EVALUATION OF WIND TUNNEL WALL BOUNDARY-LAYER CONTROL FOR 2-D HIGH-LIFT AERODYNAMIC AND AEROACOUSTIC TESTING

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Abstract

Experimental work has been conducted to evaluate the effectiveness of applying suction at the wind tunnel working section walls, around a 2-D high-lift wing model. The system was designed to control the three-dimensional effects caused by the interference between wind tunnel wall boundary layer and the low pressure region generated at 2-D wing models by the application of suction. This system consists of a perforated plate near the wing model, at the turn-tables, that communicates with a plenum chamber controlled by a suction system. Measurements of the pressure distribution at three different chord positions and two different span positions were performed with and without suction along with central wake mapping, flow visualization and acoustic measurements with a microphone array. Results show that this technique minimizes the three-dimensionality of the flow in 2-D testing, and the results are sensitive to the suction area only at the low-pressure surface of the wing. The technique was applied to a larger experimental set-up with different three-element high-lift wings, and the results showed that 2-D flow can be enhanced by controlling the correct suction area and mass flow. Also, control of the 2-D flow with minimum suction self-noise can contribute to aeroacoustics measurements.

1 Introduction.

Two-dimensional testing, especially with high-lift devices such as slats and flap, is an important part of the aircraft design process, in which information about wing sections is revealed. The results provided must be precise enough for use in later wing design. Wind tunnel tests of this kind should guarantee precision and repeatability over the complete range of incidence angles and configurations. The very low-pressure upper surface of a high-lift wing induces the formation of a strong vortex between wing and wind tunnel wall or splitter plates causing non uniform circulation distribution over the model. Therefore, a two-dimensional experimental set-up without any wall boundary layer control can produce wrong results and should be avoided as reference data for both aerodynamic and aeroacoustic measurements. Even at low incidences, a HLW (high-lift wing) will produce strong horseshoe vortices that will induce not only a tri-dimensional flow over the surfaces but also extra turbulence and vortex noise at the model borders. Fig. 1 shows a schematic demonstration of the horseshoe vortex formation between a wing and a wall boundary layer.

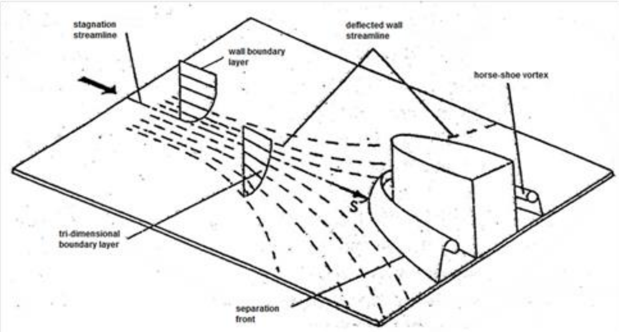

Fig. 1 Horseshoe vortex formation a flat plate and a wing with circulation. [1].

This horseshoe vortex for a HLW 2-D model is asymmetric been more strong at the suction side of the model and induce a separation at the main element and flap. Wind tunnels around the world commonly use two techniques to reduce the effects of three-dimensionality: sidewall suction or blowing. The pressure gradient over a high-lift 2-D wing and the walls of the test section of a wind tunnel can be minimized through suction or tangential blowing over certain regions of the walls, thus reducing the interaction of the wall boundary layer and the wing pressure field.

The suction solution is widely used in important research centers. Paschal et al. [2] at NASA Langley Research Center, compared the suction technique with the tangential blowing boundary layer control (BLC) system and concluded that the suction technique could maintain uniform spanwise flow on the model over a wider range of Reynolds numbers than blowing. Valarezo et al. [3] used suction as boundary layer control BLC in the Low Turbulence Pressure Tunnel of NASA Langley, to study the performance of multi-element airfoils at various Reynolds and Mach numbers. As the wind tunnel is pressurized the system consisted of vent areas in various positions near the wing model. The technique guaranteed good quality two-dimensional flow for the Reynolds numbers tested and only small open area strips were necessary. This (BLC) technique was also used in a study on separation control of high-lift airfoils (Lin et al., [4]), with the flow rate adjusted based on the information of pressure taps placed along the span. Lin et al. [5] also used the BLC to investigate parametrically a high-lift airfoil, to increase the experimental database on high-lift aerodynamics for later use in computational fluid dynamics (CFD). Rumsey et al. [6], tested several endplate suction patterns with different pressure gradients to drive the suction. Previous experiment set-up developed in [7] to assure two-dimensional high-lift testing used suction at discrete areas near the upper surface of a wing model with high circulation. The idea was to remove the wall boundary layer before it separates and create a horse shoe vortex. The system was eventually applied to a larger wind tunnel testing a three-element high-lift wing and became a standard system for 2-D experiments.

