AERODYNAMICS, DYNAMICS AND PERFORMANCE PREDICTION OF SAILPLANES AND LIGHT AIRCRAFT

By D.P. Coiro and F. Nicolosi

Presented at XXV OSTIV Congress, St. Auban, France

Abstract

Aerodynamic characteristic prediction is of crucial importance in order to be able to estimate aircraft performances and dynamic behavior. In this paper capabilities of a PC based computer code (named AEREO) to predict longitudinal and lateral aerodynamic characteristics of light aircraft and sailplanes is presented. Semi-empirical methods are used as main thesis, together with more sophisticated procedures for high angles of attack or more in general non linear conditions.

Aerodynamic prediction is performed in different steps. In a first preliminary step, wing, vertical and horizontal tail airfoils aerodynamic characteristics prediction is performed with a 2D code which has been developed at DPA (Department of Aeronautical Engineering). The output are Cl(a), Cm(a), Cd(a), curves up to stall and post-stall conditions. These curves along all necessary geometrical aircraft characteristics are the input to the AEREO code. In this code an iterative numerical procedure based on the lifting line Prandtl theory is then used for the prediction of loads and moments for the wing and horizontal tail up to stall and post-stall conditions. The aerodynamic curves coming from the AEREO code are used as input for the aircraft motion simulation code called DYNASIM which returns aircraft motion and dynamic behavior for a user specified control law or for an imposed air disturbances. This code solves the general 6 degrees of freedom equations using non-linear aerodynamics and it offers the possibility to fly the airplane using the mouse as stick command.

Simulation of a stall maneuver of a light single engine aircraft has been performed and numerical results are in good agreement with flight data. Comparison between predicted and flight sink polar has been shown for the ASW-24 sailplane.

Introduction

During the design phase of a light aircraft it is very useful for the designer to have a reliable and fast tool for the prediction of both aerodynamics and performances of the subject plane.

Usually semi-empirical procedures are employed to obtain aerodynamic characteristics especially in the linear range.

The idea behind the present work is that of using fast and accurate enough tools to predict the aircraft aerodynamics improving their semi-empirical nature, when it is possible, through the implementation of ad-hoc procedures which can extend the results validity to the non linear range. Standard semi-empirical methods have been abundantly used in the past, see Reference [1,2,3,4,5], but none of them tries to extend the results also to the non-linear range of angles of attack. Indeed, it is in the author's opinion, that this extension can be done without sacrificing too much in terms of computer time and obtaining accurate enough results for the established objectives.

The work to be done is that of recognizing those aspects of aerodynamic predictions that can be easily improved and that of integrating these parts to the standard semi-empirical procedures verifying the quality of the obtained results.

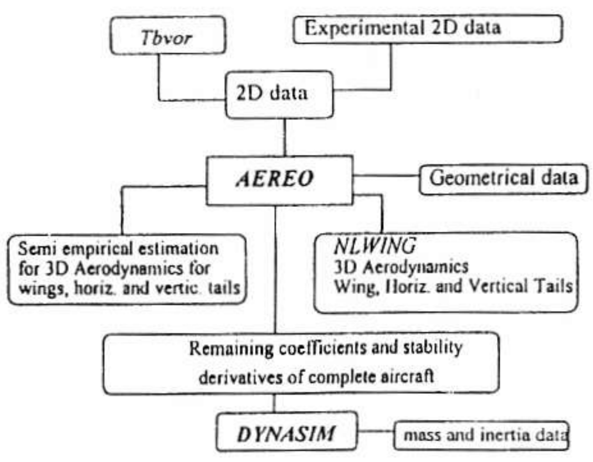
The first part that can be improved concerns airfoils aerodynamic characteristics prediction.

Aerodynamic wing behavior is mainly dependent on airfoil aerodynamic characteristics and especially in the case of sailplanes it can be said that the "airfoil makes the difference." Then a good estimation of airfoil lift, drag and moment is of crucial importance in order to have a good prediction of aircraft aerodynamics.

It is since 1985 that a code based on viscous/inviscid interaction is being developed, see Reference [6,7]. The actual version of this code, named TBVOR, as detailed in the next paragraph, is capable to predict all viscous airfoil aerodynamic characteristics also when strong interactions are present on the airfoils such as laminar separation bubbles and large turbulent separation areas.

Then, knowing wing, horizontal and vertical tail airfoil characteristics, the wing and tails complete loads can be calculated. In order to be able to predict wing's loads in stall and post-stall conditions an extension to the standard Prandtl lifting-line theory has been done following the guidelines suggested in Reference [8]. The limitations of such an approach are that well known of Prandtl lifting-line theory but the quality of the results in the non-linear range of angle of attacks is more than acceptable.

