VALIDATION OF A WALL INTERFERENCE CORRECTION PROCEDURE

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Abstract

An experimental activity,designed to verify the capability of a previously proposed procedure for the correction of wall interference effects, is described. Tests are carried out in subsonic flow conditions (M=0.58) on two different scale models of the Mirage F1, with the same balance and support system. The present research activity addresses wall interference effects on longitudinal aerodynamic characteristics, especially as related to pressure-dependent forces. .

From the analysis of the results without correction it is evident that the measured aerodynamic coeffcients are affected by a significant error, related to wall effects, that is reduced by the correction procedure.

Although the corrected values are still far from the desired accuracy, the result can be considered satisfactory, tacking into account that the inaccuracy remaining after correction is related also to other error sources.

As expected, the correction procedure appears as more accurate as more important are the wall effect to be corrected. Therefore, a great care must be taken to decide when apply the proposed correction procedure.

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. On the other hand, the importance of testing large models is evident, not only to maximize the Reynolds number but also to improve the accuracy of force measurement and of the model itself. The accuracy of classical correction criteria is not satisfactory, being based on insufficiently representative theoretical linear models. More recently, new correction methods were introduced (for a general description see Ref. 1), based on more complex procedures, which couple measurements - typically pressure and/or velocity on the wall or in the field - with numerical calculations.

Tacking these considerations and the increase in computing performances into account, a method of correction for the wall interference effects has been developed, based on pressure measurements on the wind tunnel walls coupled with a numerical procedure to evaluate the flow correction. Indeed, 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. This procedure, described in details in Refs. 2 and 3, requires the preliminary definition of the location and accuracy of the experimental measurements of the wind tunnel wall pressure. In a previous work [2] a suitable configuration was identified from a numerical sensitivity analysis.

A preliminary application of the set up methodology to the correction of the aerodynamic coefficients of a complete aircraft model in subsonic conditions has been described in Ref. 3. The results have been compared with those obtained with a “pre-test” correction method, and a satisfactory agreement has been obtained. Clearly, this was not a definitive validation of the correction procedure.

The present research activity addressed wall interference effects on longitudinal aerodynamic characteristics, especially as related to pressure-dependent forces. An accurate analysis of the drag would actually require a specialized test campaign, with an appropriate choice of instruments, testing techniques and computational methods.

In the present paper the methodology is applied to experimental data, therefore as a “post-test” procedure.

The use of different scale models, operating in a given wind tunnel under identical flow conditions, appears to be the most appropriate procedure to gain information on the validity of the proposed correction procedure.

Tests are carried out for two different scale models of the same geometry in the High Speed Wind Tunnel (HSWT) at the laboratories of the CSIR (Council for Scientific and Industrial Research) of Pretoria. The used models are 1:32 and 1:40 scale representations of the Mirage F1, a military plane featuring moderate AR (2.83).

At the present moment the procedure is available with a potential flow model as numerical solver; therefore, there are considered subsonic conditions ($M=0.58$) and angle of attack characterized by not significantly separated flow ($\alpha=4°$ and $8°$).

2 Description of the correction procedure

The adopted correction methodology is a so-called “post-test” procedure [4]; 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 correction methodology employed and the sensitivity analysis carried out to study the effects of different pressure sensors position and accuracy is described in Ref. 2.

In particular, a “one-array” correction procedure has been chosen, in which 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.

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 a few selected locations. These measurements 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. without simulation of the wall presence. 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 preliminarily 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.

