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Streamwise porosity distribution optimization for minimising wall interference in a transonic wind tunnel.

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In order to maximise the reduction of the wall interference over the widest possible Mach number range an optimised, non-uniform porosity distribution along the test section centreline can be used instead of a uniform value; an experimental investigation was carried out in the PT-1 in order to determine the best porosity distribution in the Mach range between 0.3 and 1.05. Over 360 test points were measured on different models and wall porosity configurations over the selected mach number range to find out the minimum interference configuration for the PT-1; however, as these results are not wind tunnel-specific, they are expected to be applicable to all similar facilities. The optimum porosity distribution has been achieved trough an experiment designed with a Modern Design Of Experiment (MDOE) approach.

Nomenclature

CIRA	=	Italian Aerospace Research Centre
AOA	=	Angle Of Attack
N/A	=	Not Applicable
MDOE	=	Modern Design Of Experiments
OFAT	=	One Factor At Time
RSM	=	Response Surface Model
PT-1	=	CIRA Transonic Wind Tunnel.
ANOVA	=	Analisys Of Variance
A	=	Variable indicating the position of the plate A.
B	=	Variable indicating the position of the plate B.
C	=	Variable indicating the position of the plate C.
D	=	Variable indicating the position of the plate D.
E	=	Variable indicating the position of the plate E.
c_i *i=1..27*	=	Coefficients of a generic polinomial funtion .
I_{Cl}	=	Interference factor referred to lift coefficient.
I_{Cd}	=	Interference factor referred to drag coefficient.
I_{Cmf}	=	Interference factor referred to pitch coefficient..
N	=	Number of test.
p	=	Number of coefficients in a d-order polynomial function with k independent variables.
d	=	order of a generic polynomial function
k	=	independent variables of a generic polynomial function
C_l	=	Lift coefficient.
C_d	=	Drag coefficient
Cmf	=	Pitching moment coefficients
c	=	chord length of a generic airfoil.
M	=	Mach number
Re	=	Reynolds number
α	=	Angle of attack.

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σ = Measurement uncertainty (standard deviation).
λ = Accuracy of the response surface.
Rif = Referred to "interference free" condition.
t_α = Probability for Type I error
t_β = Probability for Type II error
Kg = Kilogrammes
s = Second.
KW = Kilowatts

I. Introduction

THE ability to reduce the wall interference on the wind tunnel measurements can considerably increase the quality of both the raw data and corrected coefficients. In fact, as the correction to be applied is reduced, the error on the correction itself is smaller and, therefore, the corrected data are much more accurate.

An optimized and non-uniform porosity distribution along the test section centerline instead of an uniform value can be used in order to maximize the reduction of the wall interference over the widest possible Mach number range[1,2,3,4].

An experimental investigation (over 400 wind tunnel tests) has been carried out on different airfoils and wall porosity configurations over the Mach number range 0.25 - 1.05, in order to find out the minimum interference configuration for the CIRA transonic wind tunnel (PT-1). However, these results are expected to be applicable to all similar facilities since they are not wind tunnel-specific.

The present paper describes the test results in detail. The effects of the porosity variation along the centerline are shown, and the resulting optimal distributions at each of the selected Mach ranges are presented. A Modern Design of Experiment approach has been used to achieve the required goal.

II. Description of Facility and Experimental Setup.

The CIRA Transonic Wind Tunnel PT-1 is a small, pressurised, injection driven wind tunnel with a cross section of 0.45m x 0.35m. The facility is capable of both continuous operation in the low subsonic range (Mach = 0.1 -0.35), through a 145 Kw fan drive system. Intermittent operation in the high subsonic-transonic range (Mach = 0.35 - 1.1) and supersonic (one point at Mach = 1.4), is achieved by means of an air injection drive system (max flow rate 26 Kg/s, max supply pressure 34 bar).

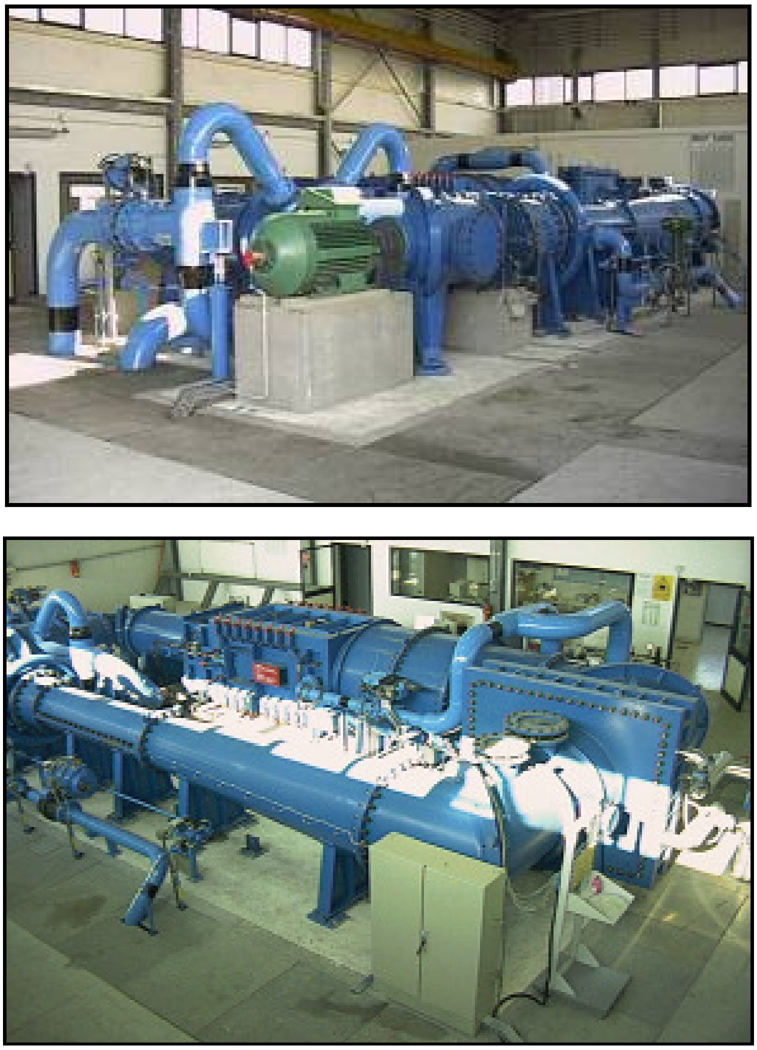


Figure. 1. CIRA PT-1 Transonic Wind Tunnel

In order to cover the described operating envelope two nozzles are available: a converging nozzle for the subsonic and transonic tests and a converging-diverging nozzle for the tests at Mach=1.4.
In the intermittent injection-driven operating mode, the Mach number set point is reached via a second throat adjustment in the range between 0.4 and 0.8. The set point for higher Mach numbers is reached via mass flow removal (up to 3% of the overall circuit mass flow) through the test section perforated walls. At high speed range, an automated control of both the total pressure and the Mach number is available, allowing to maintain the set point during α-sweep and step-and-pause test modes within 0.001 M.

