

EXPERIMENTAL AND NUMERICAL ANALYSIS OF THE TEST SECTION SLOTS IN WIND TUNNELS

Sergio Antonio de Oliveira Neto

Layra Mendonça Silva

Technological Aeronautical Institute (ITA), Pça. Marechal Eduardo Gomes, 50, Vila das Acácias - CEP: 12228-904, São José dos Campos, São Paulo, Brasil

sergioaer@gmail.com

layramendonca@gmail.com

Ana Cristina Avelar

Aeronautical and Space Institute (IAE), Aerodynamics Division (ALA), Pça. Marechal Eduardo Gomes, 50, CEP: 12228-904, São José dos Campos, São Paulo, Brasil

anacristina.avelar@gmail.com

João Batista Pessoa Falcão Filho

Aeronautical and Space Institute (IAE), Aerodynamics Division (ALA), Pça. Marechal Eduardo Gomes, 50, CEP: 12228-904, São José dos Campos, São Paulo, Brasil

falcãojbpf@iae.cta.br

Abstract. The Institute of Aeronautics and Space (IAE) has in its Aerodynamic Division (ALA) the Pilot Transonic Wind Tunnel (TTP) which is a scaled down 1:8th from an industrial facility. One of the tunnel objectives is to support research in the transonic range, helping the development of sounding rocket and satellite launcher vehicles. A long term test campaign has been undertaken to assess the pressure distribution over a NACA0012 profile as the scientific literature gives abundant theoretical and experimental results and they can be utilized in comparisons. With the aim of understanding the aerodynamic behavior of the tunnel the present work utilizes numerical simulation techniques to investigate the tunnel functionalities, concerning the behavior of the test section slotted walls. Both conditions with solid and slotted walls are simulated numerically and experimentally for the NACA0012 profile with a chord of 83 mm installed in the test section. Pressure distribution over the profile is obtained both with conventional pressure taps and with PSP technique (Pressure Sensitive Paint). The results are compared in order to confirm with both approaches the effectiveness of the slotted walls in suppressing the wave reflections and the wall presence. The numerical simulation solves the Euler equations in two-dimensional, generalized coordinates, centrally centered cells in structured grid. Mach numbers ranging from 0.4 to 0.85 are analyzed in the study cases and the slotted walls are simulated in a particular procedure to be represented by a two-dimensional simulation.

Keywords: Transonic, Wind Tunnel, Solid Wall, Slotted Wall, Wall Interference

1. INTRODUCTION

There is a group of wind tunnels at the DCTA, Aerospace Science and Technology Department, the scientific branch of the Brazilian Aeronautical Command, installed in São José dos Campos, Brazil. The tunnels are part of Aerodynamic Division (ALA) of the Aeronautics and Space Institute (IAE) from the DCTA. Among the several facilities there is a transonic wind tunnel, TWT (GOFFERT, B., ORTEGA, M.A. and FALCÃO FILHO, 2014). The Pilot Transonic Wind Tunnel (TTP) of the Institute of Aeronautics and Space (IAE) is a closed aerodynamic circuit installation driven by a main axial compressor with two stages with total power of 830 kW and a maximum rotation speed of 7600 RPM. Figure 1 shows a diagram of the tunnel's aerodynamic circuit highlighting its main components: 1 to 4 – circuit corners, 5 – main compressor installed in corner 2, 6 – cooler, 7 – stagnation chamber where turbulence control screens are located, 8 – contraction, 9 – first throat, 10 – test section, 11 – re-entry flaps, 12 – second throat, 13 – injection chamber, 14 – high speed diffuser, 15 – possible location of a F.O.D. (Foreign Object Damage) screen (in dotted line), 16 – original F.O.D. screen (in dotted line). The test section and other components close to it are enclosed by a plenum chamber to equalize the pressure outside the semi-open tunnel walls in order to establish uniform transonic regime flow. The tunnel runs continuously in the Mach number range from 0.2 to 1.2 and intermittently with combined action of the injectors up to Mach number 1.3. Auxiliary compressor (not shown in figure) works through tubing and control valves (partially indicated in figure) to adjust the stagnation pressure in the circuit from 0.5 bar to 1.2 bar, and a cooling system to control

the total temperature (FALCÃO FILHO and MELLO, 2002).

