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NUMERICAL, WIND-TUNNEL AND FLIGHT TESTS FOR P92J AND P96 LIGHT AIRCRAFT

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Abstract

This paper presents the results of long time scientific activities related to two light planes: high wing P92J and low wing P96 aircraft. Both aircraft are built by the TECNAM industry. The investigations have regarded numerical calculations of aerodynamic characteristics (global coefficients for airfoils, wings, total aeroplane, etc.) followed by the simulation of static and dynamic behaviour of the aircraft. Then wind tunnel tests on body, wing-body and complete aircraft models have been done and a complete flight test campaign for both P92J and P96 aircraft has been performed. As far as it concerns numerical calculations, this paper will present results obtained using three in-house developed codes, namely *TBVOR* (2D viscous analysis), *AEREO* (complete aircraft aerodynamics) and *DYNASIM* (interactive aircraft motion and dynamic behaviour prediction for an user specified control law via mouse or for an imposed air disturbances). The flight tests have been performed using an in-house developed apparatus which is easy to use and to install and which stores all signals taken by different mounted devices (accelerometer, angle measurements, etc.) The results presented in the paper will regard comparison between numerical, wind tunnel and flight test for the P92J high wing aeroplane while for the P96 aircraft only numerical and wind tunnel test will be discussed.

Introduction

A fast and reliable numerical tool is very useful during the design phase of an aircraft. Such a tool should be able to predict both the aerodynamics and the performances of the designing aircraft with sufficient accuracy. If the designer has also the possibility to *fly* the aircraft using an interactive flight simulator this will strongly help him to find the most appropriate design choices.
Despite of all CFD codes and of fast computers available today to predict aerodynamics, it is still unthinkable to use such tools in an iterative and repetitive way, as it is necessary during preliminary design phases. In fact, if we only think of the time necessary to prepare just the computational field grid around a complete aircraft by an expert person (this time is around 15 working days) and of the time needed to obtain a reasonable and reliable (when this is possible) solution for only one configuration, it is immediate to realise that the total time is so high that such an approach is impracticable. 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 for subsonic flows(1,2,3,4,5), but none of them tries to extend the validity of 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 main wind tunnel belonging to the Dipartimento di Progettazione Aeronautica (DPA) has been used to test both P92J and P96 aircraft models. Three components internal strain gauge balance has been used to measure longitudinal forces and moment for both wing/body and complete configurations. Main tunnel characteristics and test results will be discussed in a following section.

Flight tests have been performed on the P92J real aircraft. Stall as well as standard certification manoeuvres have been performed and monitored with an *ad hoc* light measurement instrumentation designed and built to be easy to use, install and handle. This instrumentation has been connected to many devices as explained in the paragraph related to the instrumentation. In flight polar has also been determined. Results coming from flight tests will be compared to those obtained in tunnel and to those coming from numerical calculations.

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Aerodynamics and dynamics prediction

The work done in this field has been that of recognising 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 has been improved regards airfoils aerodynamic characteristics prediction. It is since 1990 that viscous/inviscid interaction codes are being developed(6,7). The actual version of *TBVOR* code (subsonic flow) is capable to predict all viscous (mono or multi-component) airfoil aerodynamic characteristics also when strong interactions such as laminar separation bubbles and large turbulent separation areas are present on the airfoils.

Then, after that wing, horizontal and vertical tail airfoil characteristics have been calculated, complete loads for wings and tails can be predicted. To evaluate wings load in stall and post-stall conditions an extension to the standard Prandtl lifting-line theory has been done following the guidelines suggested in(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.

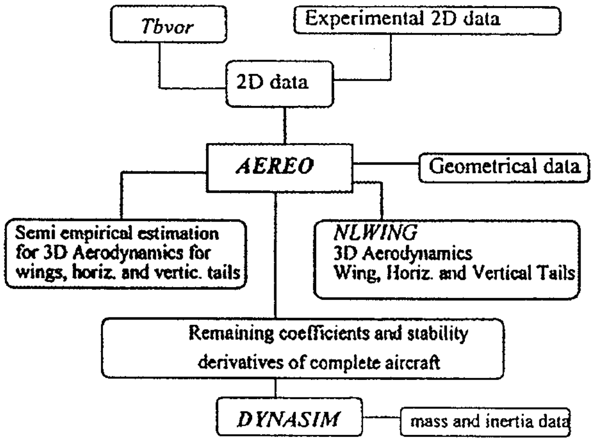
Fuselages and wings/body intersections are treated in semi-empirical manner. To this aim hundreds of graphs have been spliced out and put as database form to be used by *AEREO* code. The final output is in fact of *look-up table's* type and it contains longitudinal and lateral aerodynamic coefficients and stability derivatives in function of angle of attack α, sideslip angle β and 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 organisation of a complete calculation set.