For testing on 2D airfoil models in the subsonic-transonic Mach number Range, the test section is equipped with perforated ceiling and floor, with a 6% open area ratio porosity obtained with 60° slanted holes. This is the typical configuration of most transonic facilities, as it is known to achieve an optimum wall interference reduction at near sonic and supersonic Mach numbers through an efficient wave cancellation[5].

For this activity, five plates about 0.1m wide (1/6 of the useful test section length) were mounted on the external surface of both floor and ceiling. The plates are capable to translate normally to the flow direction with respect to the walls. Each plate bore milled-through stripes having the same inclination and stagger as the holes pattern on the walls, making it possible to partially or totally cover the holes on the perforated walls just translating the milled plates.

Therefore, this device is able to locally vary the porosity distribution between 100% open and completely closed holes.

Five plates for each wall have been used; each plate moving independently. In this way, it is possible to obtain practically unlimited combinations of porosity distributions along the streamwise direction.

The effects of different section geometries on the optimal porosity distribution was recognized using three different airfoils. Two CAST 7 airfoils of different size (0.13 and 0.09 meters chord length) were used as representative of a supercritical geometry, and a NACA 0012 (0,13 meter chord length) as representative of a more conventional subsonic geometry.

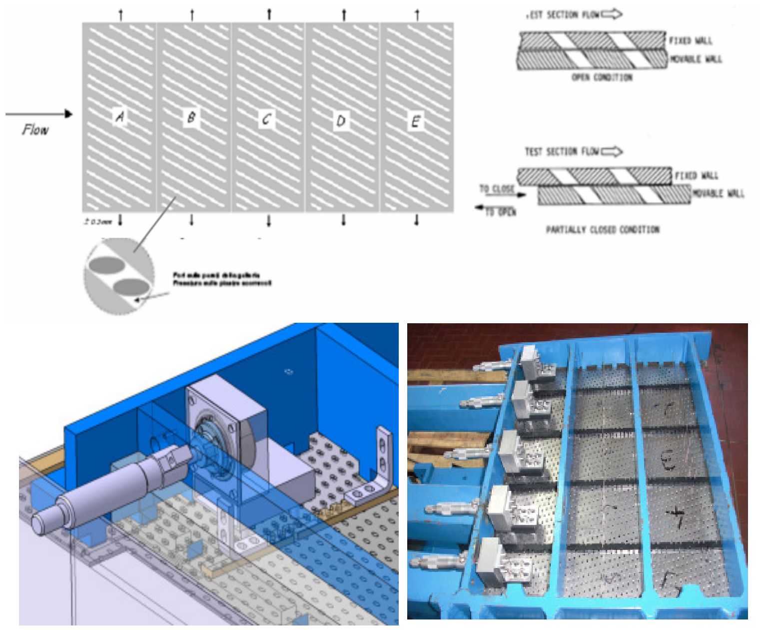


Figure 2. System adopted for the wall porosity variation.

The CAST 7 airfoil has been developed by Dornier Company. It is a supercritical airfoil with maximum thickness of 11.8% chord length and 0.76 design Mach number. On the CAST7 airfoil with 0.13m chord length, 28 pressure taps were installed on the upper surface and 17 on the lower surface. Instead, 30 pressure taps were installed on the upper surface and 17 on the lower surface of the CAST7 airfoil with 0.09 m chord length. The NACA0012 airfoil is typically used to validate measurement techniques in wind Tunnels and computational methods. The CIRA NACA0012 airfoil (0.13 m chord length) was instrumented with 25 pressure taps on the upper surface and 17 pressure taps on the lower surface.

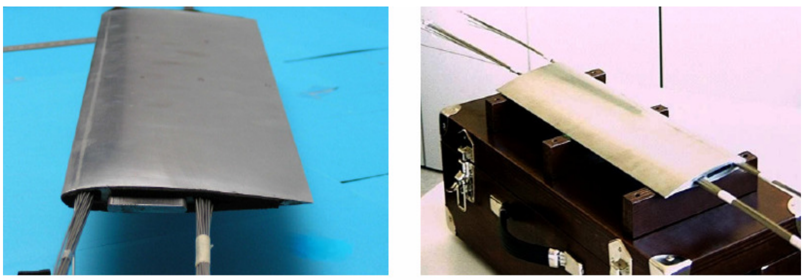


Figure. 3. NACA 0012 airfoil and CAST7 supercritical airfoil

The models are positioned in the test section between the plate C and D, the plate A and B are positioned upstream of the model and the plate E is positioned downstream.

The Mach number range of interest was divided into two sub-regions (a subsonic range, with 0.25<M<0.73, and a transonic range, with 0.73<M<1.05). Four test campaign were defined:

- in the Mach range 0.25÷075 both the NACA 0012 and the CAST 7 airfoil (0.13 meter chord length) models were tested.
- in the Mach range 0.75÷1.1 both the CAST 7 airfoils were tested at the same conditions.

The huge number of factor combinations (plates positions and Mach numbers) made practically impossible to follow a traditional One Factor At a Time (OFAT) approach. Therefore, the optimum porosity distribution has been achieved through an experiment designed with a Modern Design of Experiment (MDOE) approach. In particular, in the first Mach range (described above) two **MODE models** were obtained using tests results on the bigger CAST7 and NACA0012 airfoils respectively. An other MDOE model was obtained in the second Mach range using tests results on both CAST7 models.

III. MDOE Approach for Response Surface Modelling

The Modern Design of experiment (MDOE) is a technique for highly efficient experiment designs, first introduced at NASA Langley Research Centre in 1997 to improve quality, productivity and experiment costs for wind tunnel experiments.

MDOE provides a means to develop highly efficient experiment design providing results within a specified accuracy. Moreover, MDOE massively relies on *randomisation* to convert all *unexplained variance* (hidden systematic errors affecting the results) into *chance variation*, that can be accounted for with a proper statistical analysis: Any error from variations in the system during the test campaign can be overcome through the randomization of the tests execution. Within the MDOE approach we have selected a technique called RSM (Response Surface Modelling), which explores the relationships between several explanatory variables and one or more response variables. For the RSM experiments developed in this study, a D-optimal design strategy was performed. The design points have been chosen in order to minimize the variance associated with the estimated coefficients of the model.[6]

The selected factors were the position of the five plates (i.e. the wall porosity on five different wall segments), which were allowed to vary between the fully open and fully closed holes conditions (the 5 plates positions were called variables A,B,C,D,E) and the Mach number (called variable M), which was made to vary between 0.25 and 1.1.