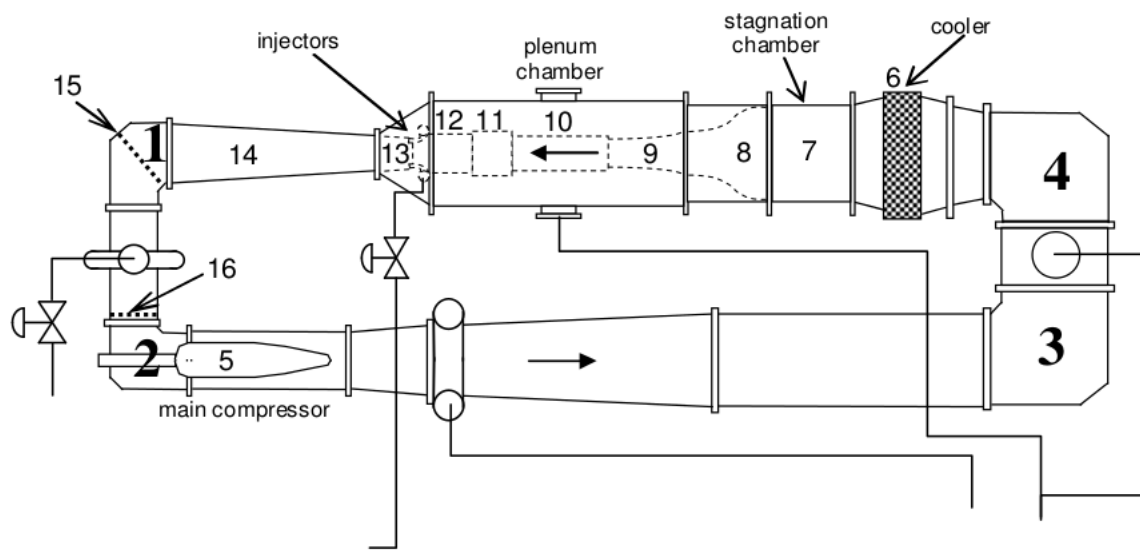


Figure 1. Scheme of the aerodynamic circuit of TTP.

One of the most defying problems in the evolution of wind tunnel technology is the transonic flow establishment. The solution came with the introduction of openings in the test section walls. This discovery brought to the scene the so called slotted or perforated walls — see Fig. 2 (an example of slotted walls). Besides the choking phenomenon there are other undesirable effects at the Mach one range, namely, shock and/or expansion wave reflections at the walls and a modification of the streamlines pattern when compared to the free flow. These effects are avoided, or at least much alleviated, by the presence of the openings. In order to maintain a good control of the aerodynamic circuit stream it is proper to install a plenum chamber. The plenum chamber isolates the test section, and permits the return to the circuit of all mass flow that eventually crossed the walls at the test section. Figure 3 illustrates this important effect (GOFFERT, B., ORTEGA, M.A. and FALCÃO FILHO, 2014).

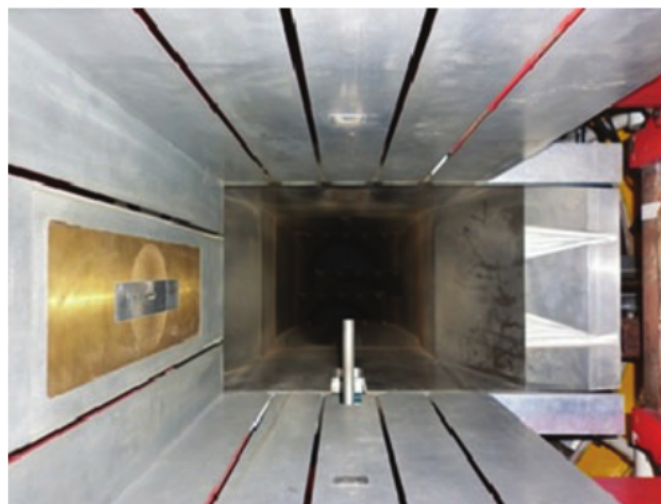


Figure 2. Test section of the TTP showing the slotted walls.

The transonic speed regime is classified, somewhat arbitrarily, as the range of free stream or flight Mach numbers between 0.7 and 1.3, and a transonic wind tunnel is one which will efficiently produce all Mach numbers within this range. But it is best defined the transonic regime as one in which there is supersonic and subsonic regions coexisting. The Reynolds number and/or model size are of such great importance that to require one tunnel also to cover a wide Mach number range results in a very large tunnel of great complexity and exorbitant cost. Thus one finds that existing and proposed tunnels are designed for a limited speed range. The typical transonic wind tunnel has good efficiency for all Mach numbers below 1.3, but, because of high operating costs, is seldom used below $M = 0.5$.

In subsonic ($M < 0.4$) flow, compressibility effects are usually small and wind tunnel testing techniques are straightforward in that wall interference and model - support - system interference corrections can be easily determined and applied. In the supersonic ($M > 1.3$) flow range, model support methods are more limited but the flow characteristics are well understood. Testing in the transonic range is difficult because the aerodynamics theory is complicated by the coexistence of large subsonic and supersonic flow fields around the model, so that the basic transonic flow equations must have both the elliptical characteristics of subsonic flow and hyperbolic characteristics of supersonic flow. This mixed flow culminates in the phenomenon of "choking" at $M = 1$ for conventional solid wall tunnels, and in the development of flow fields around the model which bear little relationship to free flight conditions.