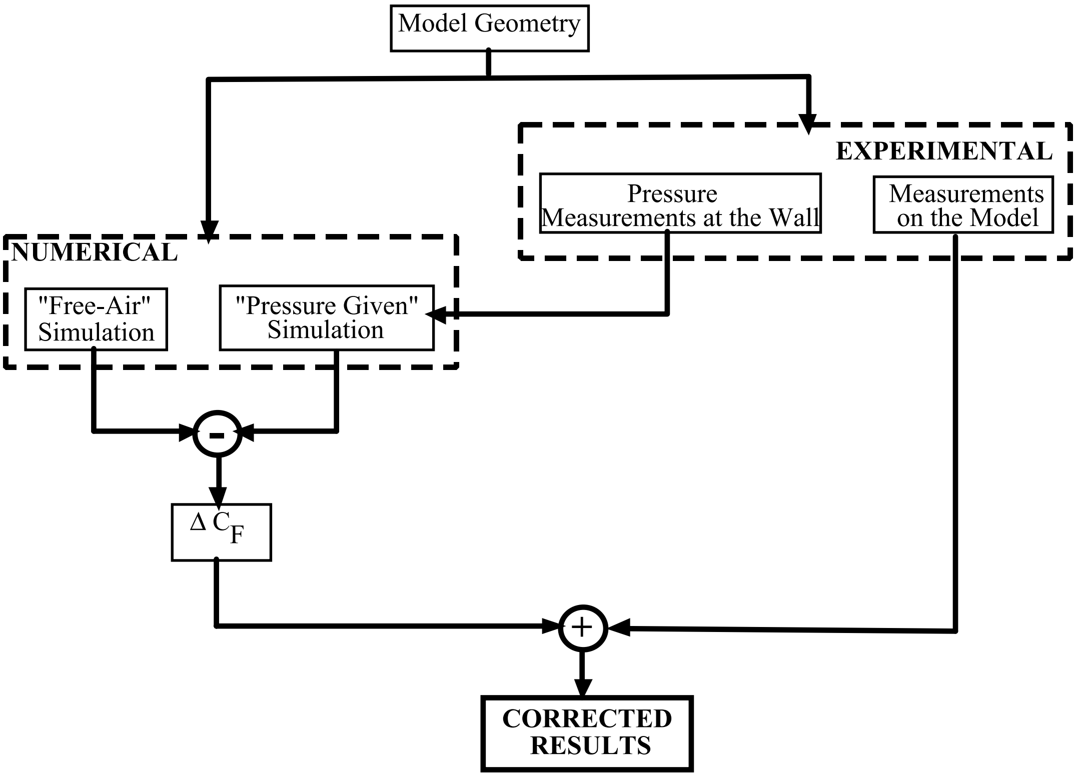


Fig. 1 – Scheme of the correction procedure

Thus, the choice of the numerical solver will depend on the considered configuration and flow conditions. In the present paper a potential flow solver was used [6, 7]. It is based on Morino's formulation, with a wake relaxation procedure.

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

3 The experimental set-up

Tests were carried out in the HSWT of the CSIR Laboratories: The HSWT is a trisonic, open circuit blow down type tunnel. It's operational speed ranges from M=0.55 to M=4.3 (set through an automatically controlled flexible nozzle) with stagnation pressure varying from 120 KPa to 1200 KPa. The test section has a 0.45 m x 0.45 m square section and the length is 0.9 m. The run time varies between 10 and 30 seconds depending on Mach number and stagnation pressure chosen.

The total uncertainty in the data can be attributed to instrumentation, reference dimension evaluation (surfaces, lengths and moment reduction points), data acquisition procedure and the difference in Reynolds number. It should be noted that, because of the use of the wind tunnel under identical flow conditions (for a given Mach number), the bias uncertainty should not be considered in its entirety when comparing the two models; indeed, it contains a part, dependent on flow measurements, force measurements and on the evaluation of the model dimensions, that is the same in both cases.

3.1 Balance and support system

The models are supported by means of a sting and the aerodynamic forces are measured by means of an internal six-components balance, (19 mm balance); it has been chosen because it is the one with the highest allowable loads that could fit for both models; in this way, the bias component of the error is the same, and, therefore, the errors in the comparison of the results for the two scale models are reduced. Values are averaged on 5 seconds, at a sampling rate of 500 Hz. The complete characterization of the balance accuracy, as resulting from the calibration procedure, is shown in Tab. 1.

	Mean	Standard Deviation	Range
NF	0.0046	0.071	0.9
PM	-0.0034	0.17	1.7
SF	0.0046	0.18	1.6
YM	0.0063	0.19	1.5
AF	0.0087	0.28	2
RM	0.034	0.3	1.9

Tab 1: Calibration errors for the 19mm Balance

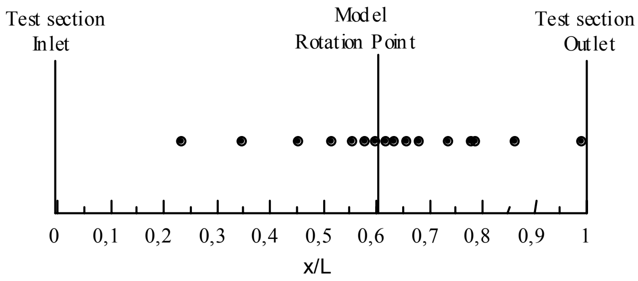
The error in the model pitch angle is lower than 0.1 degrees, and data are corrected for the sting deflection.