Three different "**Cost Factors**" were considered and used to create three response surfaces, respectively for the airfoil lift, drag and pitching moment coefficients. Therefore, for each **MDOE model,** these were the selected **response variables** properly defined in order to provide a meaningful measure of the difference between the baseline, interference free curve and the curve measured with each porosity distribution. The cost factors (I_{Cl} , I_{Cd} and I_{Cmf}) for the airfoil lift, drag and pitching moment are defined as :

$$I_{Cl} = \frac{\sum_{i}^{N-1} \frac{1}{2} \left|\Delta\alpha_i + \Delta\alpha_{i+1}\right| \Delta Cl_{i+1}}{\Delta Cl_{max}}$$

$$I_{Cd} = \frac{\sum_{i}^{N-1} \frac{1}{2} \left|\Delta Cd_i + \Delta Cd_{i+1}\right| \Delta Cl_{i+1}}{\Delta Cl_{max}} . \qquad \text{(eq. 1)}$$

$$I_{Cmf} = \frac{\sum_{i}^{N-1} \frac{1}{2} \left|\Delta Cmf_i + \Delta Cmf_{i+1}\right| \Delta Cl_{i+1}}{\Delta Cl_{max}}$$

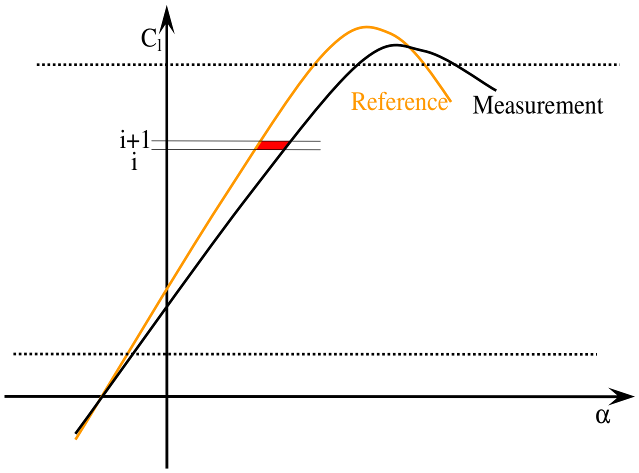


Figure. 4: Generic scheme applied to calculate the cost factors.

In the lower Mach range, the experimental results were compared to the available PT-1 and literature data.[7,8,9] In the higher Mach range, where no literature data were available, the cost factors have been obtained comparing the test results on the bigger Cast7 airfoil to the test results on the small Cast7 airfoil at the same conditions (plates position, Mach and Reynolds numbers).

During the design phase, each response variable was supposed to have a **second order dependency** on the plates position and Mach number. A lower order (linear function) would not allow to find a minimum of wall interference whitin the design space, and an order higher than second was unfeasible due to the huge number of data required. In fact, the number of coefficients p in a polynomial function grows rapidly as the order d of the model and/or number of independent variables k increases:

$$p = \frac{(d+k)!}{d!k!} . \qquad \text{(eq. 2)}$$

Where p represents also the ***minimum number of data*** required to fit such a kind of model.

Acquiring only p points would force the response surface through each point and leaves no additional degrees of freedom to assess the quality of the model. By obtaining more than the minimum p points, it is possible for the response surface to “float”. This allows to estimate the quality of the fit by examining the residuals. The total number of points necessary to construct a d^{th}-order model in k independent variables that predicts the response within a specified tolerance is given by :

$$N = \frac{(d+k)!}{d!k!} (t_\alpha + t_\beta) \frac{\sigma^2}{\lambda^2} . \qquad \text{(eq. 3)}$$

Where, σ is the standard deviation in the measurement, λ is the precision requirement for the response surface, and t_α and t_β are statistics related to acceptable inference error probabilities for Type I and Type II errors, respectively.

A Type I error occurs when we infer a difference between two results, say, when none exists, or when we include a response model term erroneously. A Type II error is failing to observe a true difference, or rejecting a response model term that truly exists.[10]

From the previous equation it is possible to note that for a 2nd-order model in 6 independent variables (model with p=25 terms), assuming 5% inference error probabilities (95% confidence levels) for both error types, the total data volume varies as a function of the parameter σ/λ as follows:

Figure 5 shows how the number of data points grows rapidly as the precision requirement increases. In this activity, for each one MDOE model the (three) response surfaces have been calculated by using 85 runs (corresponding to approximately 1.8*σ in the precision requirement). This was deemed to be sufficient as the standard deviation of the PT-1 wind tunnel tests was known to very low.

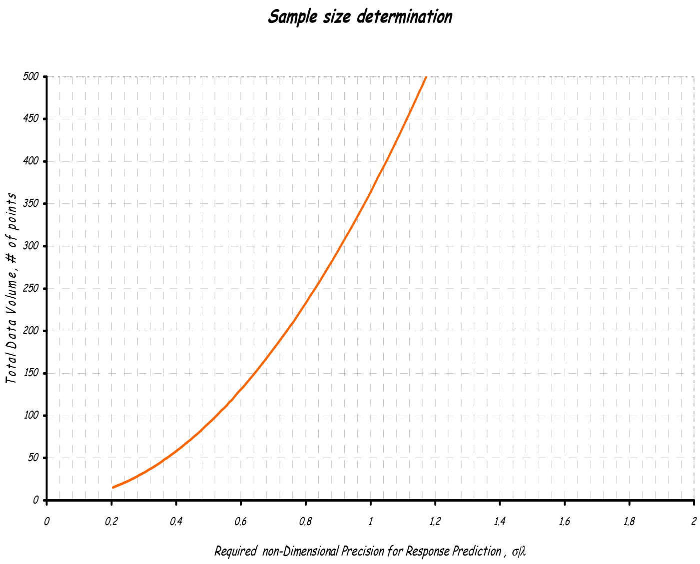


Figure. 5. Data Volume as function of the parameter σ/λ.

Specialized software packages identify the candidate points that satisfy certain statistical criteria. The STEAT-EASE Design Expert software package[12] has been used for both design and Surface evaluation phases

IV. Experimental Results

Figure 6, Figure 7 and Figure 8 show the effect of different porosity distributions on the lift curve, drag polar and pitching moment on the Cast7 (0.13m) airfoil obtained at Mach number 0.6. However, the same results were obtained at different Mach number.