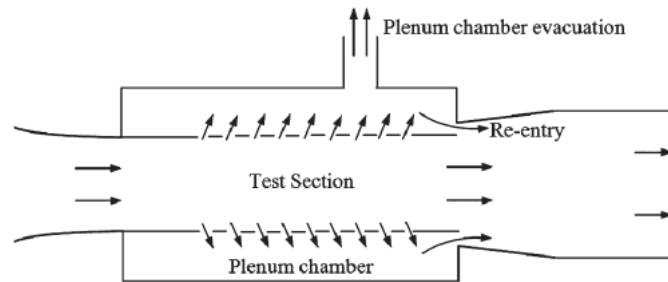


Figure 3. Transonic wind tunnel sketch showing the system of forced extraction and reentry flaps.

In subsonic flow all of the tunnel walls or boundaries will modify the flow pattern around the model, while in supersonic flow the wall can affect the flow around the model only by reflecting the Mach waves emanating from the model back to the model. In transonic flow, both types of wall interference are encountered. Below $M = 1$ there are local supersonic regions around the model which rapidly grow larger as the free stream Mach number approaches unity. Even at Mach numbers as low as, for example 0.8, these local supersonic regions may extend to the tunnel walls and the tunnel chokes. Above $M = 1$ there are local subsonic regions around the model, as well as shock waves radiating from the model, and, as the free stream Mach number decreases toward unity, the subsonic regions rapidly grow larger until they extend to the tunnel walls and chokes or the shock wave reflections from the walls approach and finally strike the model. (DONOVAN, A.F., GODDARD, F.E., 1961)

Models and their support struts reduce the area of the wind channel and cause choking to occur at Mach numbers close to 1.0. Both wall and support-strut interference on the model become very large and unpredictable as the choking Mach number is approached. The wall interference limitation can be alleviated and higher choking Mach numbers reached by reducing the size of both model and strut, but it is impossible to prevent choking entirely unless ventilated walls or other special techniques are used. It should be mentioned that for some model attitudes and configurations, important regions of mixed flow are obtained at free stream Mach numbers as low as 0.15 and much higher than 1.3. For example, maximum wing lift and the flow around blunt bodies both are severely affected by free stream Mach numbers of 0.15 or more. These extreme cases of mixed flow are not considered to be in the realm of transonic flow even though they may involve contiguous regions of subsonic and supersonic flow. (DONOVAN, A.F., GODDARD, F.E., 1961)

2. SHORT OVERVIEW OF THE PILOT TRANSONIC TUNNEL (TTP)

The reader can get an overall idea of the installation by observing Figs. 4 and 5a. The Pilot Transonic Tunnel (TTP) is a 1/8th version of an industrial tunnel. With an 830 kW two - stages axial main compressor, the TTP is able to provide continuously a steady - stream up to a Mach number equal to 1.2 and intermittently with the help of injector up to Mach number 1.3. The main dimensions at the test section are: 30 x 25 x 85 cm, respectively, in the width, height and length. The TTP was designed by the American Company Sverdrup Technology, Inc. The industrial tunnel was also designed by Sverdrup and also use injectors which consists of a battery of supersonic nozzles downstream of the second throat of the tunnel — see Fig. 5b. The function of the nozzles is to deliver a sort of "boosting effect". Suppose, for example, that the main compressor is delivering the maximum power to the current. In this situation one is able to reach a maximum Reynolds number in the test section. If, at this point, the supersonic injection is activated, a surplus of fresh energy is delivered and it is possible to reach greater values of the Reynolds number. In technical terms one is enlarging the operating envelope of the tunnel. What matters here is basically an intelligent usage of the main compressor, the most expensive piece of the whole facility about one third of the total price. The injection permits the envelope expansion without needing to rise the total power of the compressor.

Whenever a technological novelty is introduced in a very expensive installation, it is advisable to design and build a pilot facility, in order to assess the result of the new idea. The results obtained by running the down-scaled apparatus

are then used to eventually feedback the design of the industrial machine. Figure 5b shows the main components at the interior of the plenum chamber.



Figure 4. Part of the aerodynamic circuit of the TTP showing the opened plenum chamber.

The reader can observe the system of high-pressure injection, and that the changing-form segment (a stretch that transforms the rectangular cross-section shape at the exit of the second throat to a circular shape at the entrance of the first diffuser) is also used as the injection chamber. At the start, the pressure at the reservoirs is equal to 40 bars. The injectors controlling valve regulates the stagnation pressure in the range 4 – 12 bars, what guarantees a Mach number of 1.9 at the exit section of the supersonic nozzles. The mean stretch of time for steady state at the test section during injection is about 25 s.

