NUMERICAL ANALYSIS OF BLOCKAGE EFFECTS IN SLOTTED WIND TUNNELS

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Abstract

A procedure is proposed for the correction of wind tunnel blockage effects on the experimental measurement of aerodynamic coefficients. The correction is obtained as the difference between the values obtained in two different 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 necessary preliminary step is the choice of the number, location and accuracy of the pressure measurements. A strategy is proposed to determine these parameters, based on the same correction procedure in which the experimental part is replaced by numerical simulation. This strategy is applied to the subsonic flow around a complete aircraft configuration by means of a potential flow solver. Preliminary results for transonic flow around a wing section, obtained through a Navier-Stokes solver, are also presented.

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 [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 [2], based on more complex procedures, which couple measurements - typically pressure and/or velocity on the wall or in the field - with numerical calculations. The implementation of these procedures is complex 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. 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. In a previous work [3], an analysis on the blockage effects in the Medium Speed Wind Tunnel (MSWT) of the CSIR Laboratories, in South Africa, was presented. The MSWT is a closed circuit variable density transonic wind-tunnel, with operational speed from M=0.25 to M=1.5; the test section has a 1.5m x 1.5m square cross section, and the length is 4.5 m. All four walls are equally longitudinally slotted for a total porosity of 5%. The results showed that very low blockage factors are required to have small wall interference effects.

Tacking into account this consideration and the increase in computing capabilities, we decided to develop a method of correction for the MSWT, based on pressure measurements on the wind tunnel walls coupled with a numerical method to evaluate the flow correction.

This method is described in detail in section 2. In section 3 the problem of the definition of the number and location of the pressure measurement points on the wind tunnel walls is investigated. In particular, a sensitivity analysis is carried out in which the experimental pressure measurements are simulated numerically by different flow solvers.

2 The correction procedure

2.1 Description

The correction methodology employed in the present analysis is a so-called "post-test" procedure [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. The choice of a post test procedure is motivated by the fact that slotted walls do not allow accurate analytical boundary conditions to be devised and this makes "pre-test" corrections not suitable.

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.