3.2 The wall pressure measurements

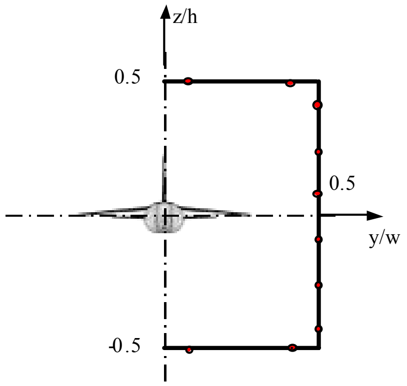
Number and location of the measurement points must be defined, as well as the required accuracy of the pressure measurements. It seems difficult to find *a priori* criteria in this case. Indeed, the best choice will depend on many different factors, namely test section geometry, wind tunnel wall type, model geometry and flow conditions. These aspects are highlighted in Ref. 2, and the results of the analysis carried out are applied in the present work.

In order to reduce the number of the required pressure data, it was 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. 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.

A configuration characterized by 16 and 10 sensors in the longitudinal and lateral directions, distributed as shown in Fig. 2 and defined in Tab. 2, was identified, which represents a good compromise between accuracy and experimental costs.



a) longitudinal



b) lateral

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

As far the present application, two different runs were carried out: a first one was carried out without the model, to have the wall pressure distribution in empty conditions, the second run with the model. The wall pressure data are obtained as the difference between the two runs.

For the present experiments the test section cart has been modified; holes of 1 mm diameter have been drilled on half part of the walls following the scheme shown in fig. 2.

Pressure probes (holes) are connected to the Scanivalve trough *Festo* connectors and silicon tubes. Pressures are measured at a sampling rate of 20 Hz; the maximum measurable pressure for modules is 103 KPa. The uncertainty in the pressure measurements, for the present tests, was evaluated to 0.03 KPa.

Once the pressure data are obtained in the points defined by the procedure, they are linearly interpolated in the longitudinal direction; following the results in Ref. 2, 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 and cubic splines on the lateral wall.

3.3 The models

The Mirage F1 model was selected because available in different scales: 1:15, 1:32, and 1:40, as required for the purpose of the experiment. Only the two smaller models have been used.

The Mirage F1 with a wing tail configuration featuring moderate AR (2.83).

The nominal blockage factors, defined as the ratio between the model cross section area and the test section area at zero angle of attack, are reported in Tab. 3.

	1:40 Model	**1:32 Model**
Blockage Factor	0.0101	0.0158
b	0.210	0.263
b/w	0.467	0.584

Tab 3: Blockage chacteristics

The model span and the ratios between the model span and the wind tunnel width are also shown. The aerodynamic forces are non-dimensionalized with the dynamic pressure and the wing plan form area, while the reference length for the moment coefficients (referred to the quarter chord point of the mean aerodynamic chord) is the wing mean aerodynamic chord itself; the nominal values of the reference data are reported in Tab. 4.

	1:40 Model	**1:32 Model**
Wing area	0.0157	0.0245
m.a.c.	0.826	.1032
$x_{\mathbf{m.a.c.}}$ (from nose)	0.215	0.269

Tab 4: Reference values

To reduce the effects of Reynolds number, models will be provided with fixed transition stripes, located at 10 % of the wing chord.

A sketch of the 1:32 scale model in the wind tunnel is shown in Fig. 3.

Fig. 3 - Mirage F1 1:32 scale ready to go

3.3.1 Geometry verification

A quality control inspection was carried out on the models; it was accomplished on a 2202 DEA IOTA Coordinate Measuring Machine with computerised measuring and recording capability. The uncertainty in the linear measurements is lower than 0.01 mm.

Four wing sections are verified, as defined in Fig. 4: the root section, the tip section, and two section (referred as A and B) immediately in-board and out-board of the leading edge discontinuity.

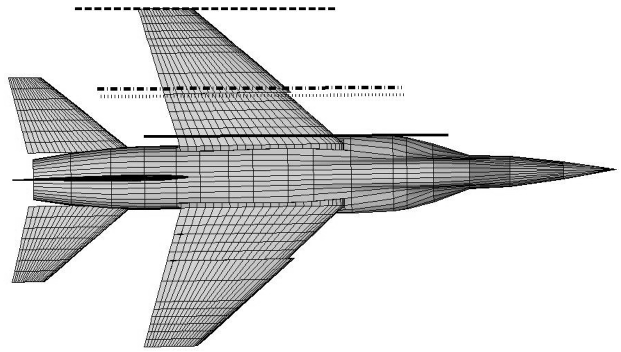


Fig. 4 – Definition of the verified sections

The differences in the geometry section are very small. The most significant dimensions for the two model wings are reported in Tab. 5, together with the corresponding full scale values, while the general geometrical features are shown in Tab. 6.