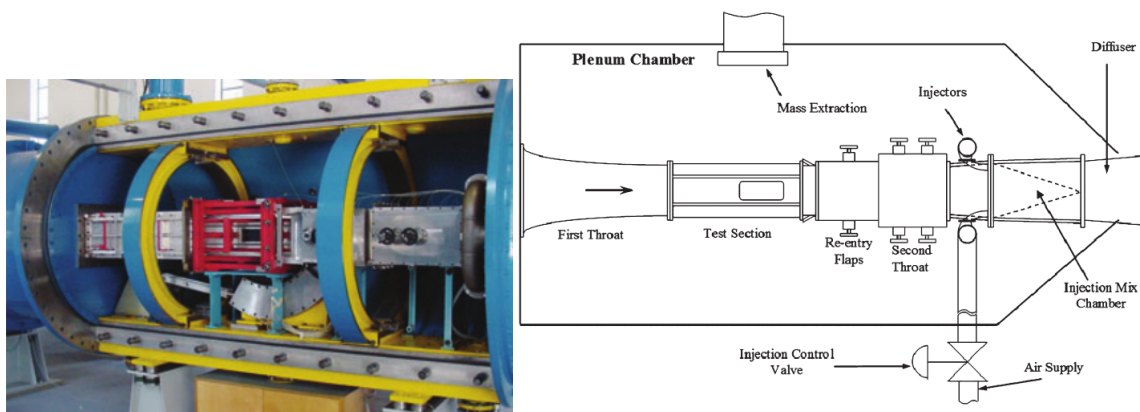


Figure 5. a)Detail of the TTP showing the test section (closed) in red. b)Sketch of internal view of the TTP.

3. STATEMENT OF PROBLEM AND INVESTIGATION STRATEGIES

When it comes to aerodynamics experiments, many of those used as reference for future research, it's expected to obtain results able to faithfully reproduce the aerodynamic characteristics and therefore the aerodynamics performance of a body in flight conditions. At this data is used high reliability.

There are a number of factors that determine the reliability of the results obtained in wind tunnels, it is namely the quality of the flow is one, if not the most important as it is possible to consider an overly exhaustive procedure due to a varied amount related sources of error in an experiment of this kind. In our case study, transonic flow, there may be occurrences of shock waves, among numerous complications that may arise in experiments in wind tunnels. There is a considerable number of factors that can influence the measurement of aerodynamic forces and static pressure in the

model, among them: static pressure fluctuations, of stagnation pressure and temperature in the test section, magnitude and direction of flow velocity, purity fluid in accordance with the effect of condensing impact of particulates on the model, the influence of the walls of the test section, the boundary layer effects of the test section and model blockages rate, according Steinle and Stanewski (1982). However, some authors list some of the main contributors of all experimental uncertainty errors are associated with measurements from scales installed and attached to the models and the determining of the correct angle of attack. With the existence of the walls, the streamlines are attached to the surface of the test section and no more only to the aerodynamic body (GOETHERT, 1961). In Fig. 6 it is possible to observe the behavior of the streamlines representing the flow around aerodynamic profile, free flow (a) flow in solid walls (b) and flow in open walls (c).

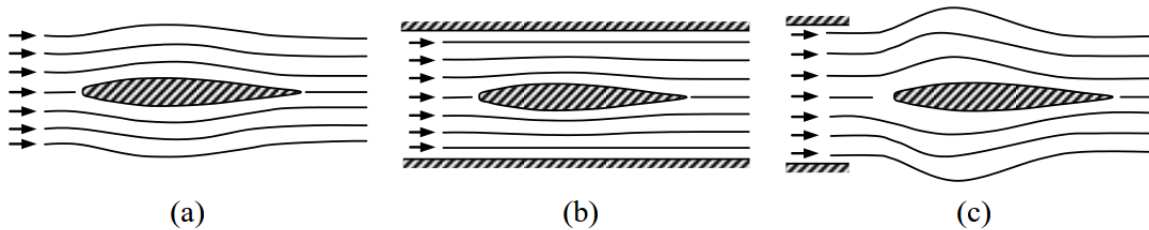


Figure 6. Representation of streamlines (a) free-flow, (b) confined flow with solid walls and (c) open walls.