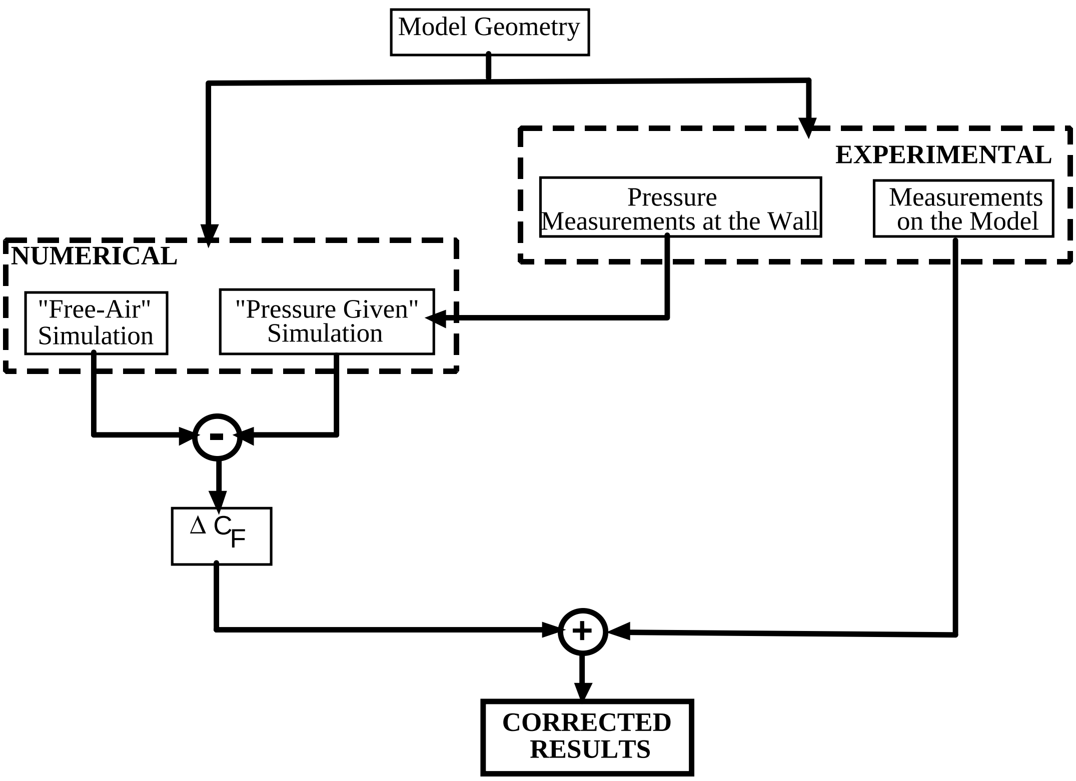


Fig. 1 – Scheme of correction procedure

The scheme of the correction procedure, which is based on the method proposed by Sickles [4], is shown in Fig. 1.

Once the model geometry is defined, the experimental tests are carried out and, in particular, 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.

2.2 Numerical and experimental issues

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

The second issue concerns the experimental measurement of pressure over the wind tunnel walls. In particular, 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 preliminary 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.

In this paper, a strategy is proposed, based on the previously described correction procedure, in which the experimental part is replaced by a numerical simulation. Thus, an additional computation (denoted as "tunnel" simulation) is carried out of the flow around the model in the wind tunnel. Then, the pressure values obtained in this simulation are used as boundary condition for the PG numerical simulation. As previously, the difference in the aerodynamic force values obtained in the PG and FA computations will give the desired correction. In this way, an analysis of the sensitivity of the correction to both number and position of the pressure sensors can be carried out. Similarly, the required level of accuracy of the pressure sensors can be estimated. The cost and time needed for this analysis clearly depend on the used flow solver; however, in all cases, they are much lower than those required by a similar study carried out experimentally. Note also that in most cases an experimental sensitivity analysis is unaffordable in practice.

3 Definition of the experimental wall pressure measurements

3.1 Preliminary choices

Some preliminary choices have been made which allow the number of free parameters in our analysis to be reduced. First of all, we decided to perform pressure measurements on only half of the wind tunnel section in the lateral 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; these are located at the center of the slats present on the wind-tunnel walls, as sketched in Fig. 2. Thus, the lateral distribution of the pressure sensors is uniquely determined by their number, N_c, and by the position of the slats over which sensors are present.

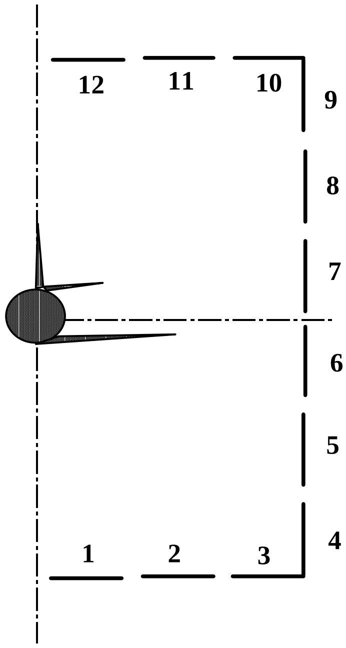


Fig. 2 - Sketch of the wind tunnel cross-section

As concerns the sensor distribution in the longitudinal direction, it is clear that the pressure sensors should be clustered in the regions where high gradients are present in the flow and, thus, near the model. The inverse of the distance between a sensor and the model rotation point is determined here from a gaussian function centered at the model rotation point. Thus, the longitudinal distribution is uniquely defined by the number of sensors in that direction, N_l, and by the standard deviation, σ, of the gaussian function.

In order to define acceptable values of the previous parameters, the acceptable accuracy of the correction method should be previously identified. Let us consider that the desired accuracy of the aerodynamic force measurements is a priori fixed. The accepted global error, ε_{tot}, is due to different sources, as sketched in Fig. 3.

By assuming that the optimal error distribution is that in which all error sources, at each level, are of the same order, the acceptable error on the representation of wall pressure distribution is $\varepsilon_{pr} \approx 1/8\ \varepsilon_{tot}$.