The porosity distribution has an high influence on the quality of all aerodynamic curves. Moreover, it is possible to notice how the effects are similar to the ones due to typical correction procedure of blockage and lift interference. These consist of a translation and rotation on the aerodynamic curves. The same occurs in this case even if no correction formula has been applied to the data. [11]

These considerations confirm the possibility of minimizing the wall interference by means of an optimized porosity distribution.

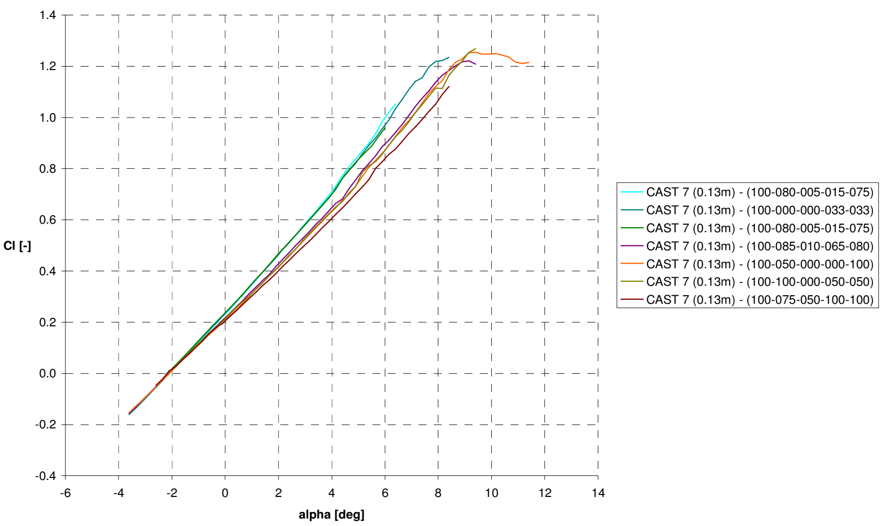


Figure. 6. Results at M=0.6 on the CAST7: Effects of wall porosity distribution on C_l

As said, the effects of different porosity configurations were measured comparing the curves obtained for each configuration with the baseline, interference free curve for the same Mach and Reynolds numbers. The meaningful measure of the interference was performed in terms of interference factors applying the equation 1. These results were used to evaluate the response surface.

In the lower Mach Range (0.25-0.73), three Response surfaces (respectively for the airfoil lift, drag and pitching moment coefficients) were evaluated with the results obtained on both the bigger Cast7 and NACA0012 airfoils. This allowed to verify whether the same results can be obtained for different models. In the higher Mach range 0.73-1.1, three response surfaces for the results obtained on the CAST7 airfoil were evaluated.

The response models were created accounting for the significant terms. These were evaluated by means of the Analysis of the Variance (ANOVA) according to “backward elimination” criteria. The backward elimination method initially considers significant all model terms. The term with the lowest correlation with the response variable is provisionally rejected, and the impact on the explained variance of the model is analyzed. If the rejection of the term doesn’t produce a significant reduction in the explained variance, the term is definitively rejected. The process continues until no terms in the model can be rejected without causing a significant reduction in the variance explained by the model.

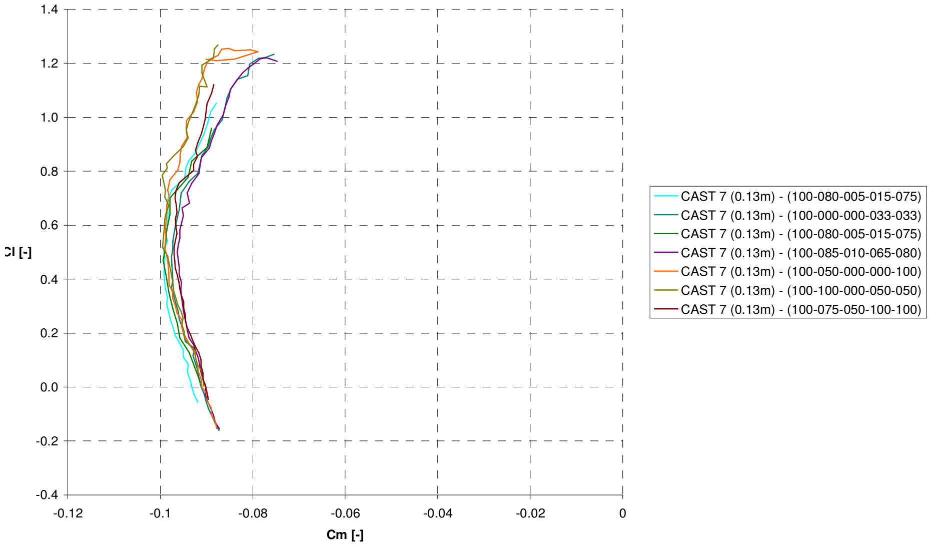


Figure. 8. Results at M=0.6 on the CAST7: Effects of wall porosity distribution on C_d

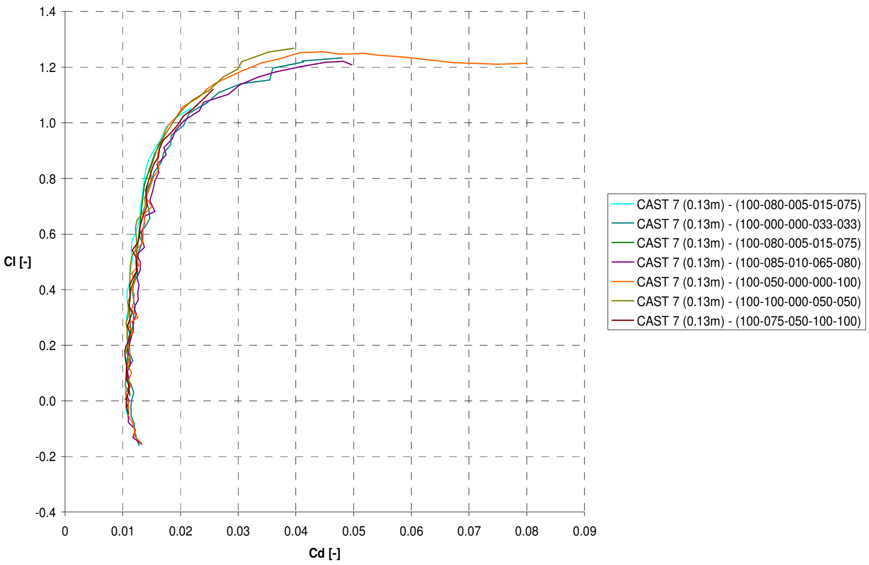


Figure. 7. Results at M=0.6 on the CAST7: Effects of wall porosity distribution on C_{mf}

The more significant factors resulted from the analysis were the plates B,C,D and Mach Number. This indicates that the most important effect for wall interference is due to the porosity distribution near the model, and to the Mach number.

