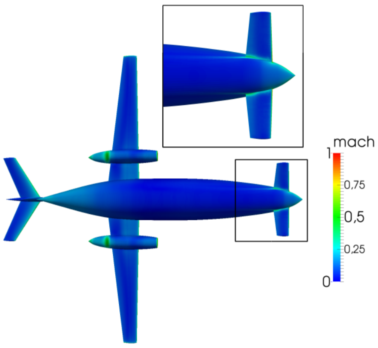
The forward canard contributes to lift, since it is a fixed surface, and the pitch angle of the forward wing is configured so that it always stalls before the main wing. The resulting automatic nose–down effect assures excellent in flight behavior at high angles of attack. These aerodynamic advantages resulting from the aircraft innovative design and construction, cause the airflow to be laminar over a very high percentage of the aircraft wing chord.

6.2.2 *Steady pull–up*

To judge the maneuverability of the Piaggio Avanti, the *elevator per g* is calculated using Euler solver, by maintaining a steady pull–up with a constant angular velocity as if the aircraft were attached to the end of a whirling arm provided very far away. Figure 11 shows the Mach plot for the full configuration aircraft with $3g$ pull–up maneuver predicted from Ceasiom–Euler, at economy cruise condition. The freestream velocity is theoretically zero (but set to very small value, e.g. 1 m/s to assure numerical convergence in CFD computation) and the aircraft is evoked by the angular velocity. Canard provides additional lift, also notice that the flow starts to accelerate at the lower side of root of the canard. This maneuver can be achieved with incremental control force and elevator deflection, in order to climb to a higher altitude, for instance, to the service ceiling altitude.



(a) Upper surface



(b) Lower surface

Fig. 11 Mach contour from Ceasiom–Euler solutions for Piaggio–avanti $3g$ steady pull–up maneuver

Euler simulations for both full and canard–off configurations for $3g$ steady pull–up maneuver are obtained, for flight at 39,000 ft. The *elevator per g* for the full configuration is -1.58 deg, whereas the value for the canard–off configuration is around -4.8 deg, indicating that the full configuration has better maneuverability.

7 Conclusions

The aircraft design stages, conceptual and preliminary, are necessarily collaborative by their very nature. An example design exercise was carried out to illustrate the collaborative aspects of design using the tools Aaa and Ceasiom, working respectively on conceptual and preliminary design. The chosen example is the Piaggio Avanti that has three lifting surfaces and has an advantage in horizontal flight performance. The exercise brought out some of the details involved when exporting the configuration geometry from conceptual design, where the model is usually not water–tight and meshable, to preliminary design where a meshed model is the necessary starting point for further design work. In the example a small computer routine was written to convert the configuration data from Aaa to input data for Ceasiom–sumo so that the configuration was water–tight and meshable [3]. The common–language used to minimize the re–work is a standard for the data describing the aircraft, i.e., the CPACS standard proposed by DLR (see Ref [11]).

Euler simulations for both full and canard–off configurations at steady and level flight conditions were computed. The trim analysis is carried out a number of different cruise conditions, showing that the full configuration with a canard has advantages with minimized elevators angle changes while no (significant) drag was added. The *elevator per g* for the full configuration is much less than the configuration without a canard, when the aircraft is under a steady pull–up maneuver, provided that the neutral point is fixed. All of these above validates that the three–lifting–surface configuration has some aerodynamic advantages than conventional configurations.

In the future a more realistic model with propellers can be made in CEASIOM for Euler simulations. The effects are well modelled for inviscid flow and these should be considered in the design process, one good example is Lötstedt's work [15].

8 Acknowledgments

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