Fuselages and wings/body intersections are treated in semi-empirical manner. To this aim hundreds of graphs have been spliced out and put as database form to be used by AEREO code. The final output in look-up table's type contains longitudinal and lateral aerodynamic coefficients



Sketch 1 : Flowchart of the simulation codes in function of the angle of attack a, of side slip angle b and of control surface deflections.

The output of AEREO code is then used as input to DYNASIM code that performs the dynamic simulation of the aircraft motion. Besides the aerodynamic input, DYNASIM needs aircraft geometry and mass and inertia data. DYNASIM can be run either in text mode or in graphics mode and in this last case, the user can fly the airplane using the mouse as stick command.

Sketch n. 1 shows the organization of a complete calculation set.

Aerodynamics prediction

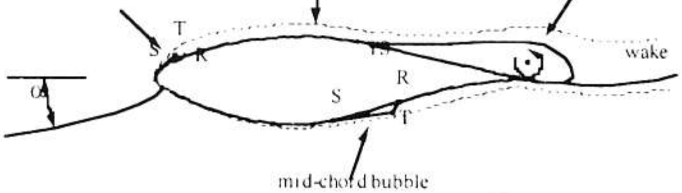
2D Data

The two-dimensional characteristics of the airfoils employed in the wing, horizontal and vertical tail can be either assigned as experimental values obtained through airfoil model wind tunnel tests or calculated via TBVOR code (Ref. 6,7).

It is evident that in the design phase reliable numerical prediction is necessary to check the influence of airfoil aerodynamics on aircraft aerodynamics, performance and dynamic behavior.

Importance of TBVOR code both in having good prediction of performances of an existing aircraft or in choosing the best airfoil for a specific aircraft design goal is clearly put in evidence.

TBVOR code has been developing during recent years by one of the authors of this paper and by Dr. Paolo Dini. Following here is just a short synthesis on the theory on which the code is based on. The main feature of TBVOR code is its capability to deal with laminar and turbulent separated flow. The turbulent flow separating from the upper (downwind) surface of an airfoil near the trailing edge, at high angles of attack, remains near the surface of the airfoil and contributes to a thicker wake than is present in attached flow conditions. This separated flow harbors a net vorticity akin to the starting vortex, where both are a direct consequence of conservation of the angular momentum of the flow. Unlike the case of attached flow at low angles of attack, however, this vorticity is not swept downstream but hovers over the trailing edge, directly affecting the circulation of the airfoil. We model this distributed vorticity with an inviscid point vortex whose strength and location we were able to correlate successfully to flow



Sketch 2. Schematic of an airfoil in stall showing the vortex and the laminar separation bubbles.

parameters such as the extent of turbulent separation and the pressure level at separation. The vortex is shown schematically in sketch n. 2, together with the laminar separation bubbles.

The most important assumption of the theory on which TBVOR code is based, is also that the flow over an airfoil in post-stall condition can be modeled accurately and reliably by an interactive boundary-layer method, complemented only by our inviscid point vortex over the trailing edge. In other words, our results seem to indicate that the basic boundary layer assumptions of negligible pressure gradients normal to the airfoil surface and or small second streamwise derivative of the velocity still hold even within the massively separated flow over an airfoil in post-stall. Apparently, the only low-order effect not modeled by a standard boundary-layer method is the vorticity of the separated flow, and this is well accounted for by the inviscid vortex which is discussed more fully in Reference 7. Thus, to determine the physical solution for given conditions our method relies on matching the inviscid and boundary-layer flows through a standard interactive algorithm, the details of which can be found again in References 6,7.

It is worth mentioning here that the main new calculation feature related to the inviscid flow (the calculation of which is based on panel method) is the automatic addition and redistribution of the points defining the panels, in order to improve the resolution of the bubble flow field. Because of the large gradients present in the bubble region, the program could not converge without adaptive variable paneling. After approximately 40 iterations the points are automatically redistributed based on the current bubble separation and reattachment locations as calculated by the boundary-layer method and the calculations are started over and brought to convergence.

Laminar Part of Boundary Layer and Separation Bubble

The laminar boundary layer is solved in the direct mode (by specifying the inviscid velocity as a function of arc length) for attached flow conditions and in inverse mode (by specifying displacement thickness as a function of arc length) when laminar separation occurs and then bubbles develop. In both cases the governing equations are complemented by closure correlations for friction coefficient C_f, for dissipation coefficient C_D and for shape factor H_{12}, all expressed as functions of the second shape factor $H_{32} = \partial_3/\partial_2$ where d_3 is the energy thickness and d_2 is the momentum thickness. As detailed in Reference 9, these correlations are derived in part using the Falkner-Skan family of velocity profiles. The reason the attached laminar boundary-layer closure relations are obtainable in a fairly straightforward way is that the Falkner-Skan attached profiles depend only on one parameter, which can be eliminated from the expressions for these three variables.