Figure 9 shows an example of the obtained response surfaces as a function of only two parameter .

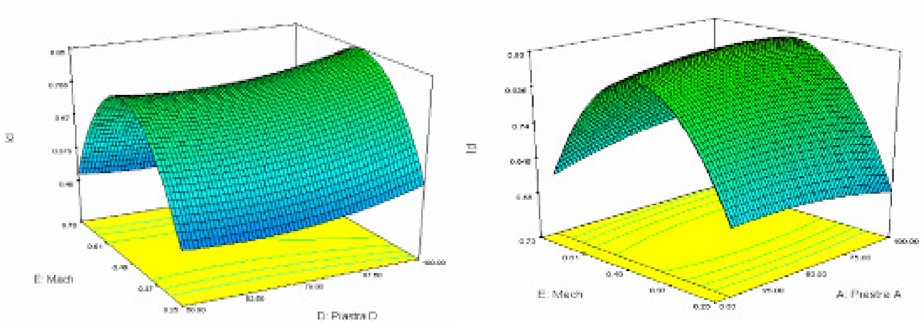


Figure. 9: Response surface: interference parameter measured on the lift curve as function of the Mach number and the position of first and fourth plates (factors A and D)

Each response surface has been confirmed before it was used to make predictions of the behaviour of a system, so 15 random confirmation points for each Model were acquired during each test campaign. These points were not used in the development of response surface, but rather, set aside for later comparisons with predictions:

- The 15 test conditions not used to build up the response surface, are checked vs the response surface predictions at the same conditions;
- the Student's T-test is carried out for each of these points, and is considered passed if the number of the test points out of the admissible error band are compatible with the 95% confidence level.

In figure 10 and figure 11 the predicted variance of the design and the normal plot of residuals of the subsonic response surface on the Cast 7 airfoils are presented (showing the capability of the second order model to fit the experimental results). In particular the predicted variance shows how the error in the predicted response varies over the design space. It depends on the number and location of the design points. For a good model design the standard error of design is flat in the design space.

The Normal Plot of Residuals, instead, is used to verify that residuals have a normal distributions with zero average and a standard deviation equal to the one resulting from the analysis of the data. This is verified if all design points are positioned along a line.

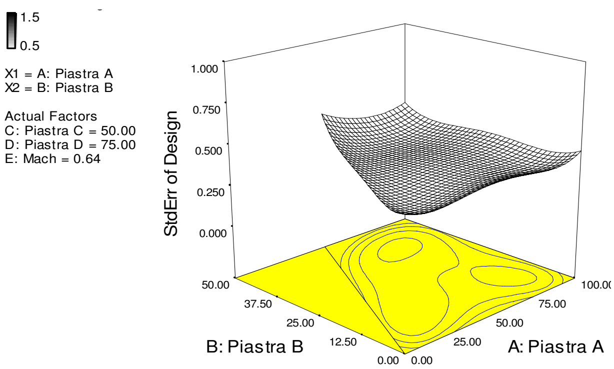


Figure. 11. Predicted variance as function of the position of the first and second plates (factors A and B).

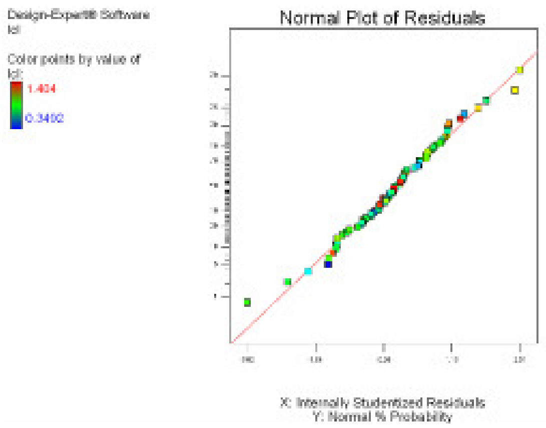


Figure. 10. Normal plot of residuals.

V. Streamwise Porosity Distribution Optimization

The optimum of the streamwise porosity distribution has been evaluated by means an optimization procedure as a weighted average of the three cost factors I_{Cl} , I_{Cd} and Ic_{cmf}.
The aim was initially to minimize principally the interference on the pitching moment, as this should result in a more uniform interference over the whole model.
This approach didn't lead to a clear result, giving back many minima all equally questionable. After a number of trials, the best compromise from a statistical point of view has been found minimizing principally C_l with respect to Cmf and Cd. but the optimization procedure is still to be upgraded.
Then, the temporary best porosity distribution for the CIRA PT-1 transonic wind tunnel, resulted from the optimization process, has been found in the whole 0.25÷1.05 Mach range.

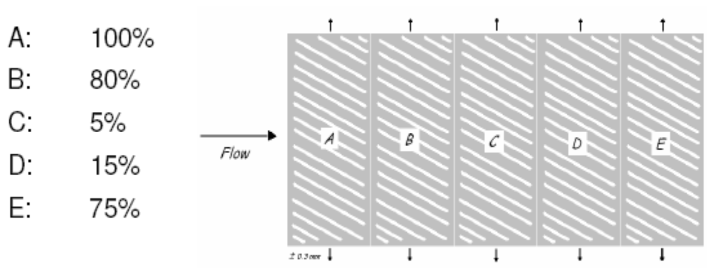


Figure. 12: Optimum configuration of plates

This result is in good agreement with the information available in literature, and with our expectations.
As a confirm of the effectiveness of the model prediction capacity, in terms of wall interference minimization, several tests for different Mach number were performed on both CAST7 airfoil at the optimal porosity configuration.
The figures 13,14, and 15 show respectively the lift curve, the drag polar and moment curves measured at the optimal porosity distributions on both the small and the large CAST 7 airfoil models at Mach 0.6.