When streamlines align with the walls, induces an undue increase in the fluid particle velocity occurred primarily by area reduction between the body surface and walls of the test section, a fact proven by the Continuity Equation applied to run off subsonic. Once ignored the confined flow acceleration improper in relation to free flow, data obtained in terms of lift coefficient is overestimated, addition to displace the possible appearance of shock waves on the surface of the profile. Note that, on the one hand the solid walls compresses the streamlines, in turn, the test section of open walls, a similar phenomenon occurs, but reverse, the streamlines slow down and them move away of model more than should. This is due to the sudden reaction between the pressure in the moving stream and the pressure undisturbed at a remote location, resulting in a larger centrifugal force compared to the force the flow into free flight conditions. This occurs because to the passage of the upset pressure undisturbed gradually and at a much greater distance.

It is possible to see a sketch of the test section at Fig. 7. The Pilot Transonic Wind Tunnel (TTP) of Aeronautical and Space Institute (IAE) is relatively young and experiments were performed minutely to quantify the influence of walls/slot on the test results. Therefore the aim was to study the role played by slotted walls, the static pressure distribution on an airfoil model in the transonic flow regime.

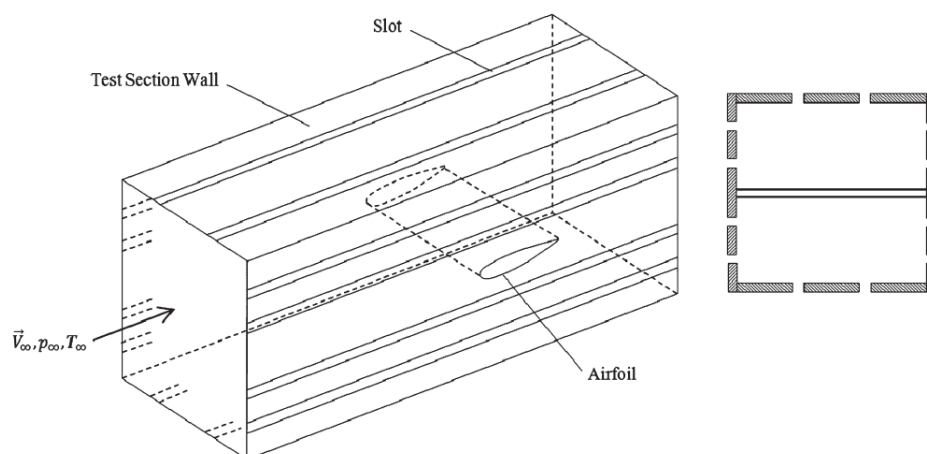


Figure 7. Sketch of the TTP's test section showing the installed NACA 0012. The smaller sketch at the right shows the position of the slots and the front shoulder of the airfoil.

This work aimed to obtain parameters

This work aimed to experimentally investigate the influences exerted by the walls of TTP testing section in the flow around the model, how the slots affect the quality of the flow of interest and, using numerical analysis tools, the variation open area of slots. The choke phenomenon also was analysed in number Mach critical conditions.

4. RESULTS AND DISCUSSION

Several cases of Mach number 0.6 to 1 were run, but the cases of interest, which well represent the scope of this study are Mach number 0.6 and 0.8, assuming a 0° angle of attack. For such cases, the comparison was made with work of Harris (1981), numerical solutions (with variation of the open area of slots) and the experiments on TTP. It is important to call attention to the fact that in the experimental results from Harris the angle of attack is not exactly the same as used in TTP. Besides, for obvious reasons, because of the difference in the length scales of the tunnels it wasn't possible reproduce the values of Reynolds number of Harris investigations.

Experiment 1: Mach number, $M_\infty = 0.6$, angle of attack, $\alpha = 0^\circ$

The static pressure field on the airfoil surface obtained through the visualization technique PSP can be seen in Fig.8, obtained from Goffert (2012). Note that this is a standard case, so there is no large gradients in surface and there are not strong three-dimensional effects.

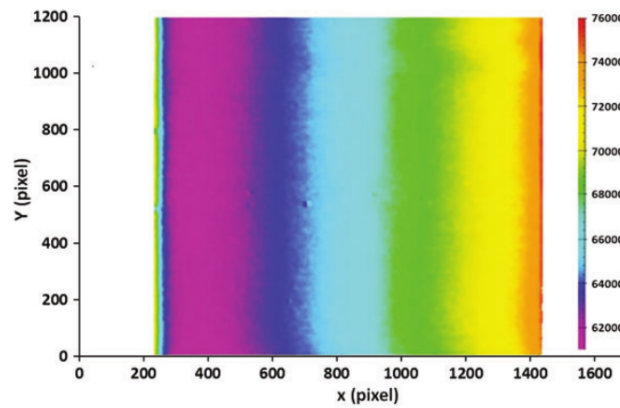


Figure 8. Static pressure on the surface of the airfoil by means of PSP painting. $M_\infty = 0.6$, angle of attack, $\alpha = 0^\circ$.