For separated flow, also the inverse boundary layer equations require closure correlations. The most popular choice has been to use the reversed Falkner-Skan profiles as, for instance, was done in Reference 10. The laser-Doppler anemometer (LDA) measurements inside the bubble, however, indicate that the reversed Falkner-Skan profiles are not a good representation of the separated shear layer in the laminar part of the bubble. Rather, Fitzgerald and Mueller suggest using the two parameter, reversed Green profiles, that were originally developed to model the turbulent wake downstream of a blunt trailing edge. This fact is not surprising once we realize that the separated flow in the laminar part of a short bubble is near-stagnant and, therefore, causes very small negative skin friction. These findings were confirmed by a finite-difference calculation performed by Drela, who found profiles very similar to the Green. From these profiles Drela was able to derive a closure correlation for the skin-friction coefficient, which has been used also in TBVOR.

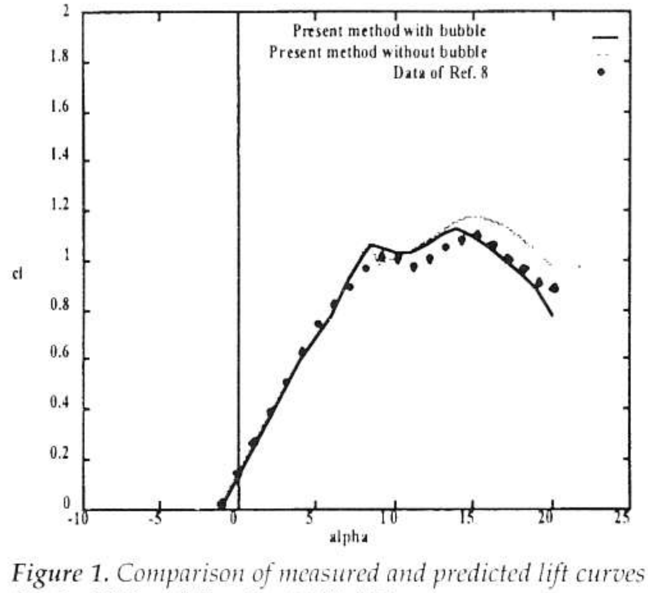


Figure 1. Comparison of measured and predicted lift curves for the S809 airfoil at Re=2.000.000

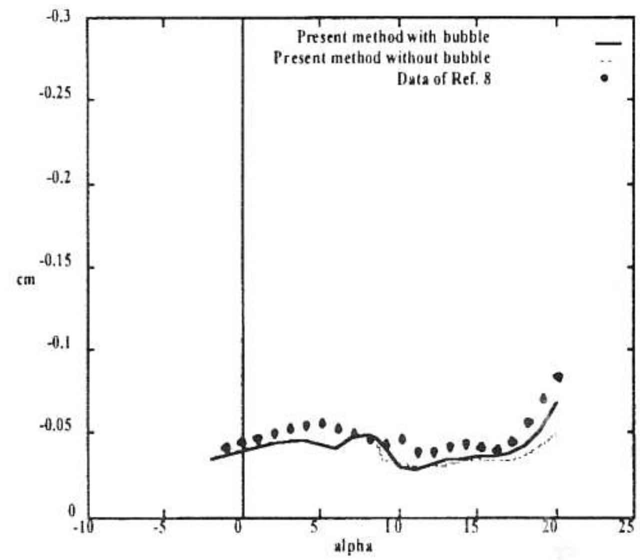


Figure 2. Comparison of measured and predicted moment curves for the S809 airfoil at Re=2.000.000

As discussed in full in Reference 11, the Green profiles are determined by two parameters and as it may be expected, the greater flexibility afforded by the two parameters also brings added complexity in determining adequate closure correlations. Now one of the closure correlations is a new and important addition to the overall model, and more details of the derivation can be found in Reference 7.

Transition

Transition is modeled by means of the linear stability, or e^n, method described in Reference 12. This method relies on a database of stability characteristics of the Falkner-Skan profiles for attached flow and of the Green profiles for separated flow, and therefore provides a transition prediction method fully compatible and consistent with the boundary layer method and with the bubble model. Unless otherwise noted, in the results below the value of the amplification factor used at transition is n = 11.

An example of TBVOR capability in calculating 2D aerodynamic characteristics is shown in Figure l and in Figure 2 where numerical results, showing Cl and Cm curves in function of the angle of attack, are compared to experiments performed at Delft University on S809 wind turbine airfoil at Re=2.0 million.

Curves at different Reynolds can be input to AERO code.