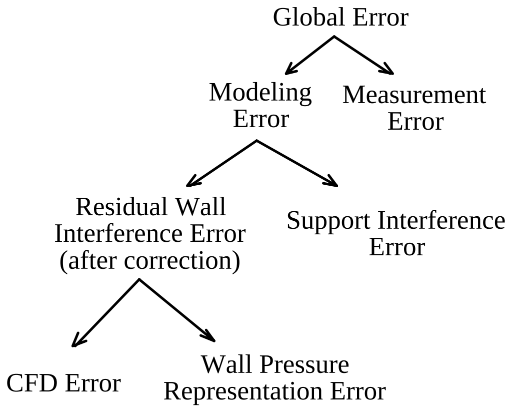


Fig. 3 – Error distribution graph

In the present study we assume as global acceptable errors the values suggested in [5], i.e. 0.01 on the lift coefficient and 0.001 on the pitching moment coefficient.

3.2 Sensitivity analysis by a potential flow solver

A first sensitivity analysis is carried out by a potential flow solver [6]. This solver is based on Morino's formulation, and its capabilities were presented, for a complete aircraft, in [7]. Boundary conditions for slotted walls have been implemented in the potential code, following the method proposed in [8].

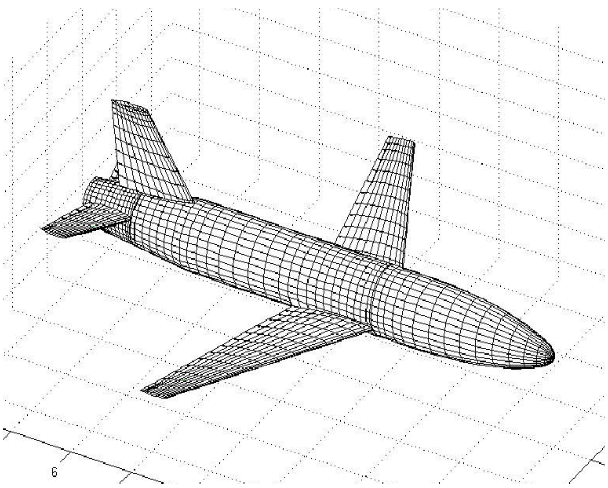


Fig. 4 – The ONERA M5 geometry

The analyzed geometry is the ONERA M5 configuration, shown in fig. 4; the reference condition is characterized by an angle of attack

α=0° (corresponding to $C_L \approx 0.25$), a Mach number M=0.4 and a blockage factor of 1.5%.

A sensitivity analysis to the number of panels has been carried out, and the presented results are obtained with approximately 7000 panels (3000 on the model).

The lift coefficient C_L and the pitching moment coefficient (referred to the wing aerodynamic center) C_m, obtained in the "free-air" simulation and for the model mounted in the wind tunnel, are shown in Tab. 1. The resulting wall interference effects, ΔC_L and ΔC_m, are also reported.

	C_L	C_m
Free-air	0.2490	0.28666
Tunnel	0.2367	0.27538
Difference Δ	0.0123	0.01128

Tab. 1 – Reference Solutions

Note that for the considered configuration the blockage effects are rather small; hence, this test case is particularly challenging for the correction method, since the required accuracy is clearly higher when we are dealing with small quantities.

As a first step in our sensitivity analysis, in the transversal direction we use all the pressure data obtained in the wind tunnel simulation ("infinite" sensors). We analyze then the sensitivity to the parameter N_l, i.e. we take only N_l pressure values among those obtained in the wind tunnel simulation, distributed as described previously, with σ=2.1. The pressure values in the remaining panels are obtained by linear interpolation of the N_l used data. The residual errors after the correction procedure are shown in Tab. 2, for both C_L and C_m.

N_l	ε_{pr} for C_L	ε_{pr} for C_m
25	.00005	.00007
20	.00012	.00016
15	.00025	.00025
10	.00032	.00050

Tab. 2 – Residual error for different longitudinal sensor number

The residual error on both C_L and C_m decreases monotonically as the number of longitudinal sensors increases. The adopted accuracy limits (see section 3.1) are always verified for C_L, while at least 20 sensors are required for C_m. This is not surprising since it is well known that the correction on the pitching moment is more critical.

Different values of the parameter σ have been analyzed, and it appeared that the residual error tends to decrease as σ decreases; however, when σ <2.5, the sensitivity is low.

