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Design of low-speed aircraft by numerical and experimental techniques developed at DPA

D.P. Coiro*, F. Nicolosi

Dipartimento di Progettazione Aeronautica, Universita' di Napoli "Federico II" Via Claudio 21, 80125 Napoli, Italy

Abstract

In this paper, a number of numerical and experimental tools developed at our Department (Dipartimento di Progettazione Aeronautica from here on called DPA) and devoted to aircraft design for low subsonic flow will be presented and summarized. These tools comprise numerical codes for analysis, design and simulation, and experimental tests performed in our tunnel and particularly devoted to light aircraft design. The importance of developing such tools in house will be highlighted. Examples of light aircraft designed using such tools will be presented and some attention will be paid to the design of a three-surface R/C model aircraft and on the adaptation of numerical codes to the prediction of its behaviour in the non-linear range of angles of attack. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Designing a light-powered aircraft or a sailplane has become easier than in the past due to an increasing number of numerical codes available along with a high level of precision attained with the recent and modern experimental techniques. In spite of all that, using tools developed by third parties, surely leads to difficulties or inability to handle particular cases that will inevitably appear during the design phase of a new aircraft. This is particularly true in view of the fact that to perform a successful new design this has to be competitive and very well done and the best way to be sure is that this can be accomplished by developing or adapting proprietary codes and techniques to the specific case under consideration. Obviously, it is almost impossible to develop or to own a number of codes or experimental facilities capable to cover all types of design, but if we restrict our investigations to a limited category of aircraft, we will try to show that this can be done in a relatively easy way. In particular, we will deal with propeller-driven aircraft or with sailplanes

* Corresponding author. Tel.: + 39-081-7683322.
E-mail address: coiro@unina.it (D.P. Coiro).

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and we will show that for this category of aircraft both general (conceptual) and detailed design can be accomplished using a combination of experimental and numerical techniques, all of them being developed in house at our department during the last year. Other authors [1–3] have developed numerical tools to help the designer to rapidly verify the effect of modifying some geometric or aerodynamic parameters on the final designed aircraft. Not only most of these tools are non-modifiable, but they also deal with low angles of attack, giving only a rough estimation of the maximum lift coefficient of the whole aircraft. The numerical tools presented in this paper try to overcome these limitations and we will highlight the necessity of their integration to obtain a complete design process, including the possibility to *virtually fly* the aircraft that is being designed.

2. Numerical 2D codes

2.1. Analysis

As far as airfoil analysis is concerned, it is since 1990 that viscous/inviscid interaction codes are being developed [4]. The inviscid part is treated using panel methods and the viscous part is modeled through integral boundary layer equations (laminar and turbulent) written in direct and inverse form. The actual version of the code (named *TBVOR*) valid for subsonic flow is capable to predict all viscous (mono and multi-component) airfoil characteristics. The code is based on viscous/inviscid interaction and is capable of evaluating airfoil aerodynamic coefficients also when strong interactions are present on the airfoil such as laminar separation bubbles and large areas of turbulent separation [5]. The code has been developed mainly to predict airfoil characteristics in stall and also in post-stall conditions, adding an inviscid point vortex at the airfoil-trailing edge to model the vorticity present in the wake at high angles of attack and with large separated areas.

2.2. Design

Based on the same 2D flow solver, *DESAIRF* is a two-dimensional design code that employs conjugate search methods to design the airfoil shape (mono- or multi-component) once the objective function, subject to user-specified constraints, has been specified [6]. It can be considered as a multi-point viscous design code if a proper combination of viscous coefficients, each of them with its own *weight*, are specified, for example, at different Reynolds numbers. It is worth noting that due to the capability of *TBVOR* in dealing separated flows, *DESAIRF* can also be used to design an airfoil specifying its maximum lift coefficient.

3. Numerical 3D codes

3.1. 3D lifting surfaces (*NLWING code*)

In order to be able to predict wing aerodynamic coefficients in the non-linear range of angle of attack, an extension of Prandtl's lifting line theory has been performed and extensively tested with respect to both numerical accuracy and reliability [7]. Using experimental or numerical (i.e. *TBVOR*) 2D airfoil aerodynamic characteristics at high angles of attack it is possible to evaluate wing aerodynamics up to stall and post-stall conditions and estimate the wing maximum lift coefficient. Obviously, since *NLWING* is based on Prandtl's lifting line theory, it suffers from the same limitations as the theory does and, in fact, it is applicable to high aspect ratio wings with low sweep angle and in low subsonic conditions. Indeed, these are the cases treated in the present paper, related to light aircraft and sailplane wings.

3.2. 3D panel code

A 3D Panel method based code [8] has been developed *in house* and has been used to evaluate aerodynamic characteristics of fuselage, wing-body and complete aircraft configurations. Aircraft paneling is done through a very *easy-to-use* pre-processor developed ad hoc. The panel code solves the inviscid flow field and evaluates the boundary layer along streamlines on the body surfaces. The viscous/inviscid interaction is performed through normal transpiration velocity on body panels applying to attached flow conditions only (weak interaction). The code is able to evaluate the viscous pressure distribution on the body surface as well as lift, drag and moment coefficients. At high angles of attack unrealistic results (in terms of lift) are expected due to the lack of separated flow prediction capabilities connected to the use of direct boundary layer coupling. The authors have been using panel codes in the last years for the aerodynamic evaluation and design of sailplane and light aircraft fuselages [9,10] and for wing–fuselage junction [11].

Aerodynamic analysis relative to wing–fuselage interference effects and leading edge fairing design for the P96 low-wing light aircraft was shown in [10].Calculation time of the order of 5 min on a Pentium 133 MHz and with the aircraft modeled by about 1500–2000 panels makes 3D panel method an efficient and sufficiently reliable tool to analyze and design light subsonic aircraft.