3D Lifting Surfaces: NLWING subroutine

As already said, in order to be able to predict the aerodynamic coefficients in the non-linear range of angle of attack, an extension of the Prandtl's lifting line theory has been performed. In fact the Prandtl's theory can be used in an iterative manner. It was stated that numerical regression and interpolation have to be used to avoid incorrect results and to smooth out the singularity present at wing tips. A deep numerical investigation of this type of problems and on the convergence of the iterative procedures was performed.

Finally a study on the relation between the relaxation factor and number of points needed to obtain a converged solution has also been performed and then the code automatically chooses the correct relaxation factor depending on the number of the points input by the user.

NLWING is used to evaluate lift and drag of wing, horizontal and vertical tail for the whole range of angles of attack.

Semi-empirical procedures

The remaining longitudinal and lateral coefficients as well as some static and dynamic stability derivatives are obtained using calculations and interpolations of graphs (References 1,2). The interpolations have been done using bi- and three-cubic spline interpolations. Hundreds of graphs have been entered to form a database needed to obtain the static and dynamic derivatives.

DYNASIM Code

Dynasim [Reference 13] is an interactive graphic code that allows the user to *fly* the selected airplane using the mouse as stick command. The airplane motion can be obtained running the code in batch mode. The solution is obtained solving 12 ordinary non-linear differential equations in which the nonlinear forces are input in multidimensional matrix form and are interpolated at each time instant.

The translational equations of motion are written in the flight path axis system and the rotational equations of motion are written in a fixed body axis system. The equilibrium values of the variables corresponding to the trimmed input condition are first found and then the integration of the differential equations starts. The code can interactively read mouse and keyboard inputs as well as files with command laws assigned in function of time. There is the possibility to record the interactive session performed and then to repeat the maneuver.

In order to have useful information about aircraft maneuver it is very important to have detailed information about the mass and inertia moment that are a crucial input for the code.

In fact, in case of the ASW-24 sailplane, we had to estimate all the glider inertia moments and the results in terms of stall or turning maneuver were not perfectly in accord with real flight sailplane behavior. At the moment of writing this paper, Dynasim has been translated and coded in JAVA and VRML language (JDYNASIM) then becoming totally platform independent and requiring just a normal internet browser, such as Netscape Navigator or Internet Explorer, to be used. It will be soon available on the internet.

Results

A complete study, with aerodynamic prediction, performances and dynamic simulation was performed on P92J light single propeller aircraft and ASW-24 sailplane.

P92J light aircraft

P92J aircraft geometry is shown in Figure 3. The aircraft is a braced high wing light aircraft with a 80 hp engine mounted in the front. The airfoil employed in the wing is a modified Gottinga airfoil.

The calculated lift, and moment coefficient curves in function of the angle of attack and of the stabilator deflection angle are reported in figures 4,5 for the P92J.

In Figure 4 the lift trimmed curve is aslo shown. In Figure 6 the aircraft predicted polars for different stabilator deflections together with the trimmed drag curve is reported.

Some of the remaining lateral steady and unsteady stability derivatives are reported in the Figure 7. It has to be noted that there is the dependence of such derivatives on the airplane angle of attack and thus on its lift coefficient.

Computer time needed to evaluate a complete set of aerodynamic force coefficients is about 5 minutes on a Pentium 133 PC.