All codes are written in Fortran 77 language with the exception of *DYNASIM* that has been written part in Fortran and part in C++.

When *DYNASIM* is run in interactive way, a Silicon Graphics computer is needed. To avoid this limitation, *DYNASIM* is currently being translated in JAVA so that it will soon run under a more common PC Internet browser and it will be totally machine independent.



Sketch 1 : Flowchart of the simulation codes

2D Data

The two-dimensional characteristics of the airfoils employed in the wing, horizontal and vertical tail can be either assigned as experimental values or calculated with *TBVOR* code(6,7). The *TBVOR* capability in calculating 2D aerodynamic characteristics is reported in(6,7). Curves at different Reynolds number can be input to *AEREO* code. Details and capabilities regarding *TBVOR* code will not be explained in this work but they can be found in the mentioned references.

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 as explained in detail in(10)

In that paper 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 procedure was performed. Then it was found a general and automatic procedure such that the code automatically chooses the correct relaxation factor depending this only on the number of points input. *NLWING* is then 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(1,2). The interpolations have been done using biand 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(9,10) is an interactive graphic code that allows the user to *fly* the selected airplane using the mouse as stick command. It is partly written in C language and partly in Fortran language. It can also be run in batch mode obtaining the airplane motion in form of values to be plotted using separate graph codes. It solves 12 ordinary non-linear differential equations in which the non-linear forces are input in multidimensional matrix form and are interpolated at each time instant. 4th order Runge-Kutta integration scheme is used to solve the system.

The translation 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 code first finds the equilibrium values of the variables and then starts the integration of the differential equations. 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 manoeuvre.

Wind tunnel tests

The tests were carried out in the low speed wind tunnel of the Dipartimento di Progettazione Aeronautica, University of Naples (DPA), Italy. This is a closed circuit type of tunnel with closed rectangular test section of 2.0 - m wide · 1.4 - m height. The free stream velocity ranges from 0 up to 45 m/s. Turbulence intensity of the flow at the centre of the test section is about 0.1%. All tests were performed at a Reynolds number relative to model chord (220 mm) of $Re_C = 0.6$ million.

The measurements were performed using an internal, in-house made 3 components strain gauge balance. The accuracy of the balance is:

Normal force:	. 1% F.S. (~ 50 Kg)
Longitudinal Force:	. 5% F.S. (~4 Kg.)
Pitching Moment:	. 2% F.S. (~3 Kg. m)

Both signals coming from the balance and from an electronic inclinometer were acquired and processed with a PC devoted to this scope.

Wing-body combination and complete aircraft with stabilator set at different angles were tested.

A picture of the model installed in the tunnel is shown in figure 1

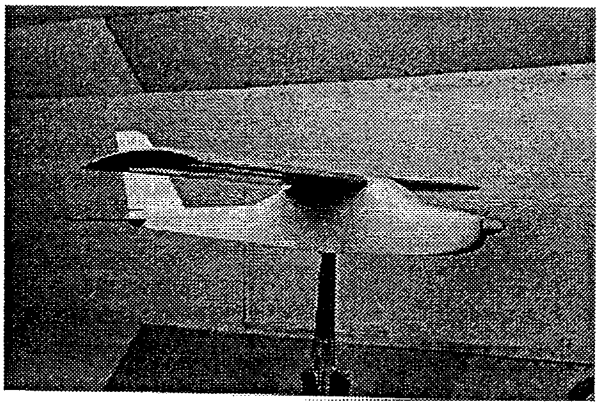


Fig. 1: P92J model in the wind tunnel

The Flight Test Instrumentation

The instrumentation used during the flight test program is one of the main features of the flight test activity. The selection of sensors and related instruments should be defined with respect to the objectives, precision, time and costs of the specific aeroplane to be certified.