3.3. AEREO code

AEREO is a menu-driven, user-friendly code capable to predict complete longitudinal and lateral–directional aerodynamic coefficients, static and dynamic stability derivatives and powered aircraft or sailplane performances. Without going into detail about the features of the *AEREO* code (they can be found in [12]) we just remind here that *AEREO* predictions are based on a mix of semi-empirical methods and on the *NLWING* routine described above. *AEREO* also predicts the power effect on aerodynamic coefficients, together with static and dynamic stability characteristics (characteristic modes, frequencies, root locus, etc.). Aircraft and sailplane performances along with manoeuvre and gust load envelopes are also generated as standard output. The *AEREO* code needs two-dimensional airfoil aerodynamic coefficients as functions of angles of attack and Reynolds number. These data are necessary for each lifting surface and they can be either experimental or numerical data. In this last case we use aerodynamic coefficients obtained directly from *TBVOR*. Examples of aerodynamic results as predicted by *AEREO* can be found in [13].

4. Aircraft motion simulation: *JDynaSim*

4.1. JDynaSim

Original code was *DynaSim*, written in C and Fortran – is an interactive flight simulation program written in JAVA [14] language, allowing it to be used by virtually any computer independently from installed hardware and operating systems. The only requirement is that an internet browser, such as Microsoft Explorer or Netscape, should be installed on it along with a shareware software CosmoPlayer. In fact, the code uses the virtual reality modeling language (VRML) , owing to which it is possible to create an environment which allows visualization of 3D aircraft motions resulting from the integration of differential equations of motion. Once communication with VRML has been established, JAVA allows the user to control and interactively *fly* the aeroplane. Much effort has been put in the process of transforming the original C and Fortran subroutines in JAVA language, especially because JAVA is not a language oriented to scientific calculations, but the characteristics of the language makes the code *user friendly* and machine independent.

The practical use of such a tool is connected to the possibility of analysing the aircraft response in real time for both interactive and pre-defined time-dependent control laws. The necessary steps to perform an interactive session are

1. Generation of geometry model (it is not necessary that this corresponds to the real geometry).
2. Generation of virtual reality model to be used by Cosmo Player. This is done through an automatic converter that translates a standard geometry data file in a VRML file.
3. Generation of geometry and mass file input.
4. Generation of non linear aerodynamic data base eventually transforming the available forces from one reference system to the appropriate *JDynaSim* reference system.
5. Run the simulation.

Steps 1 and 2 are necessary the first time only and can be avoided if the user accepts to see the geometry of the model different from the real one.

Step 4 can rely on either experimentally determined aerodynamic forces or on data deriving from numerical data base such as that coming from *AEREO* code. Obviously, data should comprise the whole range of angles of attack, including the non-linear part.

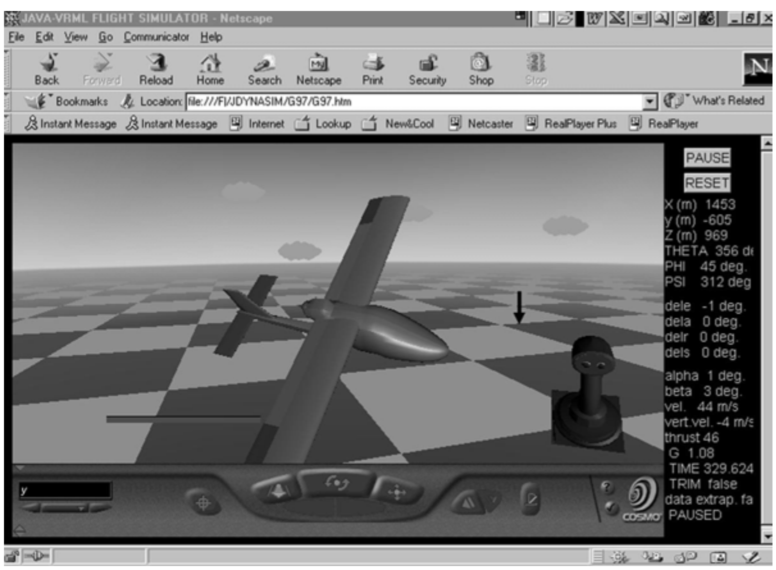

Fig. 1. Screen snapshot of *JDynaSim* simulation relative to G97 aircraft.

Previous work done in this direction [12–14] has shown that this procedure can be reliably used to predict aircraft performances and behavior. To have a more accurate simulation of the flight, atmospheric wind terms, as forcing functions of the motion, have been added in the equations. In particular a simplified thermal model has been introduced in order to investigate the sailplane performances in thermal soaring [14,15]. A screen snapshot of the flight simulation is depicted in Fig. 1.

5. Experimental tools

5.1. Wind tunnel

Wind tunnel tests have been performed in the closed circuit, closed test section (main) wind tunnel belonging to DPA. The rectangular test section is 1.4 m high and 2.0 m wide and the experimental setup allows two-dimensional test on airfoils as well as test on aircraft models. The free stream velocity ranges from 0 up to 45 m/s. Turbulence intensity of the flow at the center of the test section is about 0.1%. Airfoil tests are performed on airfoil models spanning the test section vertically. The model is provided with pressure holes and pressure measurements are performed using a liquid multimanometer (100 tubes) with high-precision optical sensors that allows automatic liquid level reading. This multimanometer has been designed at DPA but it is similar to that of Delft University of Technology, Faculty of Aerospace Engineering, from where the general functioning principles were taken, pressures are measured with an accuracy of 2 Pa. Airfoil drag is measured from wake momentum loss through a wake rake placed behind the model. To perform tests on an aircraft model a three component strain gage internal balance is used. The model is supported by a high stiffness sting which is mounted on a circular guide and can be moved through an electrical engine to change model angle of attack which is acquired through an electric inclinometer. All data are processed in real time by a PC. The maximum tunnel speed (around 45 m/s) allows a Reynolds number for aircraft models (based on wing chord) of about 0.6 million. Since the Reynolds number is rather low, transition strips have been placed on the model at locations predicted by numerical codes to simulate the correct flow transition on the real aircraft. Standard wind tunnel boundary correction procedures reported in [16] have been applied to raw test data. Two-dimensional tests on airfoil models can be performed at a Reynolds number between 1 and 2 million depending on model chord.