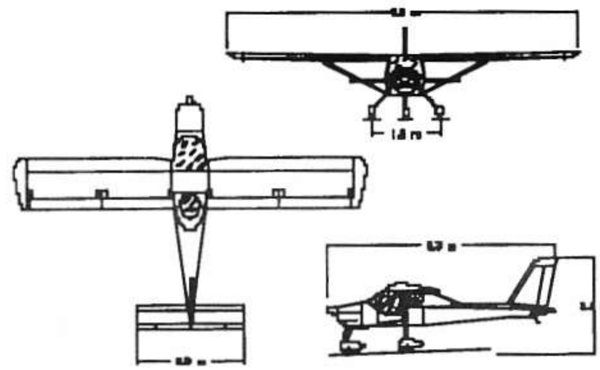


Figure 3. P92J Light Aircraft

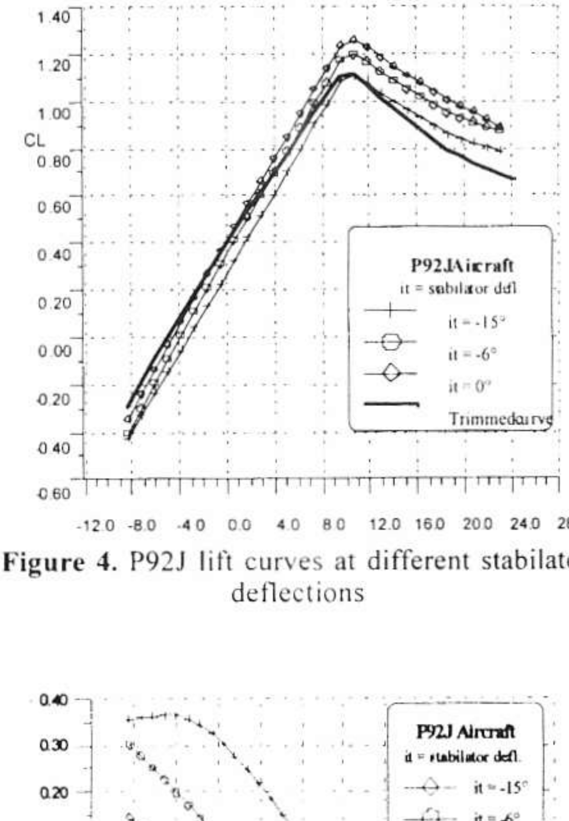


Figure 4. P92J lift curves at different stabilator deflections

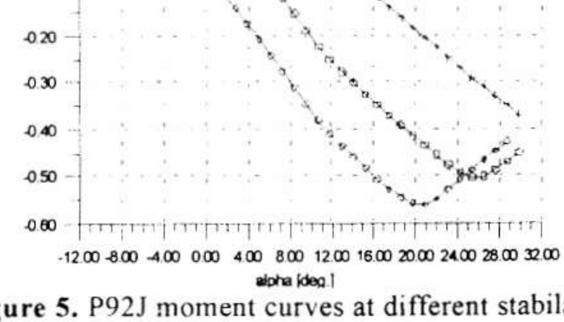


Figure 5. P92J moment curves at different stabilator deflections

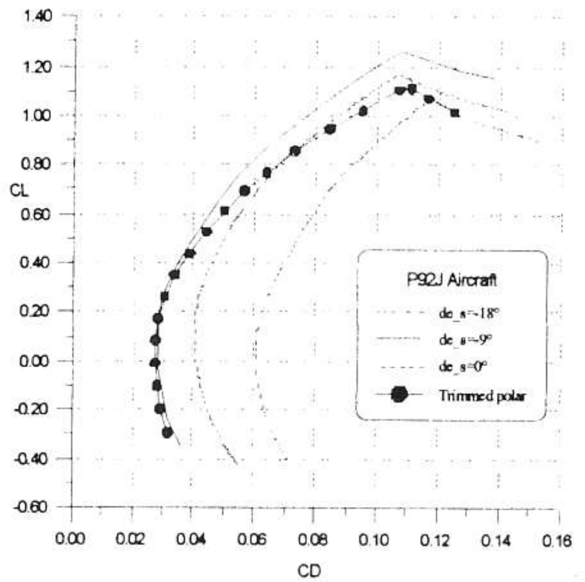


Figure 6. P92J drag polars at different stabilator deflections

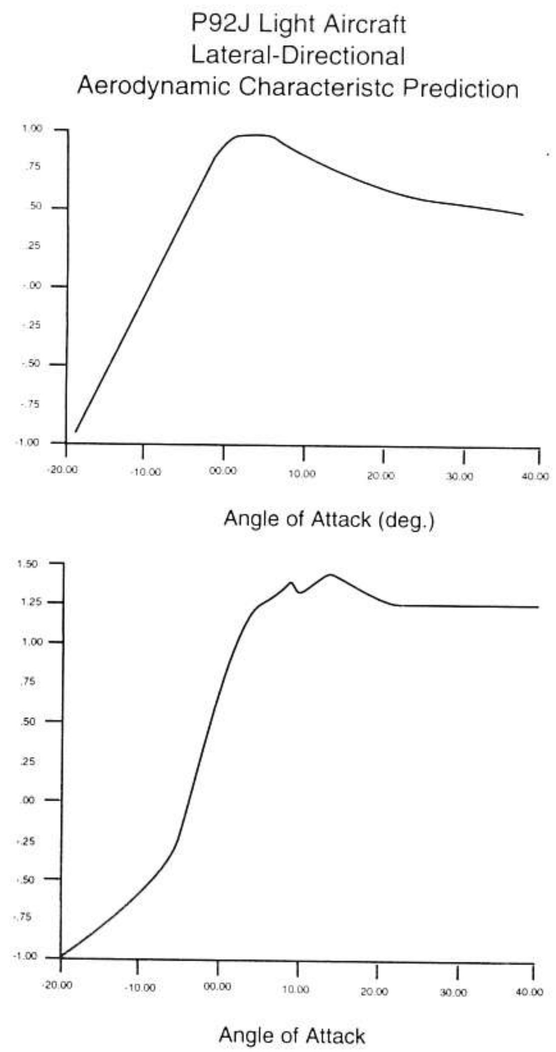


Figure 7. P92J lateral-directional aerodynamic derivatives

P92J Stall Maneuver

The accuracy of the aerodynamic derivatives prediction and dynamic motion simulation was tested comparing numerical obtained results with a flight recorded stall maneuver.