From the data in Tabs. 5 and 6 it can be seen that the model geometries are very close. The only significant difference was found on the wing dihedral angle: in fact, the 1:40 model has a dihedral angle of 6.59°, while for the 1:32 model it is 5.11°. To analyze this problem a numerical analysis of the configuration with both the dihedral angles was carried out, and the results show that negligible differences in the aerodynamic coefficient are related to this difference.

	1:32 Model	**Corresponding full scale**	**1:40 Model**	**Corresponding full scale**	**Difference (%)**
Root chord	41.275	1320.8	32.339	1293.6	0.020
Sec. A chord	93.562	2994.0	73.623	2944.9	0.016
Sec. B chord	96.973	3103.1	76.221	3048.9	0.017
Tip chord	120.42	3853.5	92.408	3696.3	0.040

Tab 5 - Comparison between the two wing models

	1:32 Model	**1:40 Model**	**Full scale Difference (%)**
Planform area	12482.0	7720.6	0.033
Span	262.95	209.88	0.0022
Mean Aerodynamic Chord	96.027	73.965	0.0371
Fuselage width at wing leading edge	4.83	6	0.006
Fuselage height at wing leading edge	3.56	4.49	0.009
Fuselage width at wing trailing edge	3.74	4.73	0.011
Fuselage height at wing trailing edge	3.52	4.49	0.020
Total length	360	450	0
Nose length	6.8	7.57	0.123
Horizontal tail span	4.5	5.56	0.011

Tab 6 - Main geometrical characteristics of the two models

4 Analysis of the results

The described procedure was applied for the flow at a Mach number of 0.58. The results for an angle of attack of 7.84°, characterized by not significant separation of the flow, are summarized in Tabs. 7 and 8, in term of lift coefficient, pitching moment coefficient and estimation of the point of application of the lift (- c_M/c_L). As an example, the wall pressure distributions along four different longitudinal lines are reported in Figs. 5 and 6, for the model scale 1:40 and 1:32, respectively.

As expected, the correction terms, both for lift and pitching moment, increase with the blockage factor, as can be seen also by analyzing Figs. 5 and 6. It is interesting to observe that these terms are significant: moving from to 1:40 to 1:32 scale models the measured lift increase from 0.536 to 0.560, corresponding to 4.3%. The difference appears significant also for the pitching moment, but it is worth to observe that the difference in the point of application of the lift appears to be quite small.

After the application of the correction procedure the lift coefficients are significantly lower, about 0.51, and the difference between the two scale models is reduced to 1.5%. This is far from the desired accuracy (see, for instance, Ref. 8), but it can be considered a satisfactory result, tacking into account that the difference after the correction, as previously observed, is probably related to experimental errors for the force measurement and model position. In all cases, results after the correction are significantly closer for the two models than the uncorrected ones. Furthermore, it must be considered that the results without correction are affected by a significant error.

For the pitching moment the accuracy appears satisfactory: the corrected estimation of the lift point of application appears practically the same for the two models.

	1:40	**1:32**	**Difference**	**Diff. %**
Experimental	0.5356	0.5599	0.0243	4.3
Correction Term	0.0252	0.0418		
Corrected Result	0.5104	0.5181	0.0077	1.5

Table 7 α=7.84°, lift coefficient values

	C_M			**- C_M/C_L**	
	1:40	1:32	Difference	1:40	1:32
Experimental	-0.08057	-0.08492	0.00435	0.1504	0.1517
Correction Term	-0.01870	-0.02200			
Corrected Result	-0.06187	-0.06292	0.00105	0.1212	0.1214