6. Tools integration

As already said, in order to perform an efficient and good design, it is necessary to integrate, as much as possible, all mentioned tools. For example, it is unthinkable to perform accurate numerical calculations regarding the effect of the fairing of a wing–fuselage junction, while it is plausible to perform this type of *fine tuning* through model testing in the wind tunnel. In fact, intelligent use of the combination of numerical and experimental tools certainly leads to a sort of design procedure standardization that becomes relatively easy to be extended to new and maybe unconventional aircraft configurations. And this is the reason why the tools should be developed as

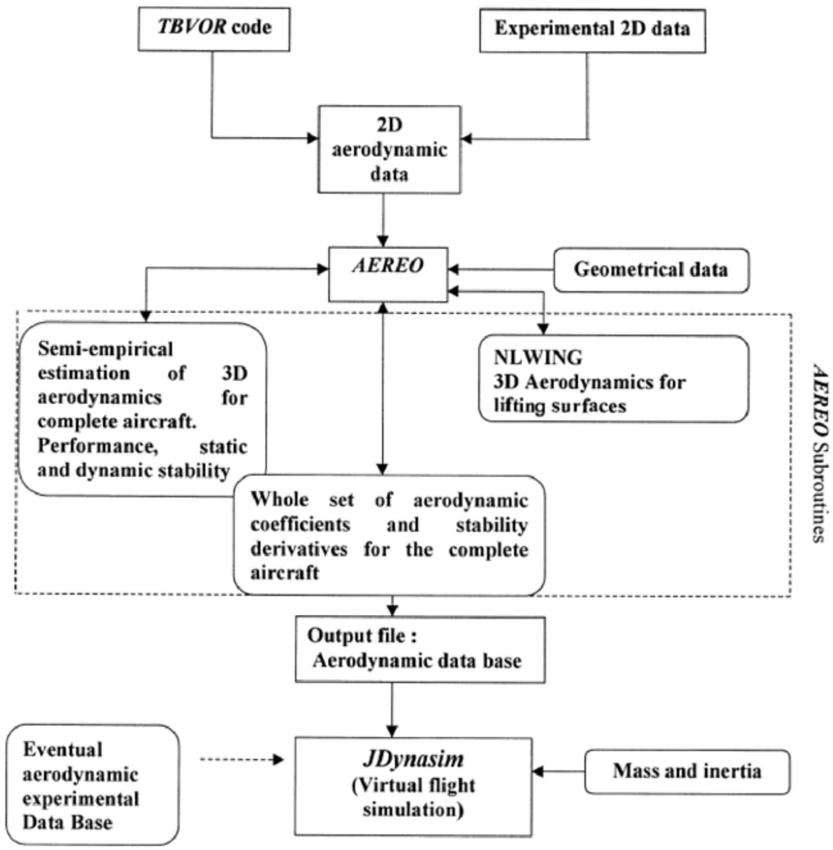

Fig. 2. Flow chart of the tool integration.

much as possible in house since it is difficult or even impossible to modify or adapt a third party tool which is not totally controlled by the designer. As far as (part of) numerical and experimental tools are concerned, these have been integrated following the flow chart shown in Fig. 2.

It is clear how the designer can go through the process as many times as he wants due to the rapid answer that each component of the process will provide to him and it is also clear how each part can be easily modified and adapted at a new situation should this appear necessary during any design loop.

7. Applications

7.1. G97[1] light aircraft

G97 is a recently designed and built light aircraft; a 3D-view drawing of the aircraft along with its main characteristics are depicted in Fig. 3 and Table 1.

[1] G97 light aircraft is built by S.A.I. S.r.l., Via Bottazzo 38, Napoli, Italy.

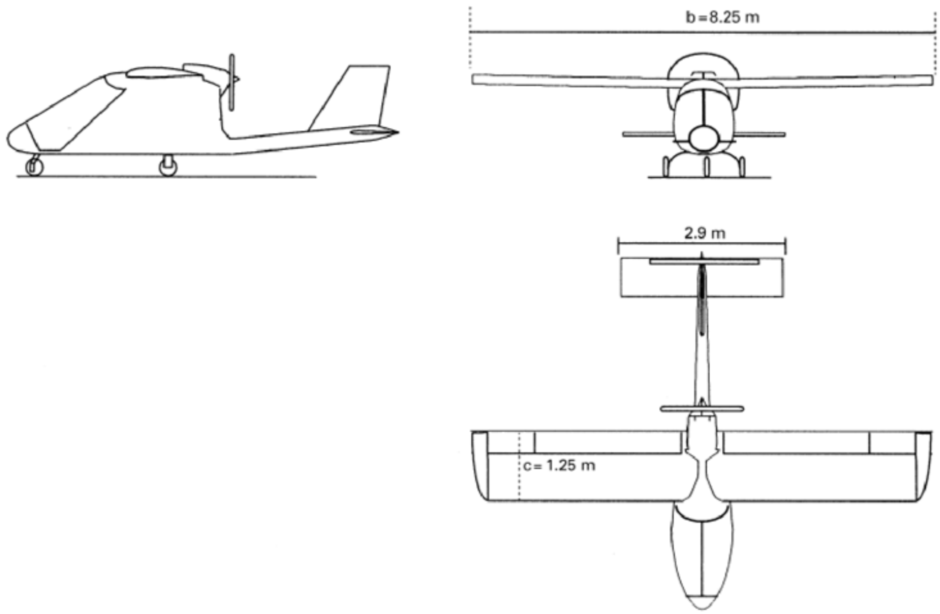

Fig. 3. 3D-view drawing of S.A.I. G97 light aircraft.