We analyze now the sensitivity to the number and distribution of pressure sensors in the lateral direction; "infinite" sensors are considered in the longitudinal direction. The analyzed configurations are summarized in Tab. 3, while the corresponding residual errors after the correction are reported in Tab. 4.

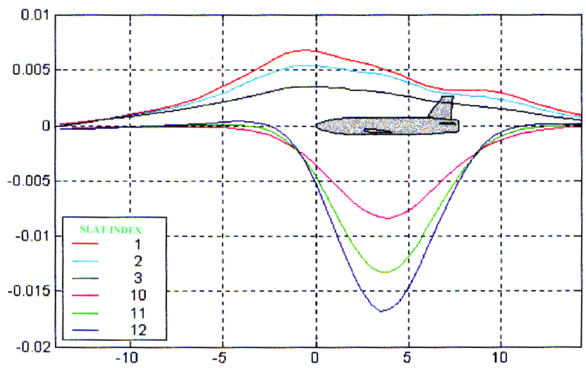
N_C Configuration	Slats with sensor
12	ALL
10	All except 2, 11
8A	1-3-5-6-7-8-10-12
8B	1-3-4-5-8-9-10-12
8C	1-3-4-6-7-9-10-12
6	1-3-5-8-10-12

Tab. 3 – Definition of lateral configurations (see Fig. 2)

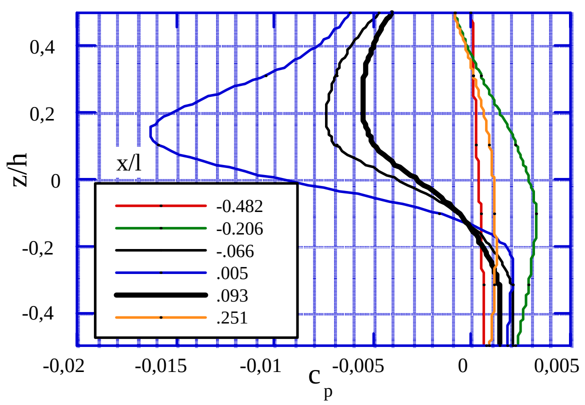
N_C Config.	ε_{pr} for C_L	ε_{pr} for C_m
12	-.00028	-.00011
10	-.00044	-.00021
8A	-.00023	-.00004
8B	-.00110	-.00038
8C	-.00103	-.00053
6	-.00092	-.00021

Tab. 4 – Residual error for different lateral sensor number

The residual errors on both C_L and C_m are globally higher than the corresponding errors due to a limited number of sensors in the longitudinal direction. Moreover, the behavior is not monotonic with respect to N_C; note, for instance, that the accuracy obtained with 10 sensors is lower than that given by 8 sensors in configuration 8A. This behavior can be explained by analyzing the wall pressure distributions obtained in the wind tunnel simulation, reported in Fig. 5. In the longitudinal direction, as expected, high gradients are present in correspondence to the model. Since in the adopted longitudinal distribution the sensors are clustered in this region, this effect is reasonably well captured also with a limited N_l. Even steeper gradients are found in the lateral direction, near the model. However, in this direction, we chose to locate only one sensor per slat; thus, these gradients are ill represented because a very low number of pressure data are used in this region and they are linearly interpolated. This explains also why the correction accuracy is very sensitive to the lateral location of the sensors. Thus, it appears that, to obtain an acceptable residual error with a limited N_c, a more accurate interpolation must be used.



a) upper and lower walls



b) lateral walls

Fig. 5 - Pressure coefficient along the wind tunnel walls

Thus, the following interpolation has also been used for the lateral direction:

- a parabolic law on the upper and lower walls of the cross-section (see Fig. 2), in which a symmetry condition is imposed on the centerline;
- cubic splines on the lateral wall.

The residual errors obtained with “infinite” sensors in the longitudinal direction and different N_c for this new interpolation law, are reported in Tab. 5.

N_c Config.	ε_{pr} for C_L	ε_{pr} for C_m
10	0.00001	-0.0000063
8A	0.00001	-0.0000188
6	0.00041	0.0000211

Tab. 5 – Residual error for different lateral sensor number with parabolic-cubic pressure interpolation

By comparison with the values in Tab. 4 it appears that, as expected, for fixed N_c, a more accurate interpolation leads to a more accurate correction. In particular, note that now acceptable errors are obtained for all the considered configurations.