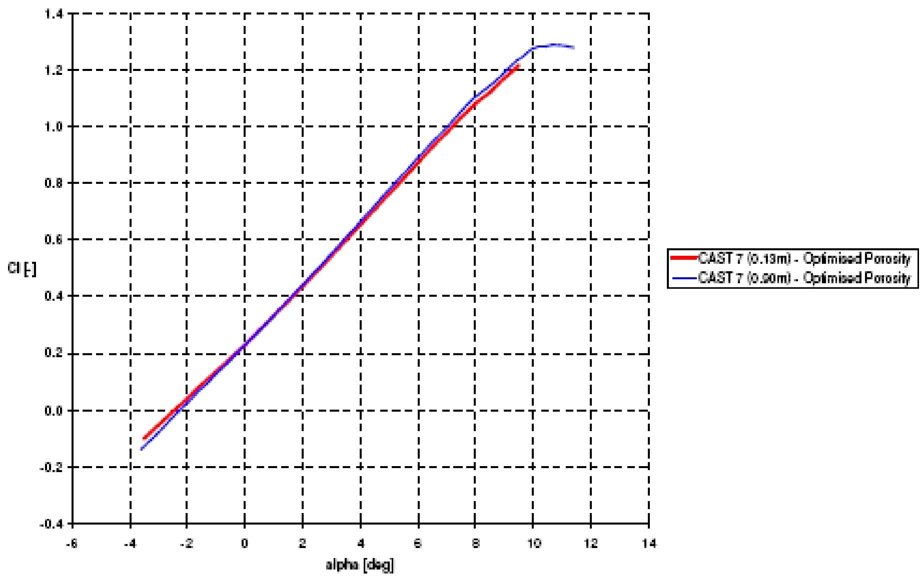


Figure. 13. Lift curve measured at the optimal porosity distributions on both the small and the large CAST 7 airfoil models at Mach 0.6

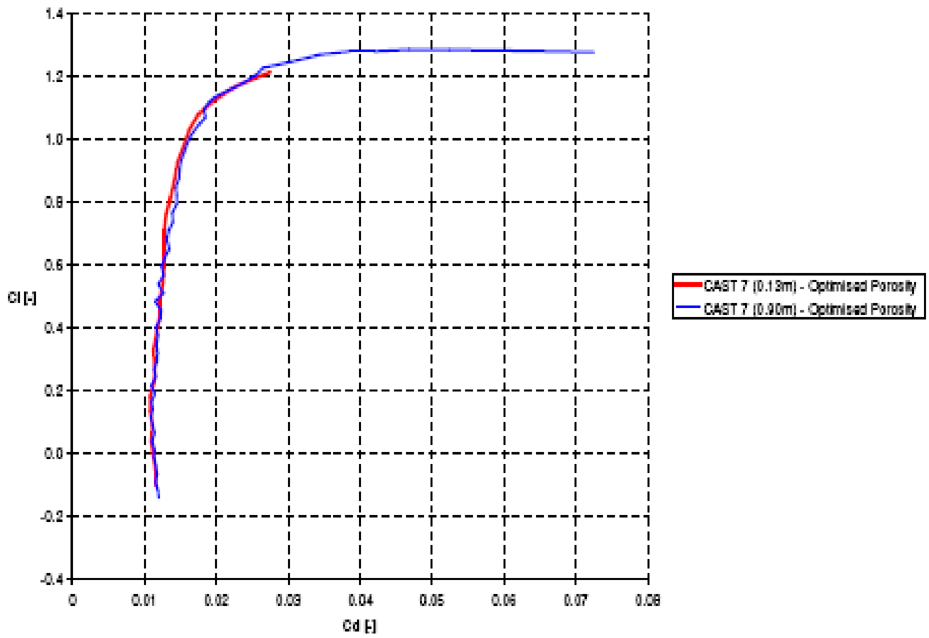


Figure. 14. Drag curve measured at the optimal porosity distributions on both the small and the large CAST 7 airfoil models at Mach 0.6

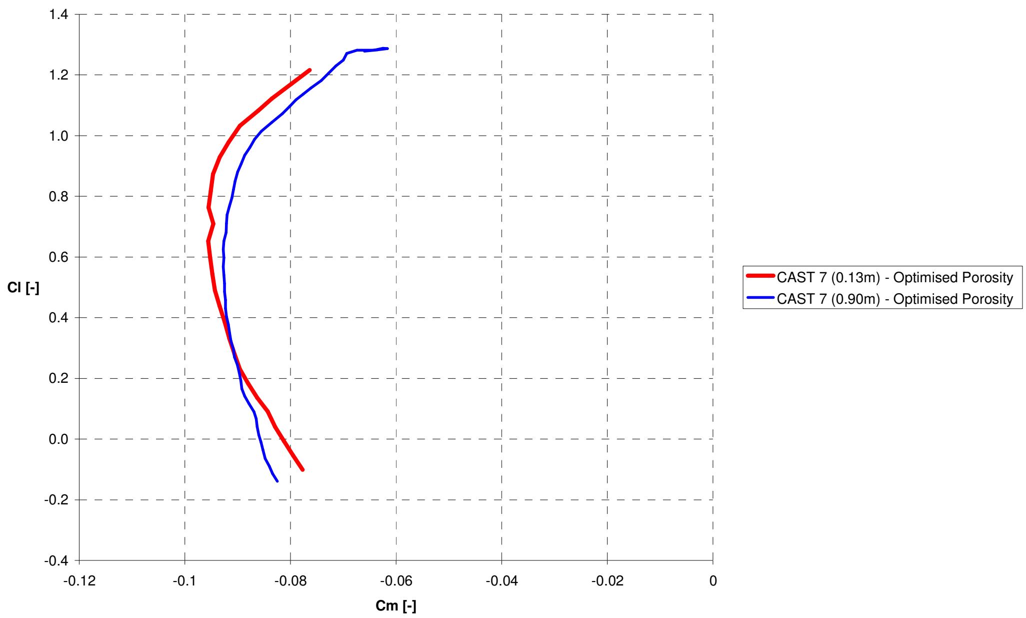
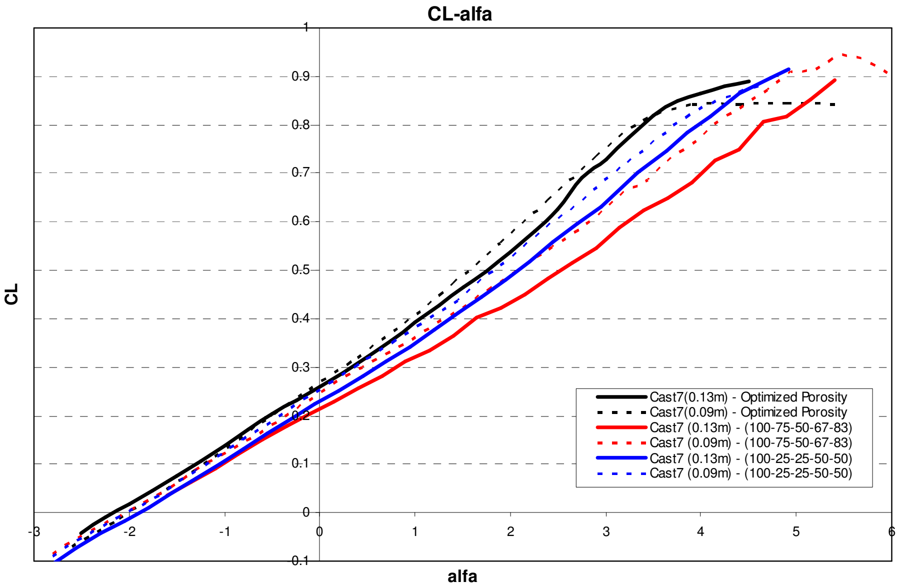


Figure. 15. Pitching moment curve measured at the optimal porosity distributions on both the small and the large CAST 7 airfoil models at Mach 0.6

The wall interference on Lift and Drag coefficients is practically eliminated. Instead, the effect on the pitching moment is satisfactory at low incidence while some residual interference is still presents for high incidences.