Table 1
G97 aircraft main characteristics

Wing span	8.25 m	Height overall	1.92 m
Wing chord	1.25 m	Wing area	10.3 m^2
Wing aspect ratio	6.6	Empty weight	265 kg
Length overall	6.1 m	Max to weight	450 kg

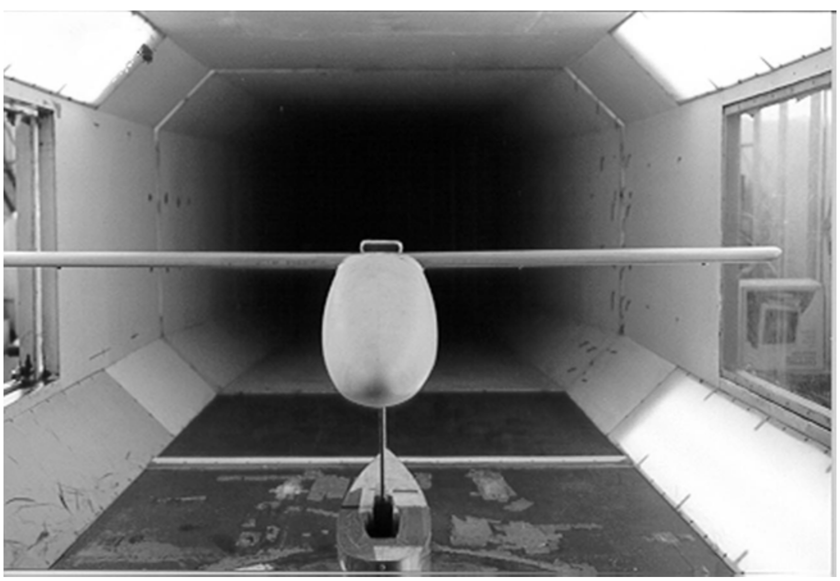

Fig. 4. 3D model installed in the wind tunnel.

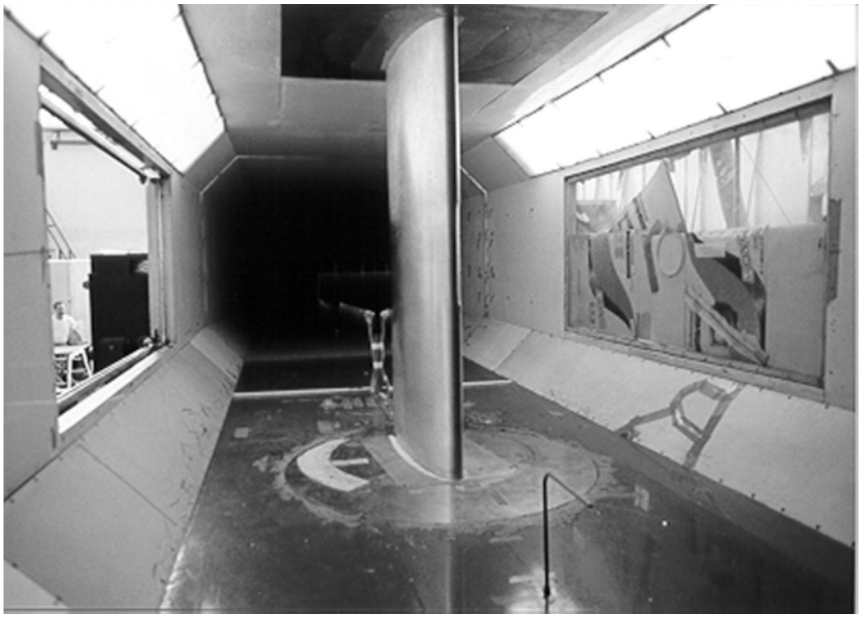

Fig. 5. Airfoil model installed in the test section.

The installation of the aircraft model and of the aluminum airfoil model in the wind-tunnel test section are shown in Figs. 4 and 5.

Comparison between numerical and experimental results on the ad hoc-designed VG 1-13H airfoil are shown in Figs. 6 and 7, where a pressure coefficient distribution along the airfoil chord and lift coefficient versus angle of attack are depicted, respectively.

An example on how 3D panel + 2D boundary layer calculation approximately predicts the transition line on the fuselage is reported in Figs. 8 and 9.

Another example why wind tunnel tests are necessary for fine tuning the aerodynamics is the wing–fuselage fairing presented on Fig. 10, with the corresponding drag reduction shown in Fig. 11. More details can be found in [17,18].

7.2. P92J[2] light aircraft

An example of *AEREO* capabilities is shown in the following figures where wind tunnel and flight results are compared to numerical ones for the popular light aircraft P92J (Fig. 12) whose main characteristics are reported in Table 2, along with those of the P96 (low wing version).

7.3. R/C canard model

An example of adaptation of the tools integration as explained above is provided by a canard R/C model design which has been totally performed through the process presented in this paper

[2] P92J and P96 light aircraft are built by TECNAM (www.tecnam.com).

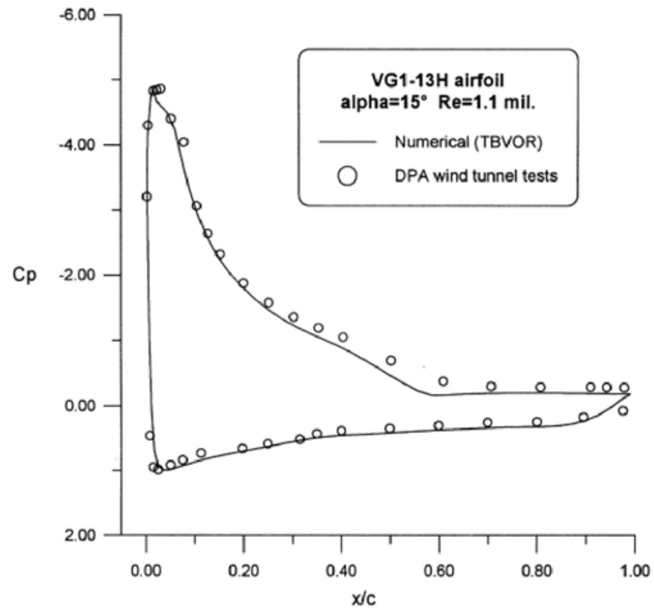

Fig. 6. Numerical and experimental pressure distribution at alpha = 15°, Re = 1.1 million.