In the case of the P92-J aircraft it was decided to set up an high accurate instrumentation system, taking advantage of the low-cost electronics and of the collaboration with the academic environment for putting together sensors, calibration systems and dedicated software development.

The result of this collaboration was the design and the construction of a light and compact 16-channel flight test solid state on board recorder with analog to digital conversion and local storage capability. This recorder may, in addition, be programmed with three different test configurations, each of them can be easily selected during the test by the flight test pilot, in order to cover different test cases during one specific flight. It is normally operated by a standard PC-computer, both for programming and for reading from memory the acquired data to be post-processed.

Figure 2 shows the block diagram of the flight test acquisition system. Before flight, the flight test recorder is programmed as desired (type and number of sensors to acquire, acquisition speed for each of the three available programs), path n. 1. After flight, path n. 2, the data acquired are transferred to a standard PC. Next, using dedicated software (visftxx.exe) these data are converted in engineering values and units visualised and analysed as necessary.

The following quantities were instrumented, calibrated ad measured: aircraft speed, pressure altitude, outside air temperature, engine RPM, ailerons' deflection, stabilator deflection, trim angle, rudder angle, flaps' deflection, stick forces, normal c.g. acceleration, stall warning, engine left cylinder temperature, engine right cylinder temperature and engine oil temperature. Obviously not all these parameters were needed for each flight and

therefore the recording system were properly programmed for the acquisition of the necessary sensors for that flight at the convenient programmable acquisition rate. Dedicated software has been prepared for assisting in the calibration of each sensor and for its rapid checking. The following figure shows a typical output from flight test data acquisition. The plots have the time as a common x-axis and each window has the user selected parameter history recorded during the test. The software has several features to help in reading and understanding the data reliability. In addition all the recorded time-histories may be transferred to other much more sophisticated programs for the desired post-process and for the data reduction in the standard atmosphere.
This approach was found very accurate and totally appreciated by the airworthiness representatives.
From the manufacturer point of view it resulted in a valuable data base necessary and very important in preparing all the documents accompanying the aircraft, but also a reference experimental data for tuning their own numerical models developed over a statistical data base coming from the open literature.
From the University point of view it has been an almost not repeatable occasion to work with a real aircraft following and participating to all the aspects of a flight test program and setting up an high qualified engineers' team for such aeroplane category which, hopefully, might also be extended to heavier aircraft.

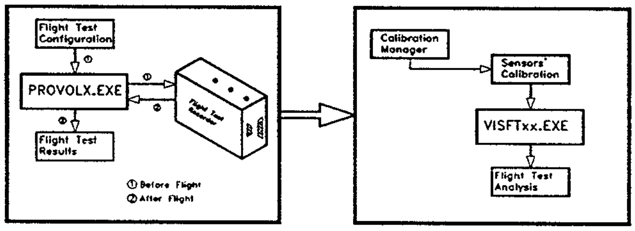


Fig. 2 - Block diagram and main components of the flight-test acquisition system (sensors not included).

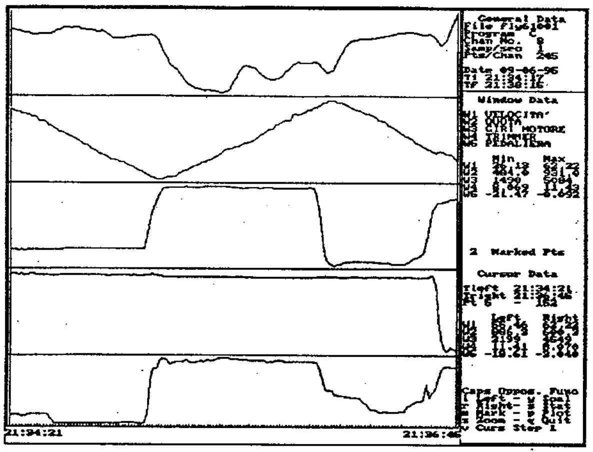


Fig. 3: Example of output from flight recorder

In figure 3 an example of recorded output variable is reported. In this case the variable are relative to the approaching and landing phase and the windows show (starting from the top) speed, altitude, engine revolutions, tab and rudder deflections, all of them in function of time.