It was plotted values of the pressure coefficient (c_p) on Fig.9.

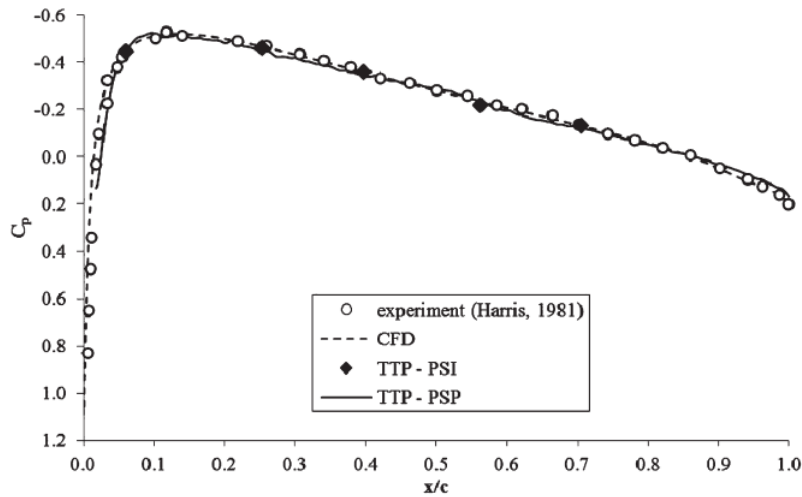


Figure 9. Distribution of the pressure coefficient along the foil chord. $M_\infty = 0.6$, angle of attack, $\alpha = 0^\circ$. (GOFFERT, 2012)

In this figure it is possible see the pressure coefficient obtained from experimental data of Harris (open circles), the CFD results are dashed lines, the black symbol represents values of the static pressure at the taps and the solid line are PSP values. Because of the gradients are not large enough the results compare quite well with Harris's work and the CFD data.

If the reader observe carefully, you will notice slight variations present in the plotted results as shown in Fig. 9 and should be borne in mind that these oscillations in no way relates to any physical manifestation. The PSP technique works better when there are strong pressure gradients, common to the transonic and supersonic speed regimes.

In order to observe and facilitate the understanding of how the slots act in the pressure field of the test section, it was plotted graphs, as of numerical simulations by varying the ratio of open slot area, see Fig. 10.

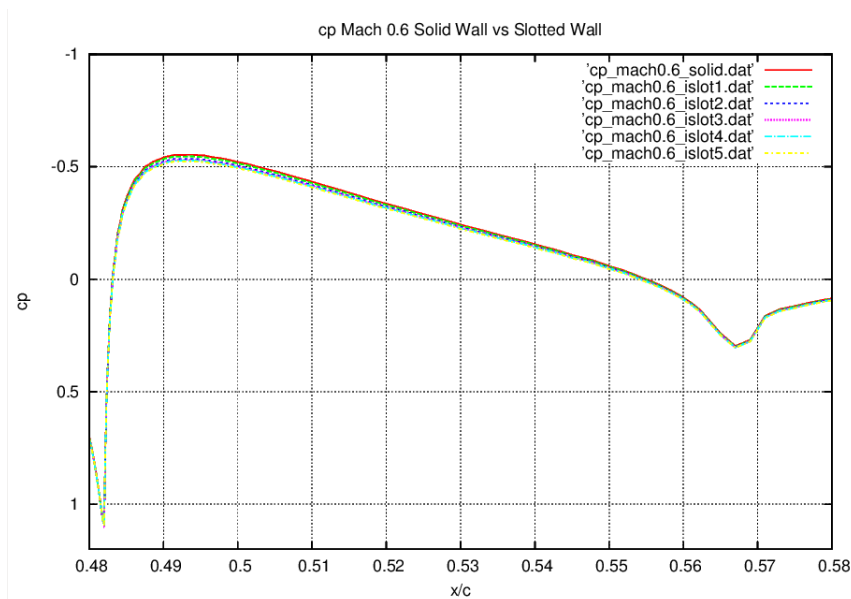


Figure 10. Comparison of the pressure coefficient obtained from numerical simulations, varying the ratio of the area of the slots. $M_\infty = 0.6$, angle of attack, $\alpha = 0^\circ$.

Figure 10 shows several curves plotted from numerical simulations, these simulation are designed to analyze the flow behavior around the model considering the solid wall test section, also with slots open area of 10% (islot1), 20% (islot2), 30% (islot3), 40% (islot4) and 50% (islot5).

Note that, for the flow velocity of Mach 0.6 scheme, the variation in the slot area ratio did not print any considerable effect even compared to the solid wall of simulation. This due to the absence of the effects of three-dimensionality. Also, the data comparing the experiments conducted by Harris (1981), the experiments made in TTP and simulated in CFD, have good accuracy.

