Transactions on Modelling and Simulation vol 30, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

Correction of the wall interference effects in wind tunnel experiments

G. Lombardi[1], M.V. Salvetti[1], M. Morelli[2]
[1]*Department of Aerospace Engineering, University of Pisa, Italy*
[2]*Medium Speed Wind Tunnel, CSIR, South Africa*

Abstract

A procedure for the correction of wall interference effects is applied to lift and pitching moment coefficients, measured over a complete aircraft configuration in subsonic conditions in the High Speed Wind Tunnel (CSIR Laboratories).

A "post-test" method is used, based on pressure measurements over the wind tunnel walls.

The location of the sensors for pressure measurements is chosen following a previous numerical sensitivity analysis. In particular, pressure is evaluated in 320 points. Those values are interpolated linearly in the longitudinal direction, while cubic splines and parabolic laws are used in the cross section.

The correction is obtained as the difference between the values given by two numerical simulations: in the first one the flow over the model in "free-air" conditions is simulated, while, in the second one, the measured pressure values over the wind tunnel walls are used as boundary conditions. A potential flow solver, whose accuracy was evaluated in several previous works, has been used.

As a first validation, the results are compared with those obtained with a "pre-test" correction method, and a satisfactory agreement is obtained.

1 Introduction

The interference effect of wind tunnel walls on the flow field around a model is known to be one of the main sources of error affecting the accuracy of experimental data. The classical correction criteria (see Kraft [1] for a review) are based on theoretical linear models, whose validity is limited to low velocities and angles of attack. However, even in these conditions, the accuracy of these criteria is not high, since they do not account for the physical tunnel characteristics. With the introduction of ventilated test sections for high-speed subsonic and transonic testing, new procedures have been devised to extend the classical wall interference methods. Because of the complex nature of the interference, a satisfactory general analytical solution to this problem for ventilated walls is far from being achieved.

More recently, new correction methods were introduced (Lynch et al. [2]), based on more complex procedures, which couple measurements - typically pressure and/or velocity on the wall or in the field - with numerical calculations. These procedures are, however, difficult to be used in practice because of the uncertainties in the measurements of the wall quantities, and due to the complexity of the flow calculation. The above considerations explain why limiting the model dimensions remains the most used way to avoid unacceptable errors. However, very low blockage factors are in general required to have small wall interference effects, as shown, for instance, in a previous analysis of these effects in the Medium Speed Wind Tunnel of the CSIR Laboratories (Lombardi and Morelli [3]). On the other hand, it is evident that it would be attractive to test large models, not only to increase the Reynolds number but, especially, to improve the accuracy of the force measurements and of the model geometry. Thus, it is important to have reliable criteria to choose the model size.

Taking into account this consideration and the increase in computing capabilities, we decided to develop a correction procedure based on pressure measurements on the wind tunnel walls coupled with a numerical method to evaluate the flow correction. This procedure, which is described in details in Sec. 2.1, requires the preliminary definition of the location and accuracy of the experimental measurements of the wind tunnel wall pressure. In a previous work (Lombardi et al. [4]) a configuration, briefly defined in Sec. 2.2, was identified from a numerical sensitivity analysis.

In the present paper, the overall procedure is applied to the correction of the aerodynamic coefficients measured in the High Speed Wind Tunnel (CSIR) over a complete aircraft model in subsonic conditions (Sec. 3).

2 The correction procedure

2.1 Description

The correction methodology employed in the present analysis is a so-called "post-test" procedure (Kraft [1]). In this kind of methods, experimental data must be provided on a control surface located near the wind tunnel walls or directly on them. The experimental data can be pressure, velocity direction or velocity components.

In particular, in the present work a "one-array" correction procedure has been chosen, in which only pressure data are provided at some locations on the wind tunnel walls. This approach, although in principle less accurate than "two-array" corrections, appears to be more affordable from a practical point of view. Moreover, in "two-array" procedures, since a larger amount of measurements must be carried out, it is difficult to control the measurement accuracy and this can significantly decrease the global accuracy of the correction.

The scheme of the correction procedure, which is based on the method proposed by Sickles [5], is shown in Fig. 1.