Results

In this study, P92J and P96 light single propeller aircraft will be used as reference aeroplanes.
The three views of both aircraft are reported in figures 4 and 5 and the main geometrical characteristics are reported in table 1.

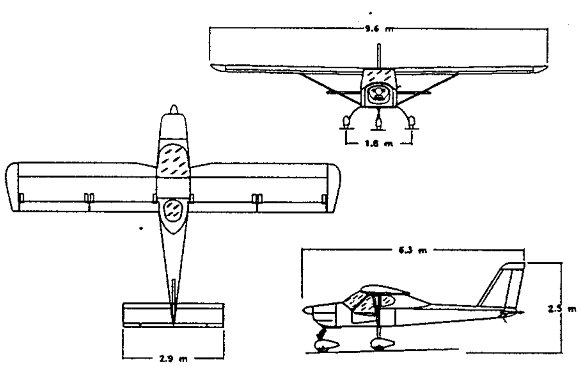


Fig. 4: P92J aircraft

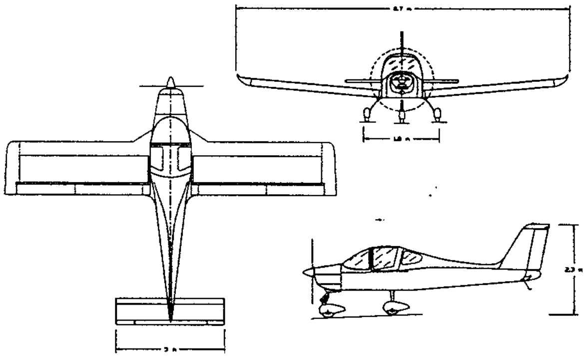


Fig. 5: P96 aircraft

Characteristics	P92 J	P96 Golf
Wing Span	9.6 m	8.7 0 m
Wing Chord	1.4 m	1.4 0 m
Wing Area	13.2 m^2	12.18 m^2
Aspect Ratio	6.98	6.21
Wing dihedral angle	1.5 deg	5 deg
MTOW	520 kg	450 kg

Table 1

P92J Results

The calculated lift, and moment coefficient curves in function of the angle of attack and of the stabilator deflection angle are reported in figures 6 and 7 for the P92J along with the airplane-trimmed curves. Capability of AEREO code in predicting the non-linear behaviour can be clearly seen in the figures. Some of the remaining lateral steady and unsteady stability derivatives are reported in the figure 8. 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.