The maneuver is composed by three consecutive power-off stalls which have been used to compare simulated data with flight ones.

Using as input to Dynasim the exact stabilator deflection time-history, the resulting simulated airplane speed in function of time is reported in fig. 8 and it is compared to flight data.

It appears that there is a general good agreement, especially for the second stall maneuver. The stall speed is very well predicted for all maneuvers.

Comparison of measured and predicted g acceleration values shows that also in this case the g-break for each stall is correctly predicted.

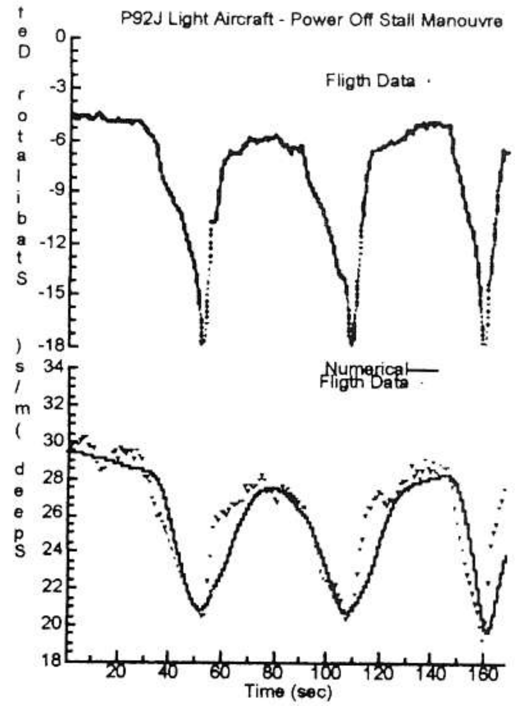
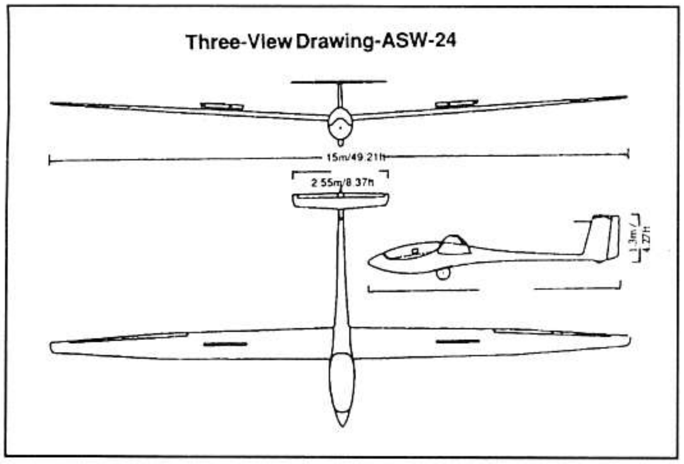


Figure 8. P92J stall manouver

ASW-24 sailplane

ASW-24 sailplane is a 15-meter sailplane of which partially data were available. The geometry of this glider is reported in Figure 9. The main problem was in particular that of moment of inertia prediction. Due to the big wing span, the x and z inertia moments prediction can be particularly critical.

Wing airfoil aerodynamics was predicted with TBVOR code and with some available experimental wind tunnel drag coefficient values.



Sailplane lift curves for different elevator deflections together with the trimmed one are

shown in Figure 10. In the same figure the contribution to the total lift of different sailplane parts is shown. In Figure 11 the moment coefficient curves are represented. It is important to notice that even post-stall values are shown and used to evaluate aircraft aerodynamic moment in post-stall conditions. Drag polars at different elevator deflections and trimmed polar are shown in Figure 12.

It is worth to notice that the predicted glider polar is far from a parabolic expression (like real flight polars) at very low lift coefficients; in those conditions a drag increase comes from airfoil behavior (the glider drag is almost totally friction drag, which comes principally from the wing).