Experiment 2: Mach number, $M_\infty = 0.8$, angle of attack, $\alpha = 0^\circ$

The Measurements by the PSP technique relative to experiment 2 can be seen in Fig. 11. Note that is possible see the location of the shock wave very well defined. Also, some three-dimensional effects can be apparent.

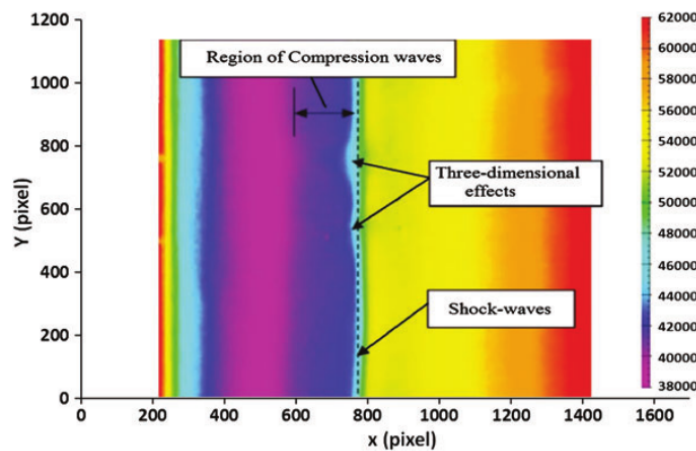


Figure 11. Static pressure on the surface of the airfoil by means of PSP painting. $M_\infty = 0.8$, angle of attack, $\alpha = 0^\circ$. (GOFFERT, 2012)

One can observe the pressure coefficient plotted for this experiment, it being Harris work pressure and taken PSI and CFD results.

For this case, the Mach number 0.8 at zero angle of attack, we have an occurrence of important physical phenomenon

for this study. This phenomenon is given by the shock wave. Many authors compared the results in terms of the positioning of shock wave for this test configuration. Because it is different experiments conducted in wind tunnels, for example, solid walls, slotted walls and perforated walls, and further, different model choke ratio, the occurrence of the shock wave may have its location varying between 35% and 55% of the aerodynamic cord, not least because the test cover a wide range of Reynolds number, very important parameter to display data on the flow condition (position of laminar - turbulent transition), which influences starkly in the event of shock wave position.

The pressure build-up occurring in curved flow as it approaches a slotted wall is directly proportional to the distance between slot centers. This fact is readily understood when it is realized that, for a given wall open-area ratio, the radial extent of the high-curvature region near the wall is proportional to the distance between slots. Also, since the distribution of the local velocities and centrifugal forces must be the same relative to slot width and distance, the total build-up of the static pressure in the high-curvature region or, as stated before, to the distance between slot centers. Thus, to maintain a desired value of the additional pressure build-up in the case of a large numbers of slots, it is necessary to reduce the slot width and thus to compensate for the smaller width of the high-curvature region by increasing the curvature of the flow in the slot region. (GOETHERT, 1961)