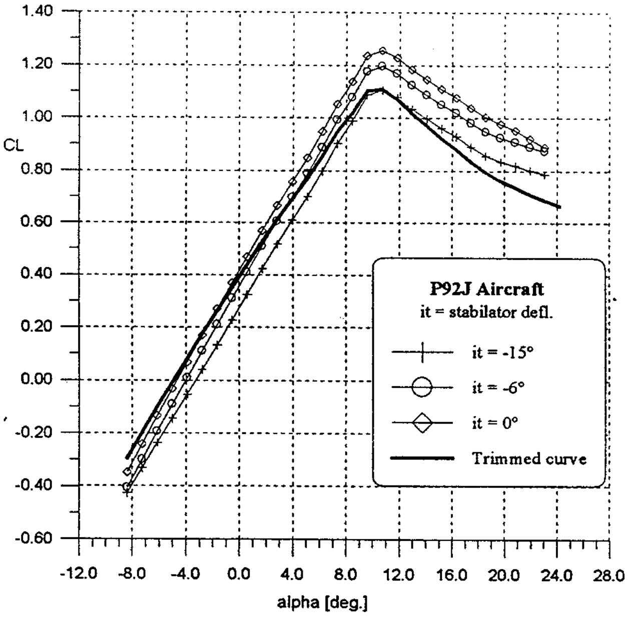


Fig. 6: Numerical lift coefficient curves

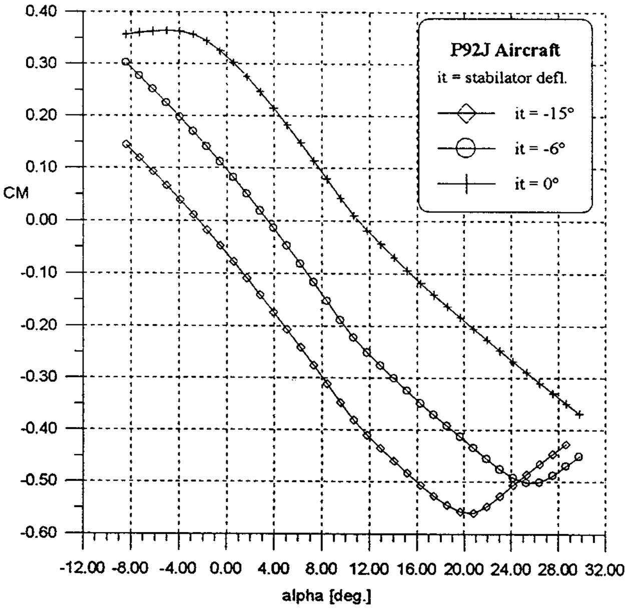


Fig. 7: Numerical moment coefficient curves

Computer time needed to evaluate a complete set of aerodynamic force coefficients is about 10 minutes on a Pentium 133 PC.

As said in a previous paragraph, starting from the airfoil aerodynamic characteristics evaluated with *TBVOR* code, comparison can be made between wind tunnel data and *AEREO* predicted curves. Lift coefficients for the P92J wing-body combination are shown in figure 9. It can be said that the agreement is satisfactory everywhere with the exception of the maximum lift coefficient value. This is probably due to the fuselage contribution that is underestimated by the numerical code since this is based on the equivalent body concept while the real fuselage cross section is of trapezoidal shape.

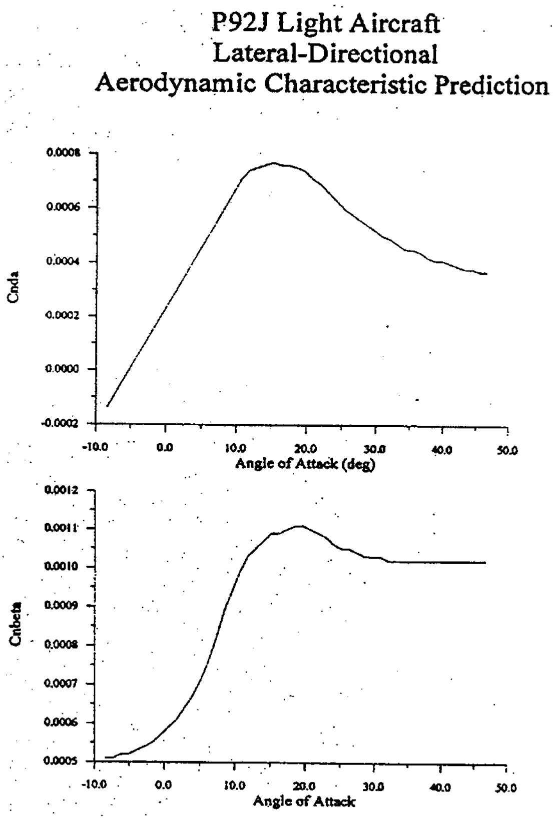


Fig. 8: Example of numerical lateral derivatives

The comparison between numerical and tunnel measurements for the complete aircraft polar is shown in fig. 10 and the agreement is quite good.

Figure 11 shows the comparison between numerical and experimental moment coefficient curves. In this case the agreement is not satisfactory as in the case of the polar, but it should be taken in account that in this case there is some uncertainty in the measurement of the model total moment.