A number of different configurations have also been analyzed, by taking a limited number of sensors in both longitudinal and lateral directions. The results, not reported here for sake of brevity, show that, for both C_L and C_m, the residual error due to limited N_l and N_c, can be reasonably expressed as follows:

$$\varepsilon_{pr}(N_l, N_c) \approx \varepsilon_{pr}(N_l, \infty) + \varepsilon_{pr}(\infty, N_c)$$

This means that the two error sources are substantially uncoupled and thus the considerations made on the basis of the previously described analyses hold also for real configurations with limited N_l and N_c.

In the previous analyses the experimental error in pressure measurements has not been considered, since the exact pressure values obtained in the wind tunnel simulations have been used. A sensitivity analysis to the error in pressure measurements has been carried out for a few selected configurations in terms of N_l and N_c, namely 18x10, 18x8, 15x10 and 15x8. The cases having 8 lateral sensors correspond to the configuration previously called 8A. To this aim, the wall pressure values obtained in the wind tunnel simulation are perturbed by a priori fixed quantities. The same quantity is added to all the considered sensors, which represents the maximum error of the pressure transducers, E. The perturbed pressure values are then used in the PG simulations.

The residual error after correction increases linearly with the error in pressure measurements, as shown, for instance, in Fig. 6, for the lift coefficient. Moreover, it is practically independent on the number and distribution of the sensors. Similar results have been obtained for the pitching moment coefficient (not shown here for sake of brevity).

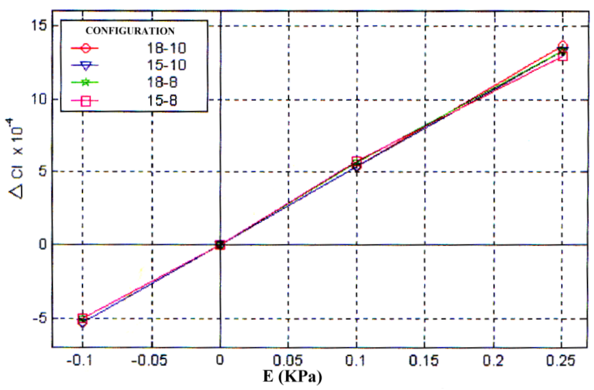


Fig. 6 – Residual error for different experimental error in pressure measurements

Summarizing, the residual error after correction, due to all the sources previously considered, can be expressed as:

$$\varepsilon_{pr}(N_l, N_c, E) \approx \varepsilon_{pr}(N_l, \infty, 0) + \varepsilon_{pr}(\infty, N_c, 0) + k\,E$$

whit k independent of N_l and N_c. For the analyzed configuration k can be estimated to be 0.054 and –0.144, respectively for C_L and C_m, if E is expressed in Kpa.

3.3 Choice of a sensor configuration

On the basis of the previously described sensitivity analysis, different sensor configurations satisfying the required accuracy of the correction have been identified.

A compromise between accuracy and number of sensors is the configuration with 160 pressure sensors, denoted as “final” configuration (FC). FC is characterized by N_c=10 and N_l=16; the longitudinal sensor distribution is that obtained as previously described with σ=2.1 and N_l=18, in which the first two up-wind transversal rows are not used, because of the negligible values of the pressure perturbations at those positions.

This selected configuration has been investigated also in different flow conditions, namely M=0.4 at α=2° and M=0.6 at α=0° and 2°. The results show that the residual errors are of the same order or lower than in the condition used for the sensitivity analysis. This confirms that, at least for subsonic flow conditions in which the correction to be applied is larger are less critical for the correction procedure.

All the previous considerations must be verified for transonic conditions. Clearly, this must be done through a Navier-Stokes solver.

4 Preliminary results by a Navier-Stokes solver

Because of the large computational cost of 3D Navier-Stokes simulations, a preliminary analysis has been carried out for the 2D flow around a NACA 0012 wing section at M=0.7 and α=8°. The chord of the wing section is c=0.4 m and the dimensions of the wind tunnel are the same as previously. This leads to a blockage factor of about 5%. The chosen conditions are particularly critical for the correction method, because the blockage factor is rather high for transonic flow, the shock-wave on the airfoil is more intense in 2D, and non-slotted wind tunnel walls are considered.