Transactions on Modelling and Simulation vol 30, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

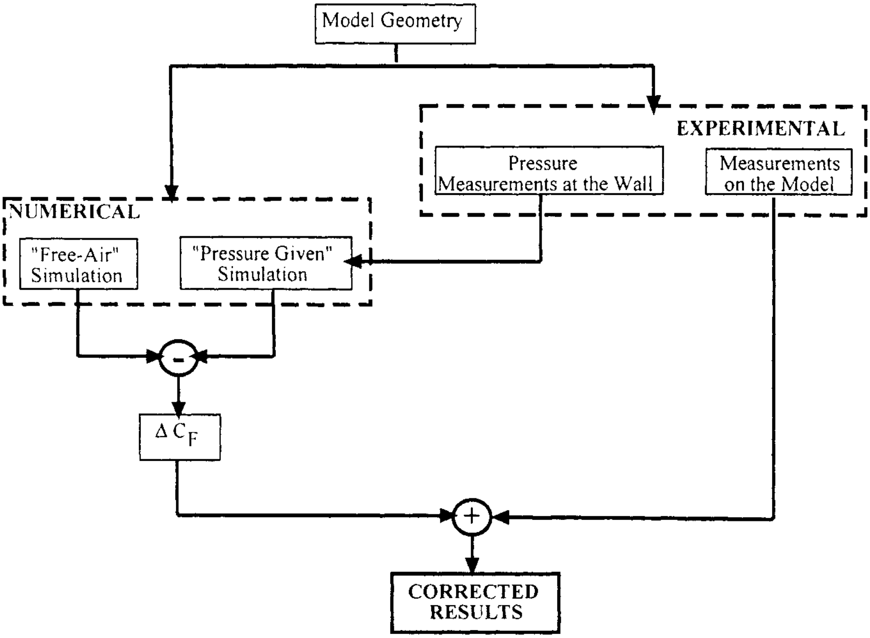


Fig. 1: Scheme of correction procedure

Once the model geometry is defined, the experimental tests are carried out and, besides the aerodynamic forces acting on the model, the pressure over the wind tunnel walls is measured at few selected locations. These data are used as boundary conditions in a numerical simulation of the flow around the same geometry ("pressure given" simulation, PG). Another numerical simulation is carried out in "free-air" conditions (FA), i.e. with a computational domain large enough to avoid spurious boundary effects. The difference between the values of aerodynamic forces obtained in these two simulations is used to correct the experimental data.

Given the previously described correction scheme, two main aspects must be preliminarly defined.

The first one is the choice of the flow solver adopted in the numerical simulations. The same criteria used in computational aerodynamics are clearly suitable also in this context. Thus, the choice of the numerical solver will depend on the considered configuration and flow conditions (see, for instance, Steinle and Stanewsky [6]). In particular, it is known that potential flow solvers give accurate results for low Mach numbers and angles of attack, with a limited computational cost.

The second issue concerns the experimental measurement of pressure over the wind tunnel walls and will be addressed in the next section.

2.2 Definition of the experimental wall pressure measurements

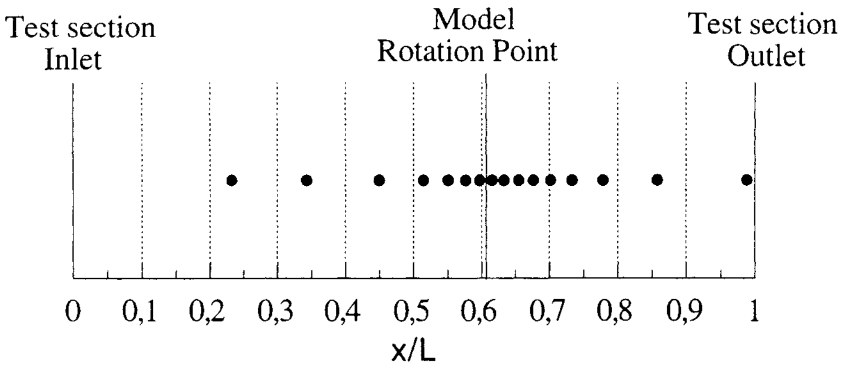
The number and the location of the measurement points must be defined, as well as the required accuracy of the pressure measurements. It seems difficult to find a priori criteria in this case. Indeed, the best choice will depend on many different factors, namely test section geometry, wind tunnel wall type, model geometry and flow conditions. On the other hand, the previously described correction procedure can be applied only if this aspect is preliminarly defined, and hence a strategy must be devised to obtain a suitable compromise between accuracy and cost of the wall pressure measurements, for each considered test.