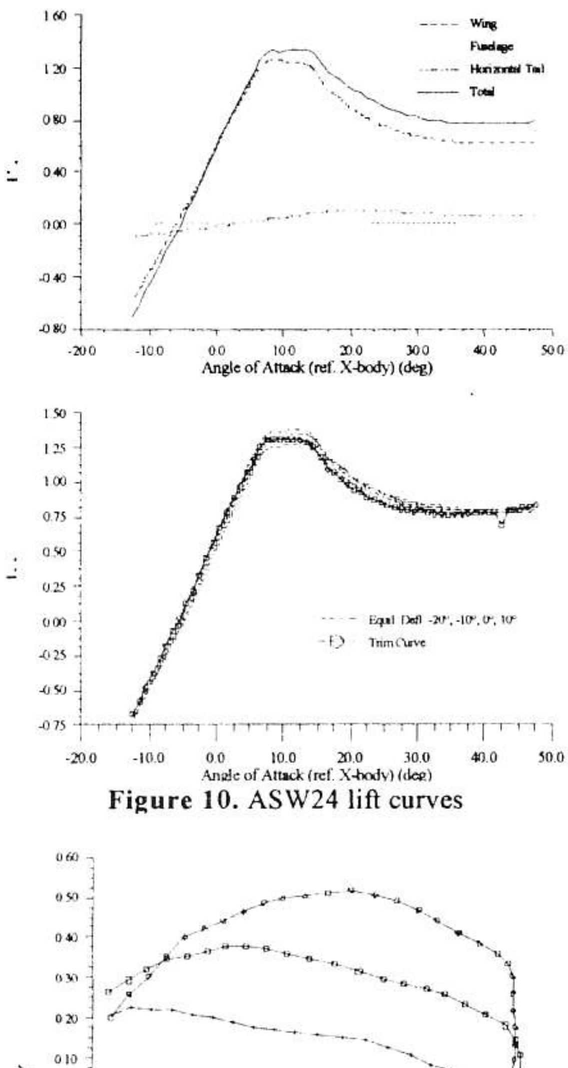


Figure 10. ASW24 lift curves

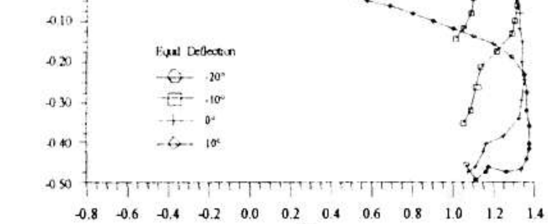


Figure 11. ASW24 moment coefficient curves

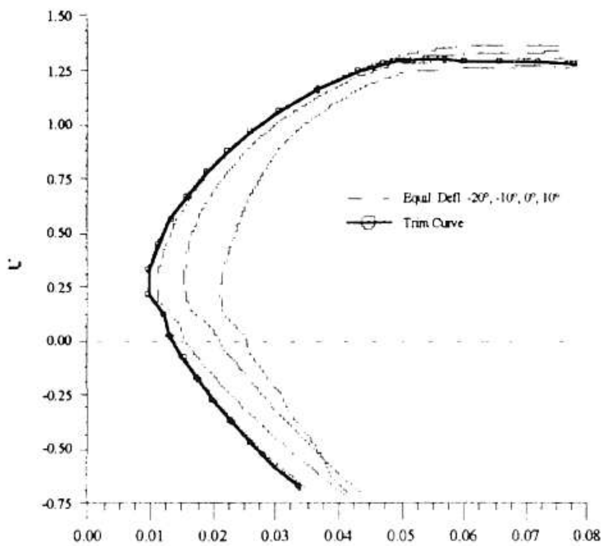


Figure 12. ASW24 drag polars curves at different equilibrator deflections

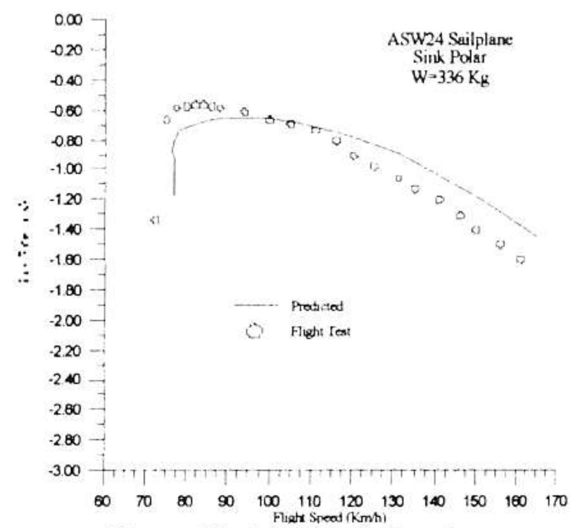


Figure 13. ASW24 flight polar

Calculated and measured flight polars are reported in Figure 13 and it can be seen that the agreement is reasonable. It should be taken in account that some data was guessed or inferred from graphs. In fact, due to the very high wing aspect ratio (22.5), some aerodynamic derivatives were evaluated from graphs by extrapolation of existing curves usually used for light aircraft with sensibly smaller aspect ratios.

An example of lateral aerodynamic derivatives estimation is represented in Figure 14.

The sailplane motion simulation performed with Dynasim was used to understand glider behavior in turning maneuvers and simulating a spin recovery. A screen view of sailplane flight simulation is shown in Figure 15.