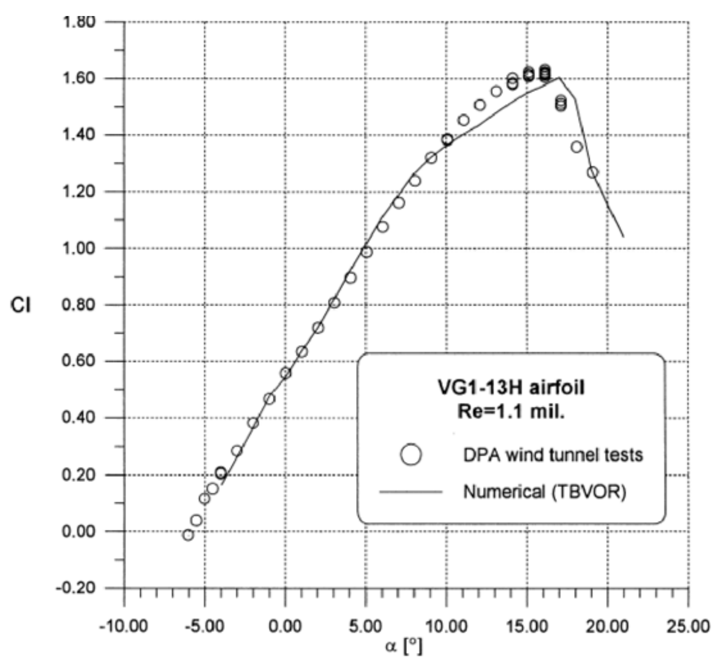

Fig. 7. Numerical and experimental lift coefficient curve for Re = 1.1 million.

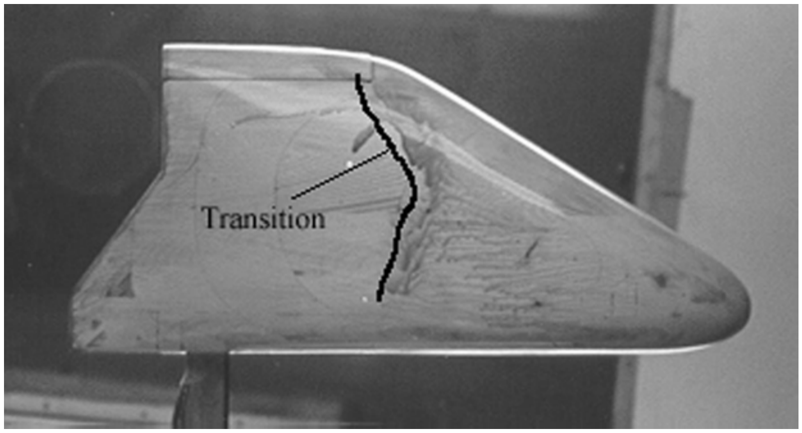

Fig. 8. Flow visualization on the fuselage at alpha = 0°, Re = 0.6 million.

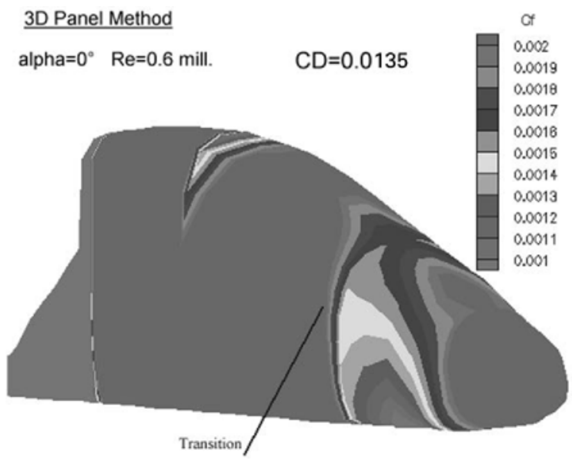

Fig. 9. Skin friction coefficient distribution on the fuselage, alpha = 0°, Re = 0.6 million.

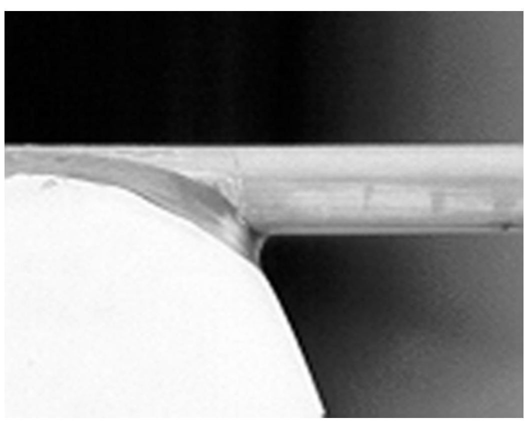

Fig. 10. Wing–fuselage junction fairing.

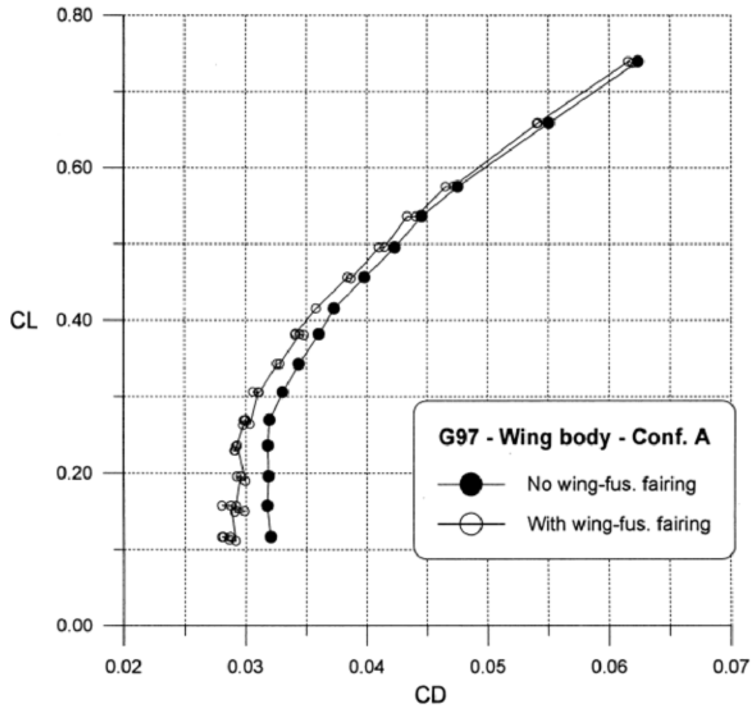

Fig. 11. Effect of wing–fuselage junction fairing on drag.