The simulations are carried out by the commercial code FLUENT 5.0, using unstructured grids having about 28000 cells for tunnel and PG simulations, and 36000 for the free-air calculation. The Reynolds-averaged Navier-Stokes equations are discretized by a second-order finite-volume method, and the standard k-ε turbulence model is used.

The aerodynamic coefficients for both free-air and tunnel simulations are reported in Tab. 6. In this case also the correction on the drag coefficient is considered.

	C_L	C_D	C_m
Free-air	1.040	0.1610	0.0100
Tunnel	1.057	0.1913	0.0410
Difference Δ	-0.017	-0.0303	-0.0310

Tab. 6 – Reference Solutions in transonic regime

Note that the correction on C_L is small, but this corresponds to significantly different pressure distributions over the airfoil, especially behind the shock wave (Fig. 7), as expected, since this configuration is characterized by large blockage effects. Indeed, the correction on both drag and pitching moment coefficients is significant.

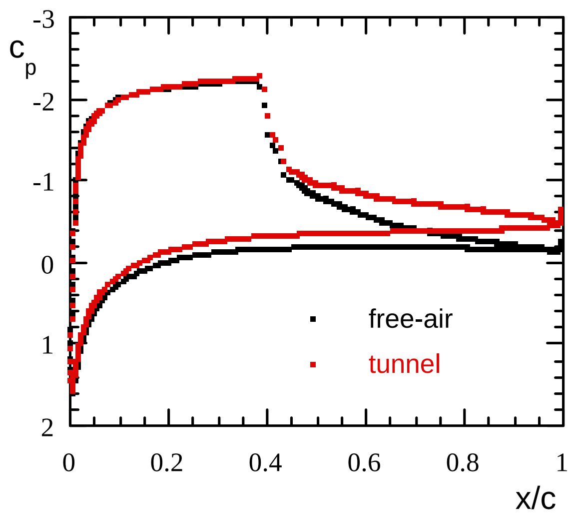


Fig. 7 – Pressure distribution along the chord

Tab. 7 shows the residual errors obtained after the correction for the PG simulation carried out with “infinite” sensors (i.e. by using all the wall pressure values obtained in the tunnel simulation), together with those obtained for configuration FC.

sensors	ε_{pr} for C_L	ε_{pr} for C_D	ε_{pr} for C_m
infinite	-0.094	-0.0057	-0.0120
FC	-0.090	-0.0057	-0.0110

Tab. 7 – Residual errors

It is evident that the correction method is not satisfactory, even when all the pressure data are considered. From Fig. 8 it appears that the blockage effects on the pressure distribution after the shock wave are rather well captured in the PG simulations. However, the location of the shock wave is significantly different than in the tunnel simulation, and this leads to large inaccuracy in the correction of the aerodynamic coefficients.

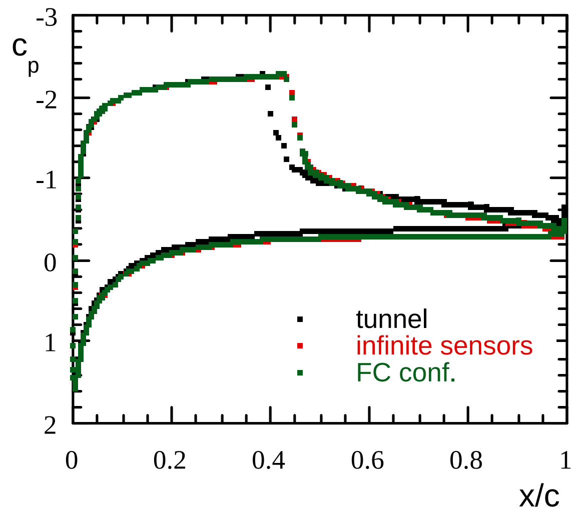


Fig. 8 – Pressure distribution along the chord

However, remark that, as previously mentioned, this test case is particularly critical for the correction method, since it is characterized by a shock wave strongly interacting with the wind tunnel walls, as can be seen, for instance, from the pressure distribution on the upper wall (Fig. 9). Note, however, that the residual errors and the pressure distribution obtained with the FC sensor configuration are practically the same as with “infinite” sensors, and this confirms that a satisfactory approximation of the wind tunnel pressure distribution is obtained with this sensor configuration.