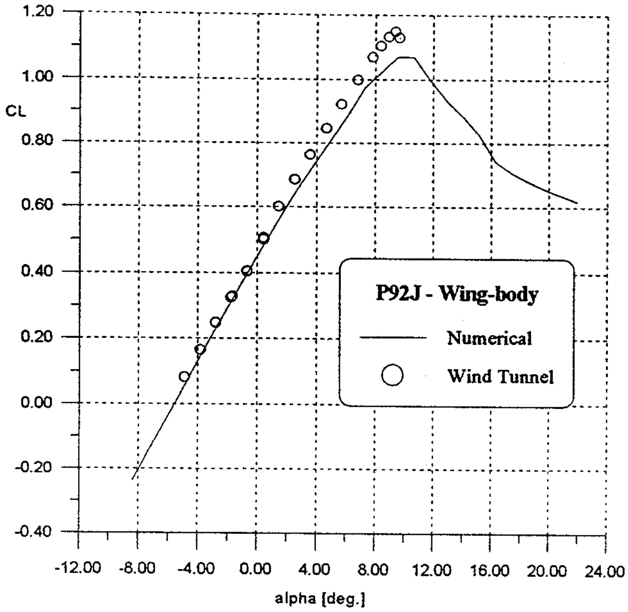


Fig. 9: Wind tunnel and numerical lift coefficient curves

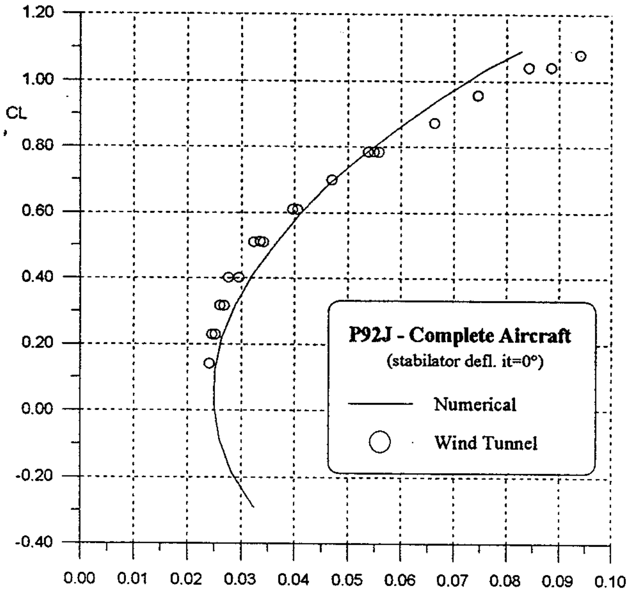


Fig. 10: Wind tunnel and numerical polar curves

P96 wind tunnel results

As far as it concerns the P96 aircraft, at the moment of writing the paper, only experimental results are available and thus they will be compared with those relative to the P92J aircraft. Nevertheless flight tests are planned in the near future.

Figures 12 and 13 show the lift coefficient and the polar for both aircraft. While there is not a great difference in the polar, the lift curve for the low wing aircraft shows a change in slope at moderate angles of attack and reach the stall with the same lift coefficient value but at a higher angle. This is probably due to an earlier appearance of separation on the wing respect to the P92J that leads to an effective reduced aspect ratio.