Some preliminarly choices have been made which allow the number of free parameters in our analysis to be reduced. In particular, we decided to perform pressure measurements on only half of the wind tunnel section in the cross direction, i.e. the right or the left part. Indeed, most of the tests in the considered wind tunnel are carried out at zero yaw angle; if this is not the case, the tests are repeated with an opposite yaw angle to avoid spurious effects of lack of symmetry in the flow or model geometry. Thus, a lateral symmetry is always present in experimental data acquisition. Moreover, we decided to adopt a constant number of sensors for each cross section.

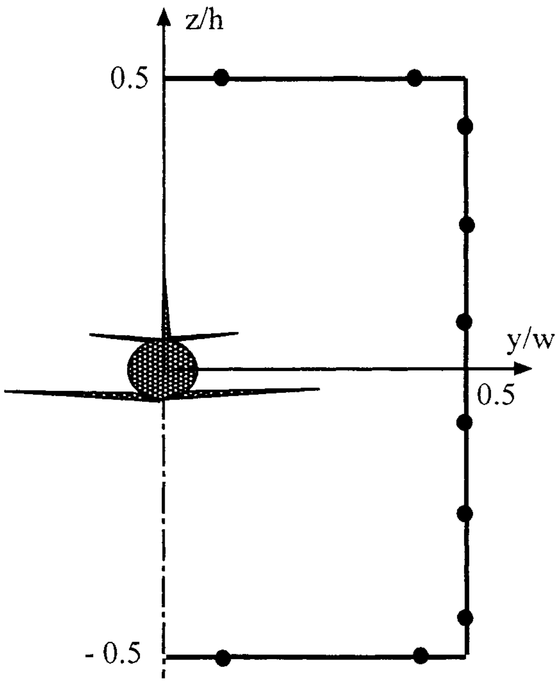
In a previous work (Lombardi et al. [4]), a strategy was proposed to define the number and position of the pressurer sensors, once the required correction accuracy is defined. This strategy is based on the previously described correction procedure, in which the experimental part is replaced by a numerical simulation (WT). Thus, an additional computation of the flow around the model in the wind tunnel was carried out. Then, the pressure values obtained in this simulation were used as boundary condition for the PG numerical simulation. The difference in the aerodynamic force values obtained in the PG and FA computations gave the desired correction to be compared with the "exact" correction computed as the difference between FA and WT results. In this way, an analysis of the sensitivity of the correction to both number and position of the pressure sensors was carried out. For the Onera M5 configuration, in subsonic conditions, a configuration characterized by 16 and 10 sensors in the longitudinal and lateral directions, distributed as shown in Fig. 2 and Tab. 1, has been identified, which represents a good compromise between accuracy and experimental costs. The measured pressure values are linearly interpolated in the longitudinal direction; following the results in Lombardi et al. [4], a more accurate interpolation is used for the cross direction, i.e. a parabolic law on the upper and lower walls of the cross-section (see Fig. 2b) and cubic splines on the lateral wall. The corresponding residual errors after correction on both lift, C_L, and pitching moment, C_m, coefficients are reported in Tab. 2.

A numerical sensitivity analysis to the error in pressure measurements was also carried out (Lombardi et al. [4]). It was found that the residual error after correction increases linearly with the error in pressure measurements, independently of the number and distribution of the sensors. The obtained values also indicated that standard accuracy in the pressure measurements would be usually sufficient to satisfy accuracy requirements for the correction evaluation.