The same results has been achieved at higher Mach numbers (M=0.73 and 0.85) as shown in figure 16, figure 17, and figure 18.



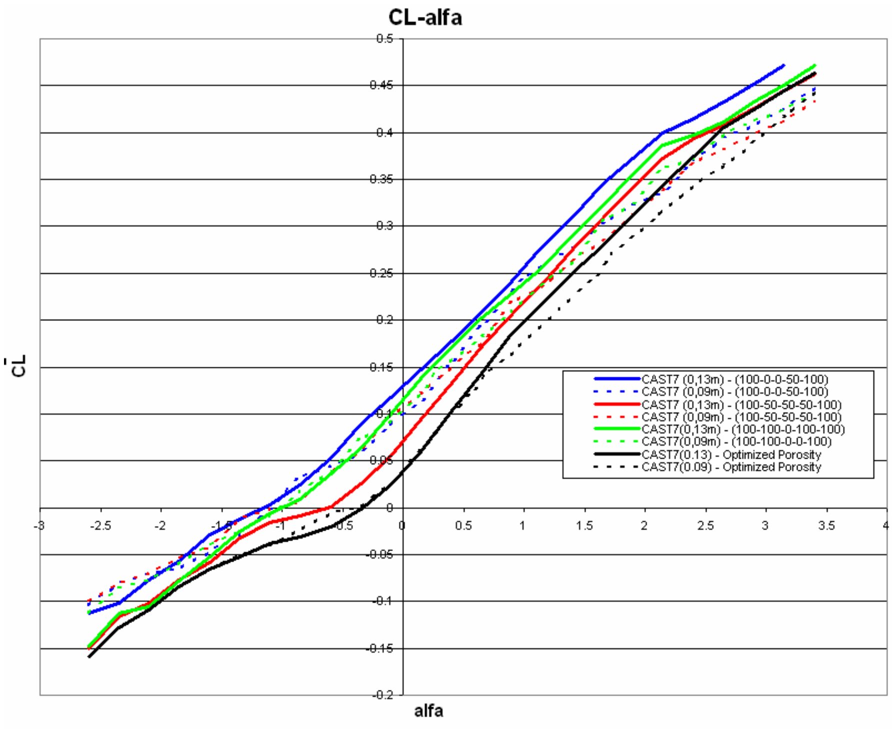


Figure. 16. Lift curve measured at the optimal porosity distributions on both the small and the large CAST 7 airfoil models at Mach 0.73 and 0.85 compared to a non optimal condition.

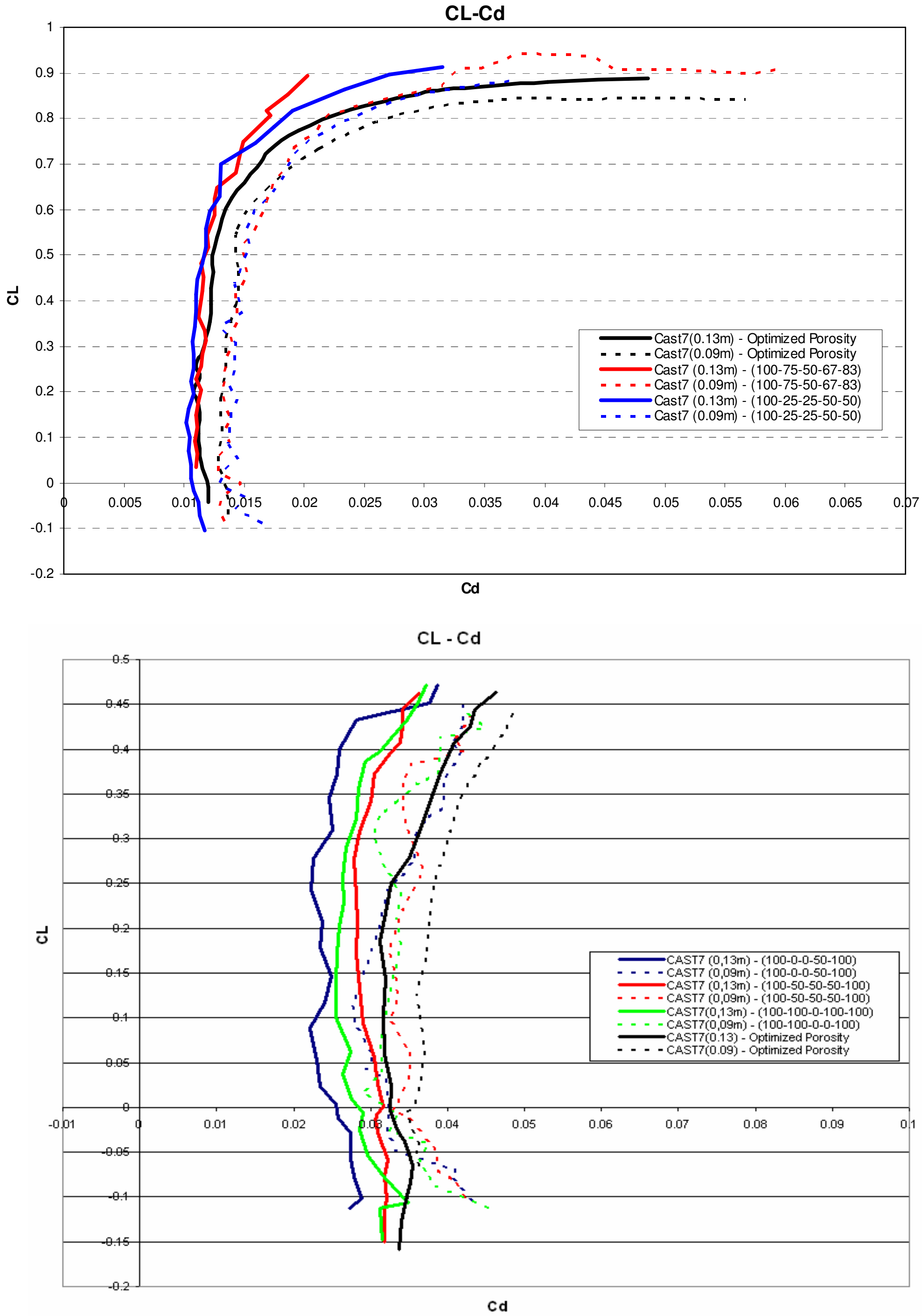


Figure. 17. Drag curve measured at the optimal porosity distributions on both the small and the large CAST 7 airfoil models at Mach 0.73 and 0.85 compared to a non optimal condition.