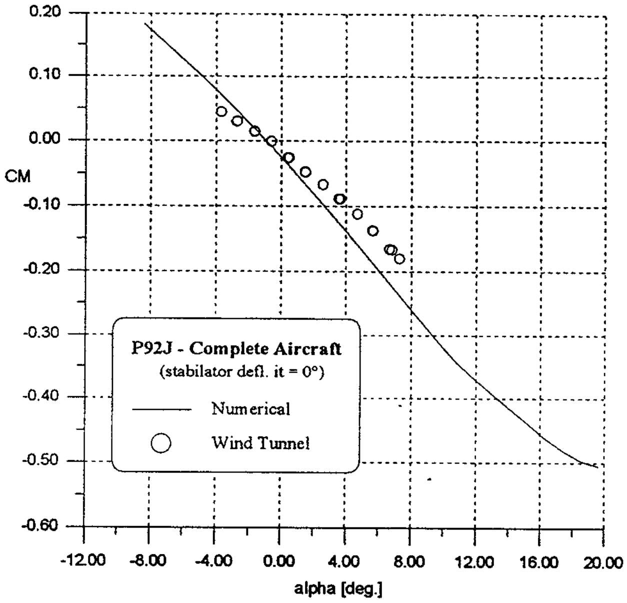


Fig. 11: Wind tunnel and numerical moment coefficients curves

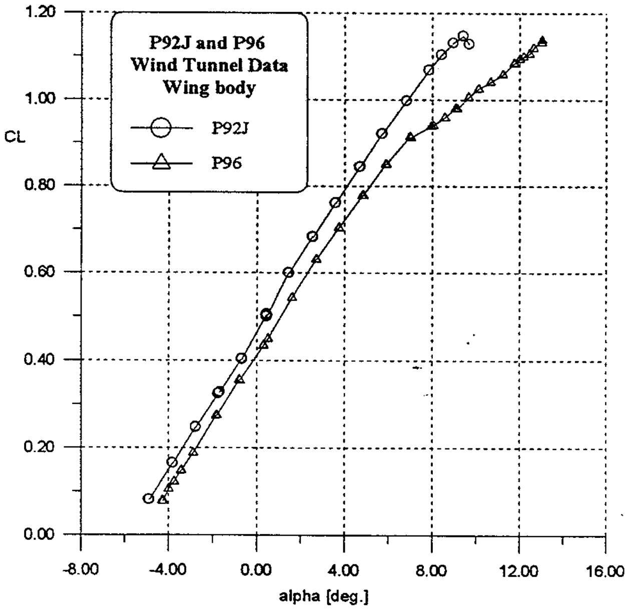


Fig. 12: P92J and P96 wind tunnel lift coefficient curves (wing body)

Flight Tests

Many flight tests have been performed to obtain the in-flight polar curve. Then *AEREO* code has been run with all input data relative to the same aerodynamic and configuration conditions (presence of wing struts, under-carriage, etc.). The comparison between numerical and flight data is shown in Fig. 14. It can be seen that the agreement is excellent

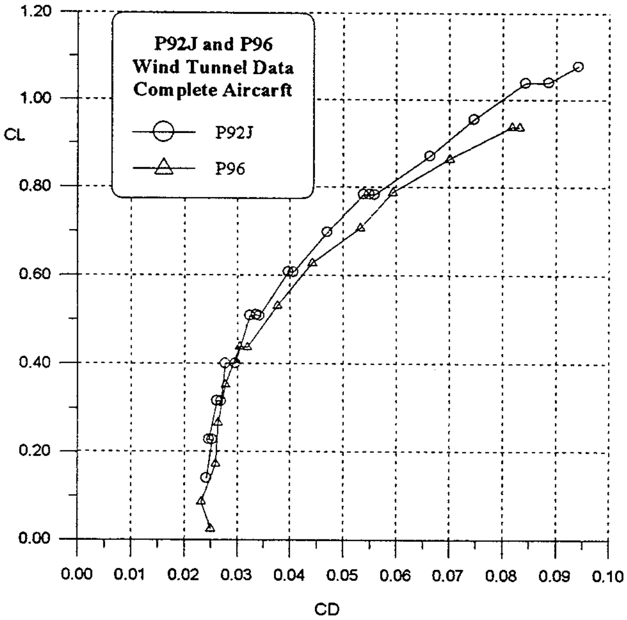


Fig. 13: P92J and P96 wind tunnel polar curves (Complete aeroplane)

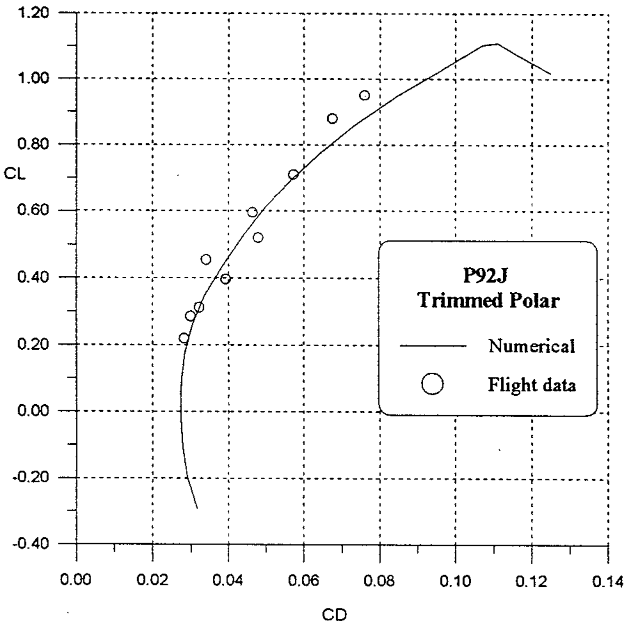


Fig. 14: P92J numerical and flight data comparison

P92J Stall Manoeuvre

During the certification phase of the P92J light aircraft, many power-off stalls have been performed and recorded. Of these, three consecutive stalls 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. 15 and it is compared to flight data.