Transactions on Modelling and Simulation vol 30, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X



a) longitudinal



b) lateral

Fig. 2: Sketch of the sensor distribution for pressure measurement over the wind tunnel walls

Transactions on Modelling and Simulation vol 30, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

Tab. 1: Sensor distribution for pressure measurement over the wind tunnel walls

Longitudinal (x/L)	
0.243, 0.351, 0.438, 0.494, 0.532, 0.562, 0.588, 0.611, 0.634, 0.660, 0.686, 0.715, 0.749, 0.792, 0.855, 0.952	
Lateral	
Horizontal (y/w)	0.083, 0.415
Vertical (z/h)	-0.415, -0.264, -0.083, 0.083, 0.264, 0.415

Tab. 2: Residual error for the chosen configuration

$M = 0.4$, $\alpha = 0°$, $C_L = 0.25$		$M = 0.6$, $\alpha = 2°$, $C_L = 0.52$	
ε_{pr} for C_L	ε_{pr} for C_m	ε_{pr} for C_L	ε_{pr} for C_m
0.00010	0.00018	0.00019	0.00004

3 Application

The above described procedure is herein applied to the correction of the aerodynamic coefficients measured, in the High Speed Wind Tunnel of CSIR, over a complete aircraft model in subsonic conditions.

3.1 Experimental set-up

The HSWT is a trisonic, open circuit blow-down type tunnel. Its operational speed ranges from M=0.4 to M=4.5 (set through an automatically controlled flexible nozzle) with stagnation pressure varying from 120 kPa to 1200 kPa. The test section has a 0.45m x 0.45m square cross section, and the length is 0.9 m. The run time varies between 10 and 60 seconds depending on the Mach number and stagnation pressure chosen.

The aerodynamic forces are measured by means of an internal six-components balance; values are averaged on 5 seconds, at a sampling rate of 500 Hz. The accuracy level of the balance, with 95% of confidence level and with respect to the maximum load, is 0.0046 for the lift and 0.0034 for the pitching moment.

The wall pressures are measured trough a Scanivalve system, at a sampling rate of 20 Hz; the maximum measurable pressure for modules was 103 Kpa. The uncertainty in the pressure measurements, for the present tests, was evaluated to 0.03 Kpa.

Transactions on Modelling and Simulation vol 30, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

3.2 Geometry and flow conditions

The used model is a 1:32 scale representation of the Mirage F1. It is a military plane featuring moderate AR (2.83), sharp leading edges and cambered profiles, especially in the outer part of the wing. A sketch of the model geometry is shown in Fig. 3. The nominal blockage factor, defined as the ratio between the model cross section area and the test section area at zero angle of attack, is 0.0158.

The model span is b=0.2639 m, with a ratio b/w=0.584. The force coefficients are non-dimensionalized with the dynamic pressure and the wing planform area, S_w=0.0245 m^2, the moment coefficients with the dynamic pressure, the wing area and the wing mean aerodynamic chord, c=0.2639 m. The reference point for the pitching moment evaluation is positioned at x_{MRC}=0.269 m from the nose of the model.

Tab. 3: Test conditions

Mach number	0.58
Angle of attack, α	3.71°
Stagnation pressure	164.56 Kpa
Static pressure	130.94 Kpa
Dynamic pressure	30.92 Kpa
Static temperature	281.1 °K
Stagnation temperature	300.0 °K

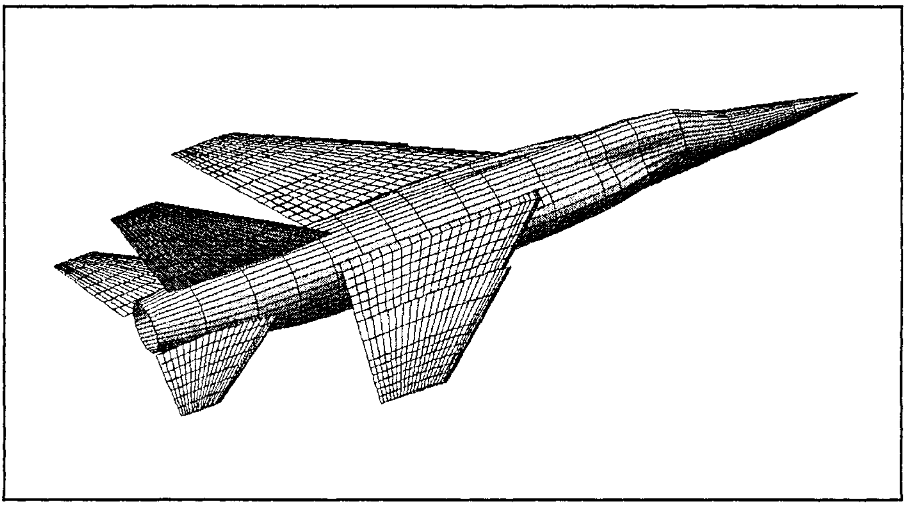


Fig. 3: Model geometry

The test considered in the present paper has been carried out in the conditions defined in Tab. 3. At the considered angle of attack of 3.71° the blockage factor is approximately 0.023.