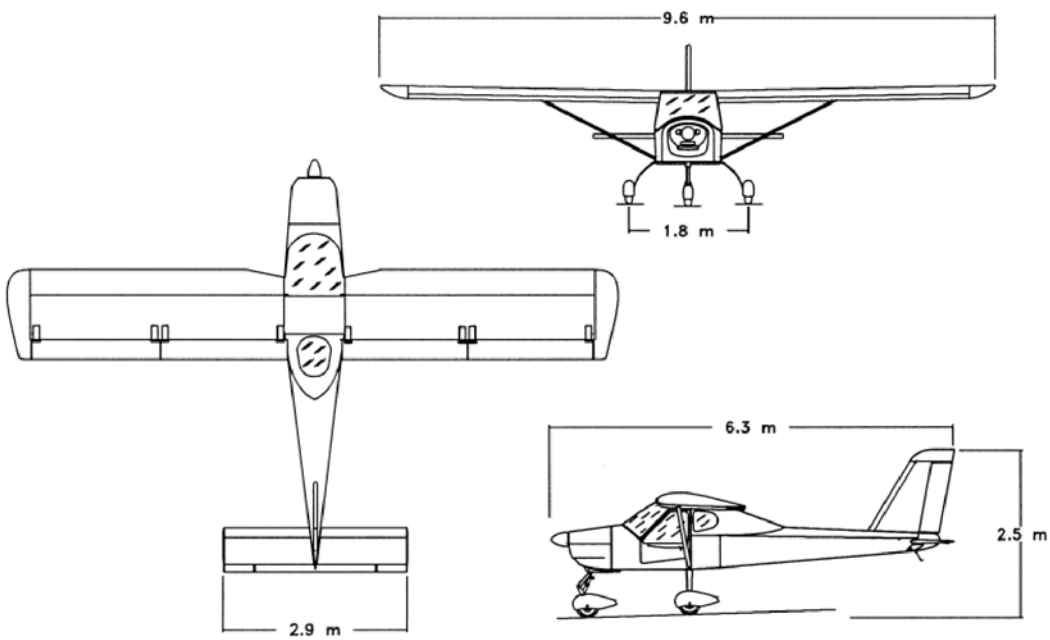

Fig. 12. 3D-view drawing of Tecnam P92J light aircraft.

Table 2
Tecnam aircraft main characteristics

Characteristics	P92 J	P96 Golf
Wing span (m)	9.6	8.70
Wing chord (m)	1.4	1.40
Wing area (m^2)	13.2	12.18
Aspect ratio	6.98	6.21
Wing dihedral angle (deg)	1.5	5
MTOW (kg)	520	450

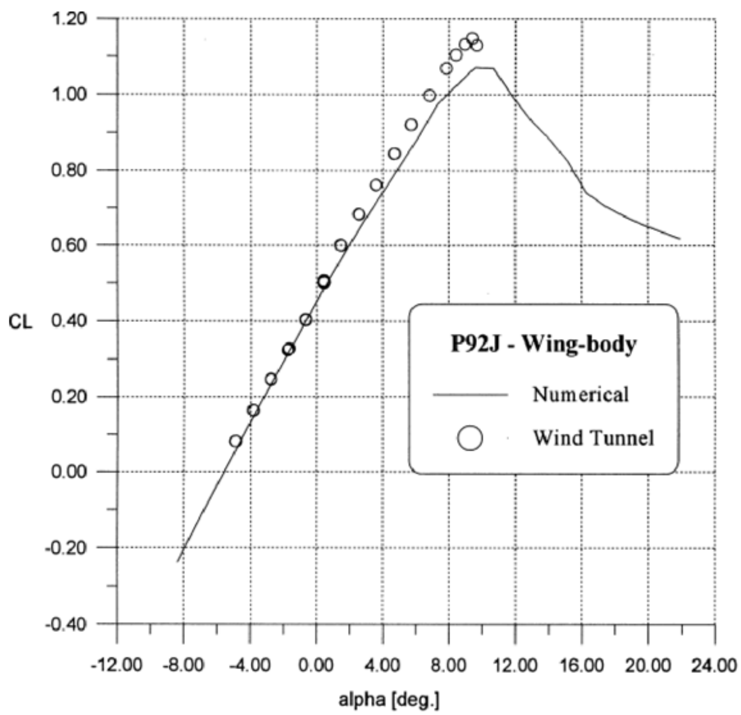

Fig. 13. Numerical and experimental model lift coefficient for Re = 0.6 million.

(Figs. 13 and 14). The whole model, along with a 3D panel + boundary layer pressure distribution on it, is shown in Fig. 15 and it is currently being built.

In this case an adaptation/modification of NLWING routine has been necessary in order to take in account the correct mutual influences of all three lifting surfaces. Then a specific iterative procedure has been set up to predict correct upwash and downwash angles relative to the three lifting surfaces in the whole range of angles of attack. This is in fact necessary if we want a close estimation of the maximum lift coefficient of the airplane and then of the stall speed which is a critical point especially for configurations like R/C model airplane. The procedure is

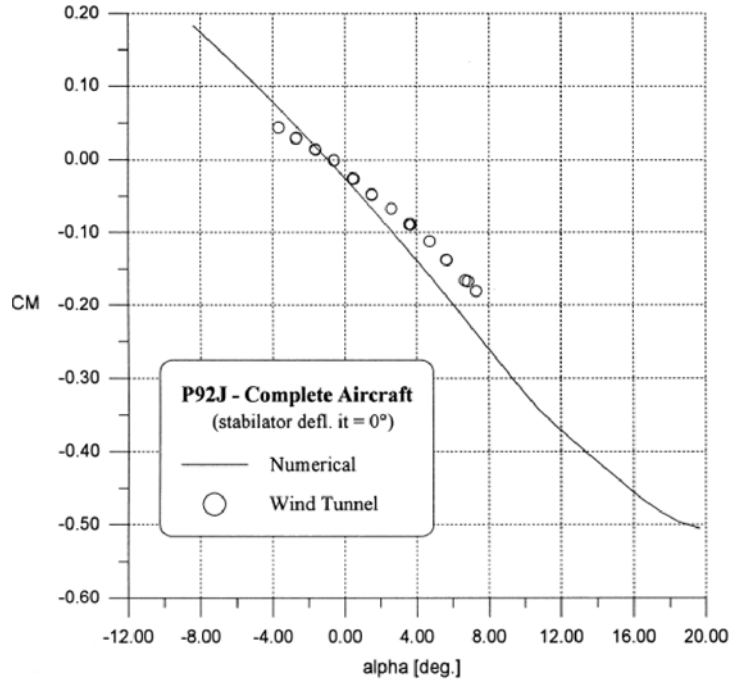

Fig. 14. Numerical and experimental model moment coefficient for Re = 0.6 million. Moment reference point is at 25% of wing chord.