Table 8 – α=7.84°, pitching moment coefficient values

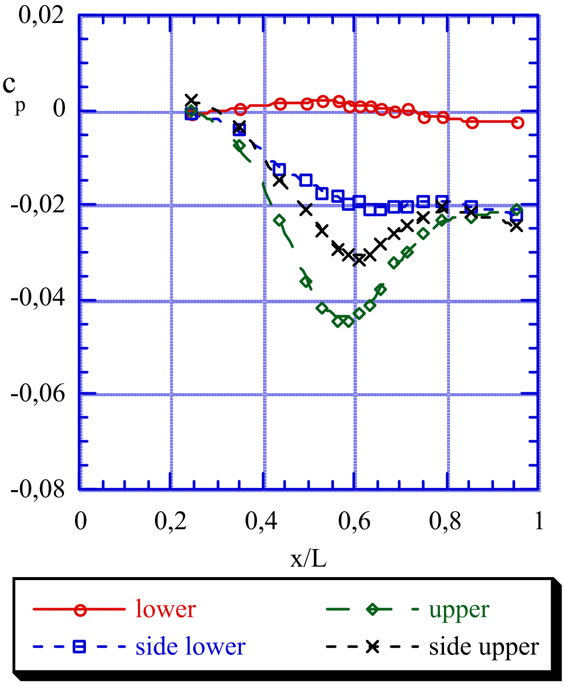


Fig. 5 – Longitudinal wall pressure distributions
α = 7.84°, scale model 1:40

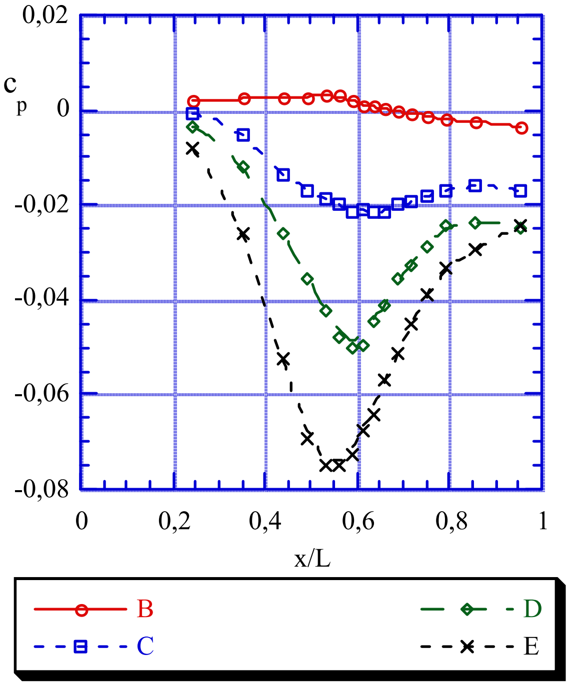


Fig. 6 – Longitudinal wall pressure distributions
α = 7.84°, scale model 1:32

The results for a lower angle of attack (3.74°) are shown in Tabs. 9 and 10, while the wall pressure distributions along the same longitudinal lines as previously are reported in Figs. 7 and 8, for the model scale 1:40 and 1:32, respectively.

	1:40	1:32	Difference	Diff. %
Experimental	0.2431	0.2555	0.0124	4.9
Correction Term	0.0078	0.0145		
Corrected Result	0.2353	0.2410	0.0057	2.4

Table 9 - α=3.74°, lift coefficient values

	C_M			$-C_M/C_L$	
	1:40	1:32	Difference	1:40	1:32
Experimental	-0.04714	-0.04817	-0.00103	0.1939	0.1885
Correction Term	-0.00127	-0.00260			
Corrected Result	-0.04587	-0.04557	0.00030	0.1949	0.1891

Table 10 - α=3.74°, pitching moment coefficient values

This condition is clearly characterized by a lower wall interference effect and this leads to a greater sensitivity to the measurement uncertainty (both for the forces and the wall pressure). Indeed, by comparing the results with those of the previous analyzed condition, it is evident that the lift coefficient is characterized by a lower accuracy after the correction procedure, with a difference of 2.4% between the two models. Also for the pitching moment results are less accurate: a difference of about 0.6 of the mean aerodynamic chord remains in the evaluation of the point of application of the lift.

This shows that, as expected, the correction procedure is as more accurate as more important are the wall effect to be corrected.