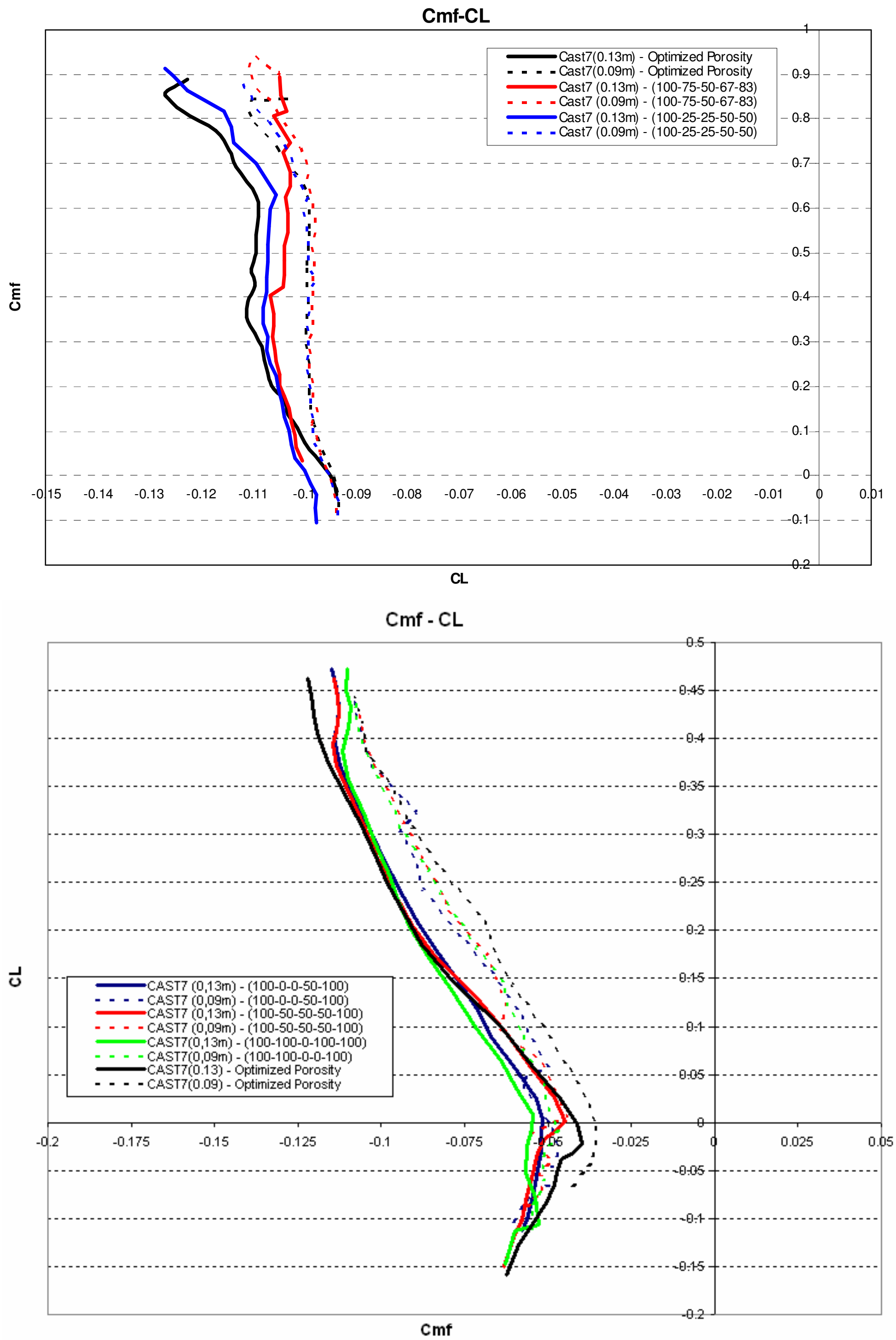


Figure. 18. Pitching moment curve measured at the optimal porosity distributions on both the small and the large CAST 7 airfoil models at Mach 0.73 and 0.85 compared to a non optimal condition.

The wall interference on lift coefficient is practically eliminated also at these higher Mach numbers. Instead, the interference on Cd coefficient is still present even if significantly reduced compared to a generic configuration. Finally, the residual interference in the pitching-moment curve for high incidences is confirmed

However, the fact that the results obtained by this temporary optimized porosity distribution are very good for lift and drag coefficients gives us confidence that the process can be improved. An optimization procedure mainly aimed to the interference of the pitching moment is presently under consideration.

VI. Conclusion

The modern design of experiment (MDOE) is a modern statistical method, first introduced at NASA Langley Research Center in 1997 to produce aerospace research results at the lowest cost consistent with a specified maximum levels of uncertainty. It has been applied in an experimental activity to study the effect of the streamwise porosity distribution on lift, drag and pitching moment curves.

A specific experimental setup consisting in five plates positioned on the top and bottom walls of the wind tunnel test section, has been designed and realized. Setting each plate independently it is possible to obtain practically unlimited combinations of porosity distributions along the streamwise direction.

During the model analysis phase a significant effect of the porosity distribution close to model stagnation and of the Mach number was noticed.

Different porosity configuration for different Mach number should be used to minimize the wall interference. However, the aim of the present activity was to find only one configuration for the whole Mach Range 0.25-1.1.

A temporary best porosity distribution has been found for the PT-1 Wind Tunnel. However, the results and/or the procedure are applicable to all similar Wind Tunnels.

Several tests were performed on the optimized configuration at the different Mach numbers to evaluate the wall interference residuals. The wall interference on lift coefficient is practically eliminate in a huge range of Mach numbers. The interference on Cd coefficient is still present even if significantly reduced, and rises as the Mach number increases; However, a residual interference is still evident on the pitching-moment curve at all Mach number.

For the future activities a new and more accurate system for changing the porosity distribution has been realized in order to verify the results and eventually find the optimal configuration.

Finally, the optimized configuration will be definitively used in the CIRA transonic wind tunnel .

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Finally, a special thank goes to Dr. Richard DeLoach from NASA LaRC, whose kind and thorough suggestions significantly eased our first steps towards the set-up of the experiment design following the MDoE philosophy.

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Computer Software

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