3.3 Results

The analyzed test condition is characterized by entirely subsonic flow, and significant flow separation is not present, as confirmed by the linearity of the C_L-α curve up to an angle of attack of the order of 8°. The measured lift coefficient of about 0.26 can be assumed as a typical representation of a cruise condition.

The pressure distribution over the wind tunnel walls is shown in Fig. 4 along the longitudinal direction, and in Fig. 5 in the lateral direction. The behaviour is as expected, smooth in the longitudinal direction and more complex on the side walls. This explains the need, already pointed out in Lombardi et al. [4], of a more accurate interpolation of pressure measurements in the cross direction. As expected, a suction peak is present close to the model position.

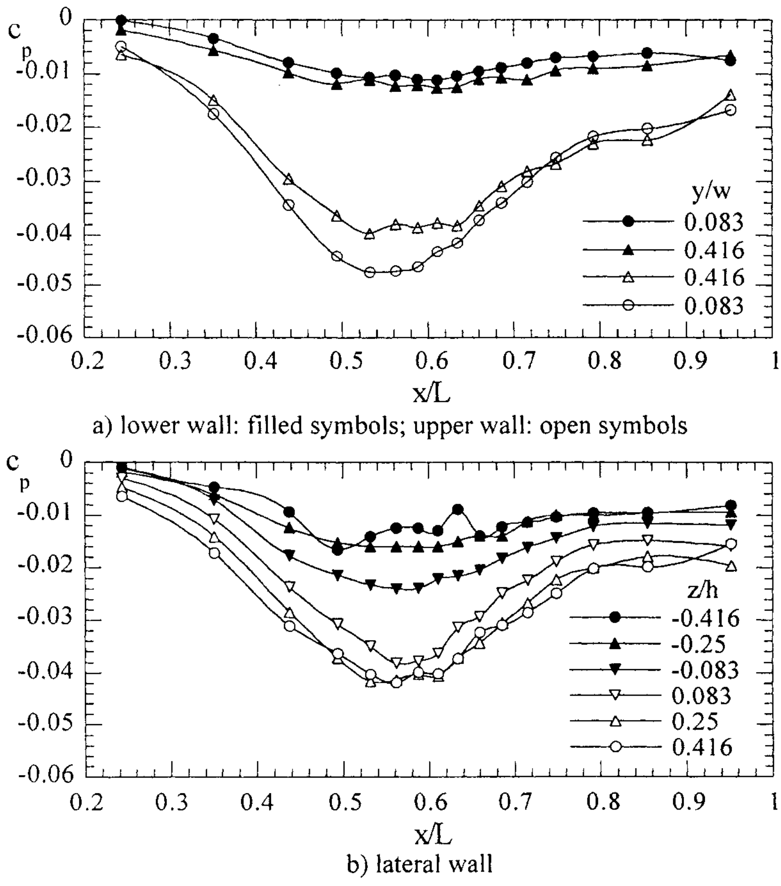


Fig. 4: Pressure distribution over the wind tunnel walls: longitudinal direction

Transactions on Modelling and Simulation vol 30, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