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

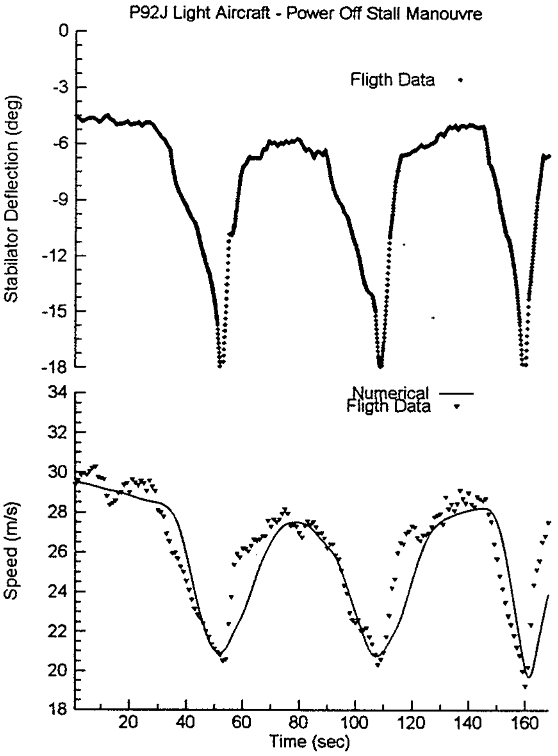


Fig. 15: P92J stall manouvre simulaion : numerical and flight data comparison

But further investigations have shown that the total energy of the system had increased during the 1st and 2nd manoeuvre indicating that gusts were present during the tests. In fact in figure 12 the ratio of total energy at each time instant to that at the beginning of the manoeuvre is reported along with the speed time-history. It can be clearly seen that for the second stall (for which the agreement is good) no energy increase has been recorded. However in fig. 16 is also reported the curve obtained with damping coefficient values reduced with respect to the original ones calculated by the *AEREO* code: the improvement in terms of agreement with flight data indicates that the predicted damping longitudinal derivatives are little higher than the real ones. Comparison of measured and predicted *g* acceleration values (not reported here) shows that also in this case the *g-break* for each stall is correctly predicted.

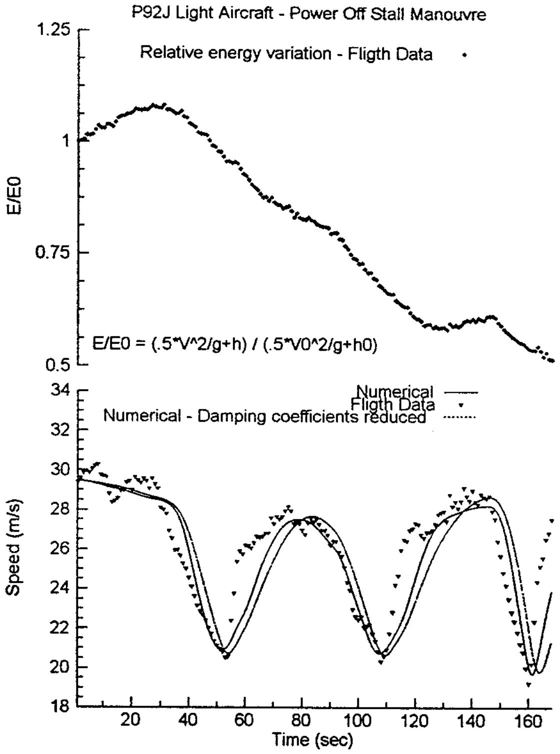


Fig. 16: P92J stall manouvre simulaion : numerical (30% reduction in damping coefficients) and flight data comparison

Conclusions

AEREO and *DYNASIM* codes represent a valid and a fast tool to predict aerodynamic and dynamic behaviour 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 15 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 behaviour 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.

Wind tunnel tests have been performed for both P92J and P96 aircraft models and results have been compared with numerical data. Flight tests devoted to the determination of polar curve and of stall speed, have been performed and the results compared with numerical simulation of aircraft motion (*DYNASIM* code). Future developments will regard the inclusion of atmospheric turbulence in *DYNASIM* code. More wind tunnel and flight tests need to be performed especially regarding the determination of lateral aerodynamic characteristics. Flight tests of the P96 aircraft are planned in the near future.

Acknowledgements

The authors wish to express their deepest appreciation to their professor Luigi Pascale without whose wealth of knowledge, supervision, and understanding this work would have never been possible. His generosity and kindness will always be remembered.

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