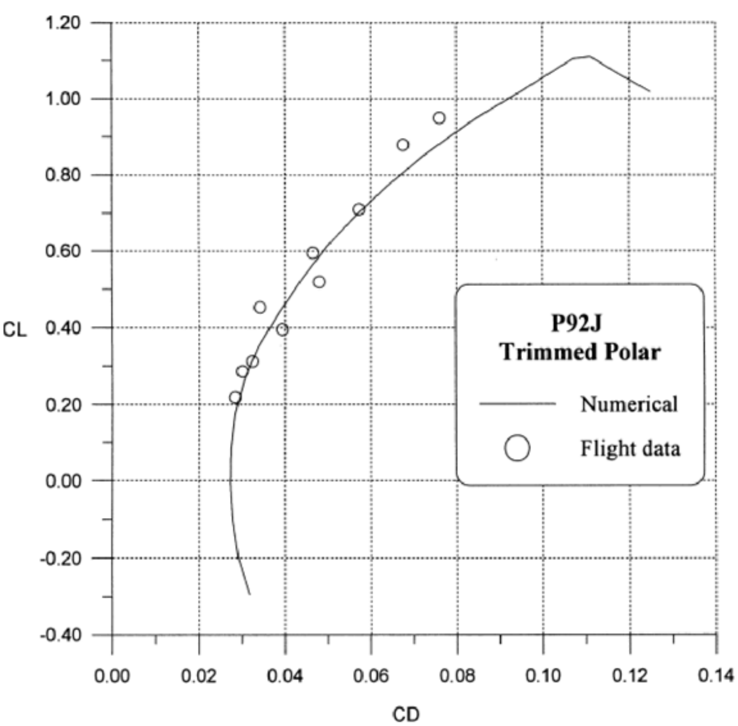

Fig. 15. Numerical and flight–test obtained aircraft polars.

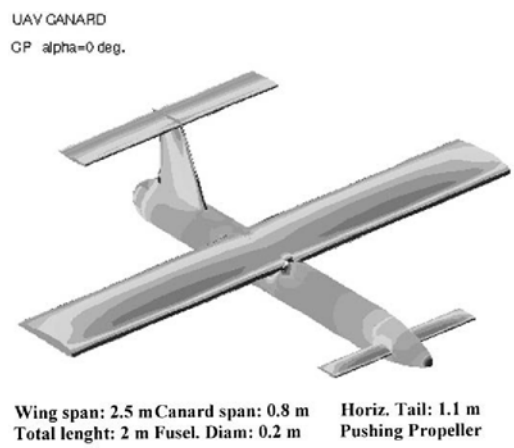

Fig. 16. *AEREO* improvement: iteration loop for the evaluation of the mutual influence of three lifting-surfaces.

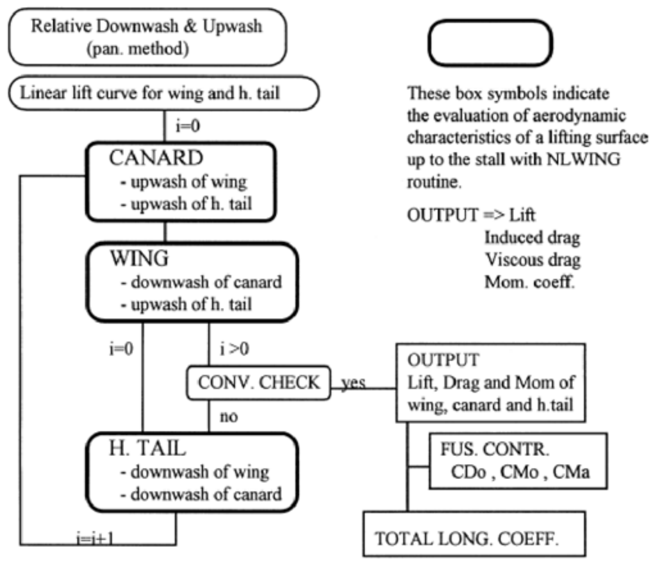

Fig. 17. Canard upwash angle induced by wing.

as follows:

1. 3D panel method is used to evaluate the distribution of downwash/upwash angles along the lifting surface each of them characterized by CL = 1 (see Figs. 16 and 17).
2. The shape of the distributions is taken as basis to be scaled at different lift coefficient values.
3. The scaled-induced angles are assigned spanwise to *NLWING* routine and this is run for the three surfaces providing new lift distributions.
4. This will, in turn, modify again the induced upwash/downwash angles relative to each surfaces.

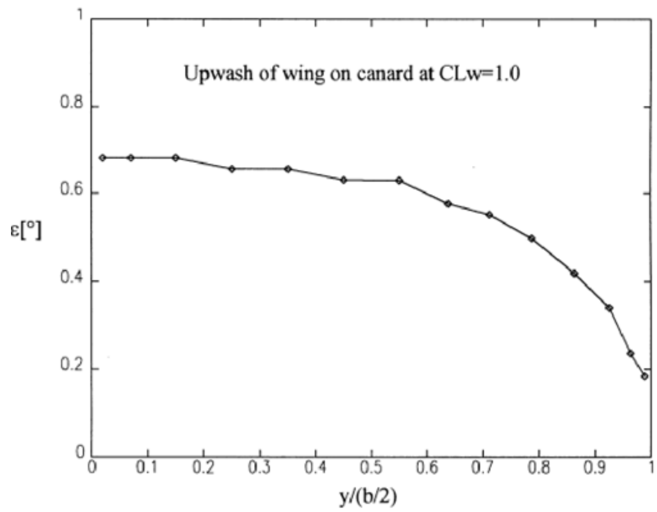

Fig. 18. Canard model aircraft.