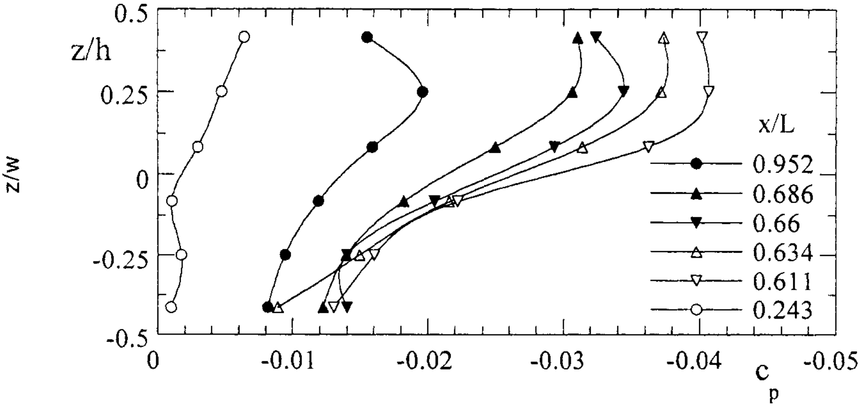


Fig. 5: Pressure distribution over the wind tunnel walls: lateral direction

Those values have been used in the correction procedure described in Sec. 2, and, in particular, in the PG simulation. As for the choice of the numerical solver, since we are interested in lift and pitching moment correction, in low-angle of attack subsonic flow, a potential solver has been used. Indeed, it is known that potential flow solvers give accurate results for low Mach numbers and angles of attack, with a limited computational cost. In particular, a solver based on the Morino formulation has been used; it was described in details in Polito and Lombardi [7] and its capabilities were presented, for a complete aircraft, in Baston et al. [8]. Tab. 4 shows the values of C_L and C_m obtained in the experiments, together with the corrections given by the proposed procedure.

Tab. 4: Results of the correction procedure

	C_L	C_m
From experiment	0.2655	-0.0472
After correction	0.2866	-0.0475
Interference term, Δ	-0.0211	-0.0003

The correction in the lift coefficient appears significant, while the pitching moment is practically not affected by wall interference effects for the considered configuration.

It is interesting to compare the present results with those of a "pre-test" method, in which the correction is obtained as the difference between the values given by WT and FA simulations. The same potential solver as previously has been used. The pressure distribution over the walls (not reported here for sake of brevity) shows the same behaviour as in the experimental data, with a sligtly lower suction peak near the model. The correction term is –0.0152 for the lift coefficient and –0.0002 for the pitching moment coefficient; they are of the same order as those obtained through the proposed "post-test" correction procedure (see Tab. 4).

Transactions on Modelling and Simulation vol 30, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

4 Concluding remarks

An application of a procedure for the correction of wind tunnel wall interference effects on the experimental measurement of aerodynamic coefficients has been presented. The correction is obtained as the difference between the values given by two numerical simulations: in the first one the flow over the model in "free-air" conditions is simulated, while, in the second one, the measured pressure values over the wind tunnel walls are used as boundary conditions.

Experimental tests on a complete aircraft geometry have been carried out in the HSWT, in low-angle of attack subsonic flow conditions. A potential flow solver, whose accuracy was evaluated in several previous works, has been used for the numerical part of the procedure.

The results have been compared with those obtained with a "pre-test" correction method, and a satisfactory agreement has been obtained. Clearly, this is not a definitive validation of the presented correction procedure. The same tests are in progress for a different scale model. The comparison between the corrected results obtained for the two different scale models, will give a more reliable assessment of the proposed procedure.

References

[1] Kraft E.M. "An overview of approaches and issues for wall interference assessment and correction," *NASA CP-2319*, 1983.

[2] Lynch, F. T., Crites, R.C. and Spaid, F. W., "The crucial role of wall interference, support interference, and flow field measurements in the development of advanced aircraft configurations," *AGARD CP-535,* 1994

[3] Lombardi G. and Morelli M. "Analysis of Some Interference Effects in a Transonic Wind Tunnel," *Journal of Aircraft*, Vol. 32, No.3, pp. 501-509, 1995.

[4] Lombardi G., Salvetti M. V. and Morelli M. "Correction of Wall Interference in Wind Tunnels: a Numerical Investigation," To appear in *Journal of Aircraft*, 2001.

[5] Sickles W. "Wall interference correction for three dimensional transonic flows," *AIAA Paper 90-1408*, 1990.

[6] Steinle F. and Stanewsky E. "Wind Tunnel Flow Quality and Data Accuracy Requirements," *AGARD AR-184*, 1982.

[7] Polito L. and Lombardi, G. Calculation of Steady and Unsteady Aerodynamic Loads for Wing-Body Configurations at Subcritical Speeds, *AIDAA Conference Proceedings,* Vol. 1, pp. 209-222, 1983.

[8] Baston, A., Lucchesini, M., Manfriani, L., Polito, L. and Lombardi, G. "Evaluation of Pressure Distributions on an Aircraft by Two Different Panel Methods and Comparison with Experimental Measurements," *15th ICAS Congress*, pp. 618-628, 1986.