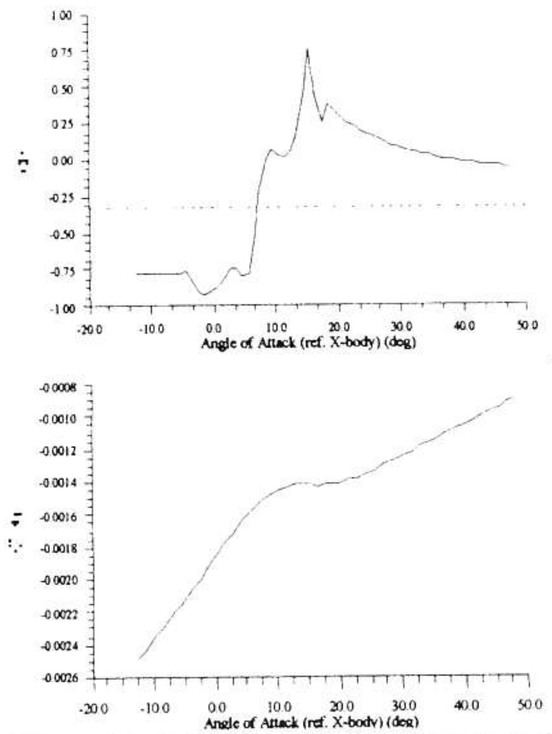


Figure 14. ASW24 lateral aerodynamic derivatives

Figure 15. ASW24 flight simulation

Conclusions

AEREO and DYNASIM codes represent a valid and a fast tool to predict aerodynamic and dynamic behavior of subsonic aircraft. Using an extension of the Prandtl lifting line theory to the non-linear range of the angles of attack, AEREO is capable to predict all the aerodynamic coefficients and stability derivatives needed to perform the simulation of the aircraft motion. The CPU time needed to obtain a complete set of coefficients is about 10 minutes on a Pentium PC -133 MHz and this makes the code usable for design purpose. The output of the AEREO is then used as input for DYNASIM code that is able to predict the aircraft behavior following an assigned control law. DYNASIM code can also be run in interactive manner and the user can fly the airplane using the mouse as stick command. Comparisons between numerical obtained data and flight data have been presented for P92J aircraft and ASW-24 sailplane.

Future developments will regard the inclusion of atmospheric turbulence and thermal air velocities distribution (glider motion simulation). More tests need to be performed and compared to flight data in order to validate the code also for lateral directional behavior.

References

1) Wolowicz, H. C. and Yancey, B. R., "Longitudinal Aerodynamic Characteristics of Light, Twin-Engine, Propeller-Driven Airplanes ," NASA TN D-6800, 1972

2) Wolowicz, H. C. and Yancey, B. R., "Lateral Directional Aerodynamic Characteristics of Light, Twin-Engine, Propeller-Driven Airplanes," NASA TN D-6946, 1972

3) Roskam, J. "Airplane Design. Part VI Preliminary Calculation of Aerodynamic, Thrust and Power Characteristic," Ed. Roskam Aviation 1987

4) DATCOM Data Sheets

5) ESDU Data Sheet

6) D.P. Coiro and P. Dini, " Stall and Post-Stall Performance Prediction of Advanced WindTurbine Airfoils ",XII AIDAA Congress, Como, July 1993

7) D.P. Coiro and P. Dini, "Prediction of Aerodynamic Stall over Wind-Turbine Airfoils, " FTEC '97 Congress, YogJakarta, Indonesia, July 1997

8) Anderson, J. "Fundamental of Aerodynamics," Mac Graw Hill, 1984

9) Eppler, R., "Practical Calculation of Laminar and Turbulent Bled-Off Boundary Layers," NASA TM-75328, 1978 (translated from IngenieurArch~v, Vol. 32,1963, pp. 221-245).

10) Drela, M., and Giles, M. B., "Viscous-Inviscid Analysis of Transonic and Low-Reynolds Number Airfoils," AAIA Journal, Vol. 25, No. 10, October 1987, pp. 1347-1355.

11) Dini, P., and Maughmer, M. D., "Locally Interactive Laminar Separation Bubble Model," Journal of Aircrafl, Vol. 31, No. 4, July-August 1994, pp. 802-810.

12) Dini, P., Selig, M. S., and Maughmer, M. D., "Simplified Linear Stability Transition Prediction Method for Separated Boundary Layers," AIAA Journal, Vol. 30, No. 8, August 1992, pp. 1953-1961.

13) D.P. Coiro and P. Leoncini, "Dynamic Stability Evaluation and Graphic Visualisation of Aircraft Motion at High Angles of Attack," XIII AIDAA Congress, Rome, September 1995.