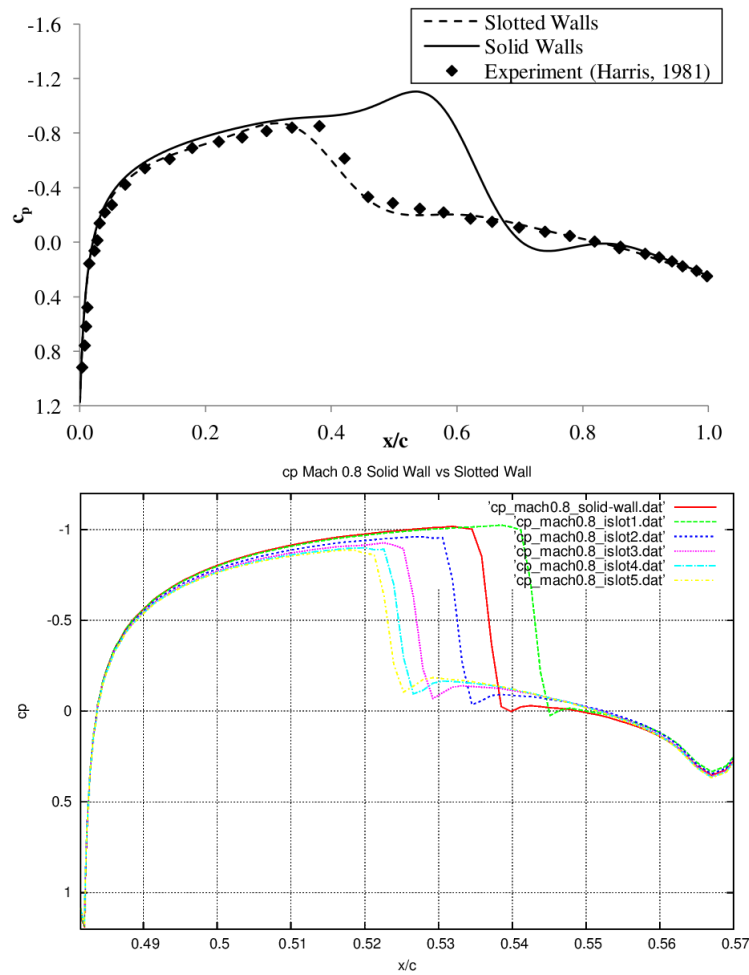


Figure 12. Distribution of the pressure coefficient along the airfoil chord. $M_\infty = 0.8$, angle of attack, $\alpha = 0^\circ$.

At this speed, Mach 0.8, you may notice a considerable displacement of the shock wave in the model due to improper action that solid wall plays in the flow, as there is no mass extraction of flow in the test section, to continuity conservation law act. This is best evident in numerical simulation where several open area ratios of slot were simulated. See Fig. 12.

5. CONCLUSION

This study aimed to complete a part of the research focus of the author's dissertation, perform an experimental analysis, using modern techniques of visualization and flow quantification / qualification to better understand the physical phenomena of interference from the walls of the TTP in the tests performed in this tunnel. Also, it proved very useful computational tool reducing the number of cases that, in principle, be analyzed experimentally and, therefore the amount of experiments was reduced. In order to study how the walls of the transonic wind tunnel Pilot (TTP), of the Aeronautics and Space Institute (IAE), interferes with the flow and consequently, altering the physical characteristics of it around a model, it was decided to use an airfoil very experimentally tested in wind tunnels, especially in the transonic speed regime, because then we would have to comparable data and then better understand the physics of the problem.

The experiments performed with aerodynamic profile NACA 0012, provided basic parameters for the reliability of the experiments, comparing the data with other experiments. It was observed that in the case of entirely subsonic flow, Mach 0.6, the pressure field on the behavior profile followed studies by Harris (1981), as regards the curves presented as also in the pressure values. It can be ignored, the open area of the slots changes, the numerical simulation, the changed data. When the speed regime change, working at high subsonic - transonic, Mach 0.8, it was possible to detect the presence of shock waves and these were equivalent to the results obtained in other wind tunnels. However, it was possible to observe that the variation of the open area of the slots to the same Mach number, and angle of attack, the pressure coefficient curve is changed, revealing a shift shock wave occurrence position, due to compressibility effects. This demonstrates the effectiveness of slots in the test section of a tunnel is to analyse models in this speed regime.

This study work continues due to the completion of the master's author, will be performed further testing, including solid walls, for TTP behavior analysis with this feature and use the Schlieren technique for visualization of flow and displacement of the shock wave.

6. REFERENCES

- ANDERSON JR., J.D. , 2011. *Fundamentals of Aerodynamics*. 5. ed. New York, NY: McGraw-Hill, c2011. 1106 p. ISBN (13): 978-0-07-339810-5 ; (10): 0-07-339810-1.
- DONOVAN, A.F., GODDARD, F.,E. , 1961. *High speed aerodynamics and JET propulsion*. Princeton, NJ: University Press , 1961. USA.
- FALCÃO Filho, J. B. P., and ORTEGA, M. A. , 2008. *Numerical Study of the Injection Process in a Transonic Wind Tunnel: The Numerical Details*. Computers & Fluids, Vol. 37, pp. 1276-1308, 2008.
- FALCÃO Filho and MELLO. , 2002. *Descrição Técnica do Túnel Transônico Piloto do Centro Técnico Aeroespacial*. IX Congresso Brasileiro de Engenharia e Ciências Térmicas. Paper CIT02-0251.
- GOETHERT, B.H. , 1961. *Transonic Wind Tunnel Testing*. Mineola, New York: Wilbur C. Nelson, 1961. USA.
- GOFFERT, Bruno. , 2012. *Análise Numérica e Experimental de Escoamento Transônico Sobre o Aerofólio NACA 0012 no Túnel Transônico Piloto do IAE*. 2012. 214f. Tese de mestrado em Aerodinâmica, Propulsão e Energia - Instituto Tecnológico de Aeronáutica, São José dos Campos.
- GOFFERT, B., ORTEGA, M.A. and FALCÃO FILHO. , 2014. *Wall Ventilation Effects upon the Flow about an Airfoil in a Transonic Wind Tunnel*. Technical Article SEM, 2014
- HARRIS, C. D. , 1981. *Two-dimensional Aerodynamic Characteristics of the NACA 0012 Airfoil in the Langley 8-foot Transonic Pressure Tunnel*. NASA TM-81927, 1981.

7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.