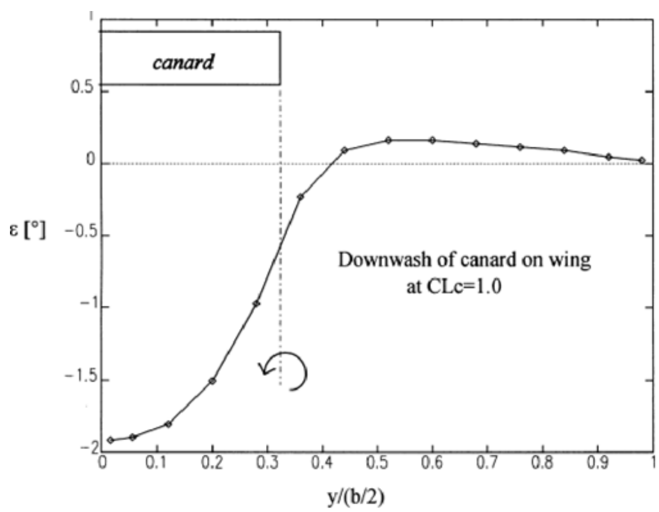

Fig. 19. Wing up- and downwash angle induced by the canard.

5. The procedure (steps 3 and 4) is repeated for each angle of attack until a satisfaction convergence level is reached and all three surfaces reach at the same time global equilibrium values for both induced angles and lift coefficients.

The flow chart reported in Fig. 18, outlines this procedures.

The complete aerodynamic longitudinal aerodynamic coefficients, as they come out from AEREO code, are reported in Figs. 19–22 where the equilibrium curves are shown as well.

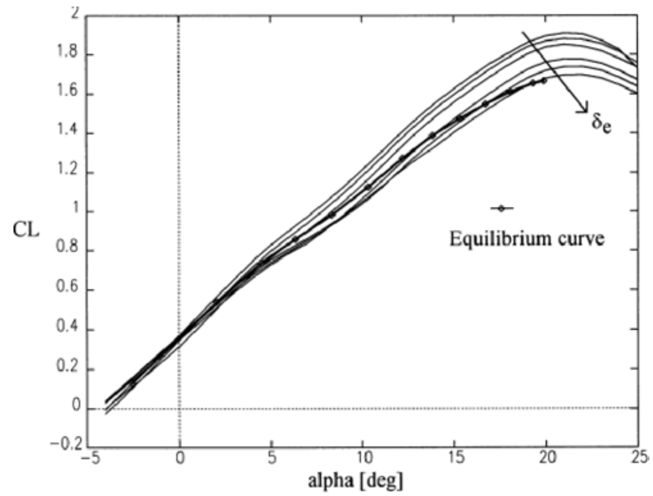

Fig. 20. Lift coefficient curves for canard model at different elevator deflections. Re = 0.6 million.

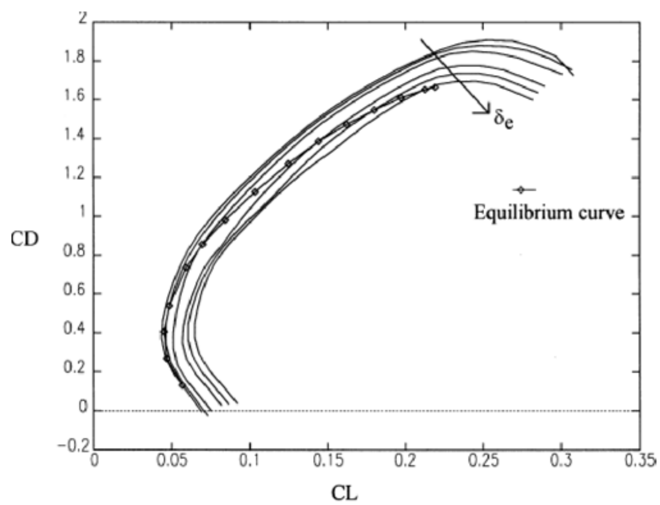

Fig. 21. Drag polar curves for canard model at different elevator deflections. Re = 0.6 million.

8. Conclusion

In this paper a number of experimental and numerical methodologies are applied to light propeller-powered aircraft and sailplane designs have been shown. All numerical codes have been developed in house by the authors at DPA. The importance of the possibility to adapt or modify the numerical tools to specific needs has also been highlighted. It has also been proposed to integrate the different numerical tools in such a way that a designer can go many times through the design process and get answers in a reasonable time. He also has the possibility of virtually flying

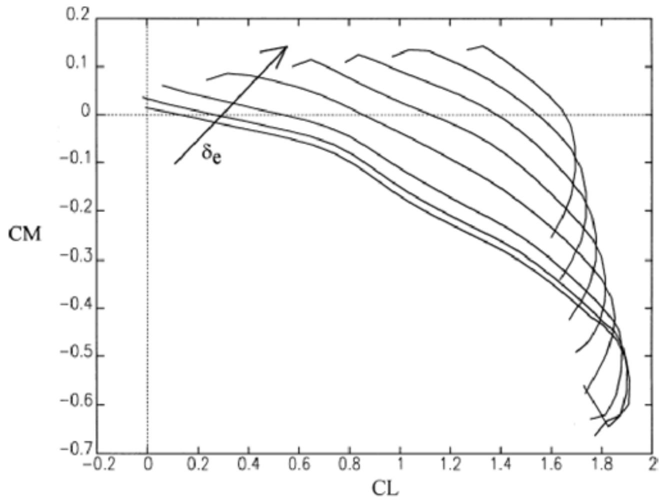

Fig. 22. Moment coefficient curves for canard model at different elevator deflections. Re = 0.6 million – moment reference point is at 13% of wing chord.

the aircraft that is being designed using the interactive and platform independent flight simulation code *JDynaSim*. Nevertheless, it has also been shown how some detailed design aspects still have to be performed through experiments that have been performed in the wind tunnel belonging to DPA. Applications of the methodologies to the light aircraft P92J and G97 and to a canard R/C model aircraft have been presented. Development of a structure/aerodynamics coupling tool and its integration into the design process is ongoing.

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