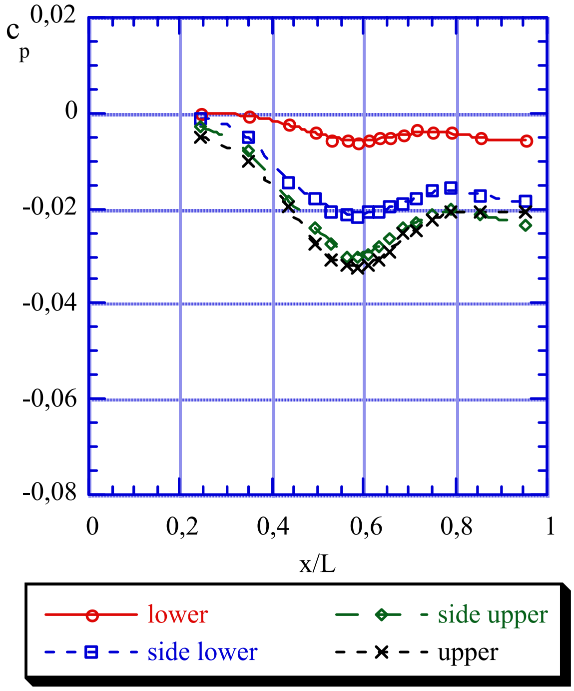


Fig. 7 – Longitudinal wall pressure distributions
α = 3.74°, scale model 1:40

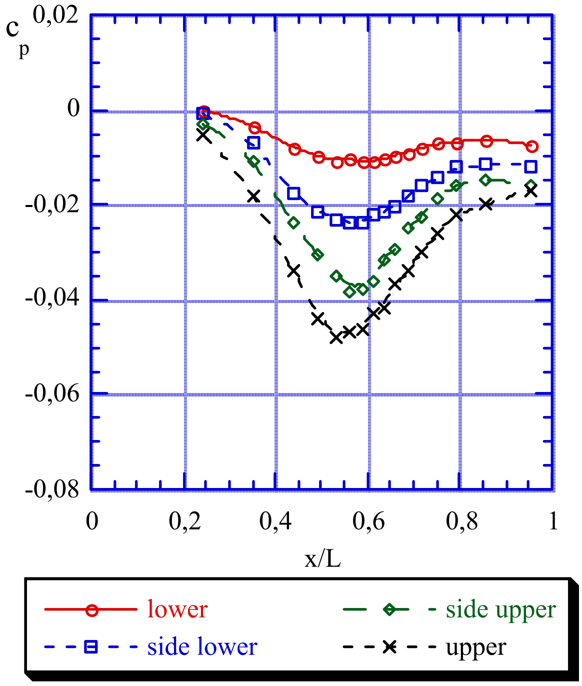


Fig. 8 – Longitudinal wall pressure distributions
α = 3.74°, scale model 1:32

5 Concluding remarks

A method of correction for the wall interference effects, based on pressure measurements on the wind tunnel walls coupled with a numerical procedure, has been developed to evaluate the flow correction. In the present paper the methodology is applied to experimental data, therefore as a “post-test” procedure.

The present research activity addresses wall interference effects on longitudinal aerodynamic characteristics, especially as related to pressure-dependent forces.

The use of different scale models, operating in a given wind tunnel under identical flow conditions, appears to be the most appropriate procedure to gain information on the validity of the proposed correction procedure. Indeed, this approach eliminates all differences due to different flow conditions, and the uncertainty in measurement comparisons is considerably reduced - being limited to the random component (which can be reduced, theoretically, to any desired values) of the measurement procedure as well as to the bias uncertainty related to balances and accuracy of the model geometry.

Tests are carried out for two different scale models of the same geometry in the High Speed Wind Tunnel (HSWT) at the CSIR. The used models are 1:32 and 1:40 scale representations of the Mirage F1.

Subsonic conditions (M=0.58) and angle of attack characterized by not significantly separated flow (α=4° and 8°) are considered; a potential flow solver, with wake relaxation, is used for the numerical part of the correction procedure.

After the application of the correction procedure the lift coefficients are significantly lower and the difference between the two scale models is reduced to 1.5% at $\alpha \cong 8°$ and 2.4% at $\alpha \cong 4°$, and the accuracy of the pitching moment prediction is increased. Nevertheless the corrected values are still far from the desired accuracy, the results may be considered satisfactory, tacking into account that the difference remaining after the correction is related also to other error sources (Reynolds number, force measurement and model position). In all cases, results after the correction are significantly closer for the two models than the uncorrected ones.

As expected, the correction procedure appears as more accurate as more important are the wall effects to be corrected. Therefore, great care must be taken to decide when it is worth to apply the proposed correction procedure: indeed, for low blockage factors and low angles of attack, when the wall effects are very small, it is possible that measurement errors in the wall pressure evaluation produce errors in the correction procedure higher than the correction term itself.

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