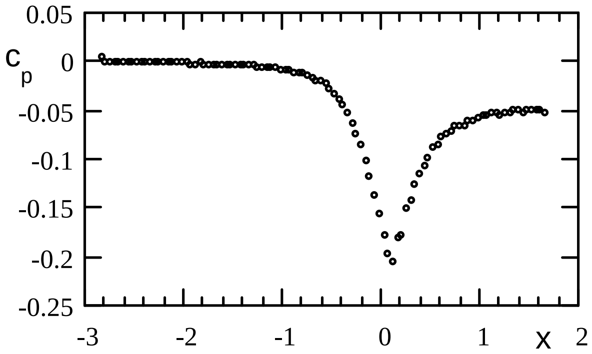


Fig. 9 – Pressure coefficient along the upper wall

5 Concluding remarks

A procedure has been setup for the correction of wind tunnel blockage effects on the experimental measurement of aerodynamic coefficients. 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 necessary preliminary step is the choice of the number, location and accuracy of the pressure measurements. A strategy has been proposed to determine these parameters, based on the same correction procedure in which the experimental part is replaced by a numerical simulation.

Some preliminary choices have been made in order to reduce the number of free parameters to be determined. First, the wall pressure values are measured only on half of the wind-tunnel cross section and only one sensor can be located on each slat. Thus, the lateral distribution of pressure sensors is uniquely determined by their number, N_c, and by the position of the slats over which sensors are present. The longitudinal distribution has been assumed to be gaussian, centered at the model rotation point; hence, it is defined by the number of longitudinal sensors, N_l, and by the standard deviation σ of the gaussian. Finally, the acceptable accuracy of the correction method has been identified, given the desired accuracy of the aerodynamic force measurements.

Then, a first analysis of the sensitivity of the correction accuracy to the previously defined parameters has been carried out using the ONERA M5 configuration in subsonic conditions, and a potential flow solver. It has been found that the residual errors on the aerodynamic coefficients after the correction can be expressed as the sum of the errors due only to the limited number of sensors in the longitudinal direction and the analogous ones in the lateral direction. The error in the longitudinal direction decreases monotonically as N_l increases and is only marginally sensitive to σ. Conversely, the residual error in the lateral direction is not monotonic with N_c, depending on the sensor location. Moreover, the errors are globally higher than the corresponding ones in the longitudinal direction. This behavior is due to steep lateral pressure gradients present on the wind tunnel walls and is significantly improved by using cubic/quadratic interpolations of the pressure data.

Finally, the residual errors after correction have been found to increase linearly with the error in the pressure measurements.

On the basis of this analysis, a configuration characterized by N_l=16 and N_c=10 has been identified, which represents a good compromise between accuracy and experimental costs.

A preliminary study is also presented to verify the validity of the previous considerations in transonic conditions. The Reynolds averaged Navier-Stokes equations have been numerically discretized. Because of the large computational cost of 3D Navier-Stokes simulations, the flow around a NACA 0012 has been simulated for a blockage factor of 5%. The residual errors after correction, obtained considering all the available pressure data on the wind tunnel walls, were not acceptable. The reasons of this behavior could be due to the numerical aspects; for instance, the grid resolution could be too coarse, especially near the walls and the airfoil, or the used numerical flow solver could be not well suited with pressure given boundary conditions. Further studies are needed to investigate these aspects. However, as mentioned previously, this test case is particularly critical for the correction method. Indeed, the blockage factor is rather high for transonic conditions, the shock wave on the airfoil in more intense in 2D and non-slotted wind tunnel walls were considered in the numerical simulations. Thus, to verify the proposed procedure for transonic flows, further investigations will be carried out in 2D, with a smaller blockage factor, and in 3D for a complete aircraft configuration. However, note that with the final sensor configuration identified in subsonic conditions, the results are practically the same as those obtained by using all the pressure data. This seems to indicate that, also in this case, a satisfactory approximation of the wind tunnel wall pressure distribution is obtained with this configuration.

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