Far field aeroacoustic measurements in a wind tunnel are performed either by single microphone measurements in a semi anechoic environment or by phased array methodologies. These methodologies rely on beamforming techniques and, despite the achieved improvements in the abilities of source quantification and identification, spectral results still depends on a good signal to noise ratio for the source studied and noise uniformity when dealing with spanwise distributed sources. Therefore, it is fundamental to ensure source uniformity over the span when looking for accurate spectral prediction for line sources such as the ones from trailing edges and slats of 2-D models and the use of BLC with suction can possibly improve the 2-D flow.

The present work, thus, discusses the application of a suction system in order to minimize wing/wall interference effects and increase the accuracy of both 2-D high-lift aerodynamic and aeroacoustic tests in a closed test section wind tunnel.

2 Experimental Set-up.

The Fig. 2 presents a plan view of the LAE-1 closed circuit wind tunnel. The wind tunnel test section dimensions are 3.00 m long, 1.30 m high and 1.70 m wide. The maximum design flow speed is 50 m/s, with a turbulence level of 0.20%, nowadays due to safety and components long range issues, this velocity is limited to 45 m/s. Its electric motor, with 110 HP, drives an 8 blades fan with 7 straighteners placed downstream of the fan. On the flow stabilization section there are two 54% porosity mesh screens followed by the 1:8 contraction cone designed using two 3rd order polynomials joined at 45% inflection point.

The suction system is installed at the turn-tables, located at upper and bottom wind tunnel working section walls. Each turn-table has a plenum chamber where suction is promoted by a centrifugal pump. The 2-D wing model is attached to the turn-table rotating shaft at 0.5chord. The shaft is hollow in order to pass the model tubing and wiring necessary for the measurements. Around the wing model end there is an open area covered by a perforated plate of 0.22% of porosity. This perforated plate is initially sealed by vinyl and the exposed area are determinate for each wing by properly cutting the seal as can be seen in Figure 3.

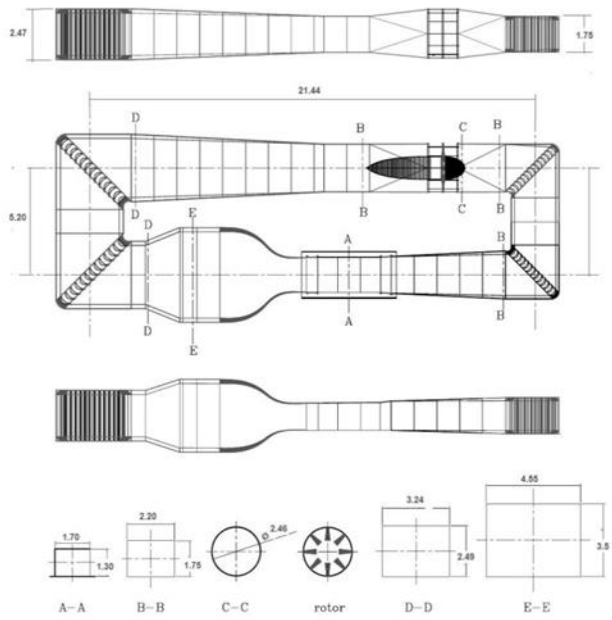

Fig. 2 LAE-1 wind tunnel lay out.

Three different 2-D high-lift wing models were tested for this study, including the 30P30N model. Details of some wing models could not be presented due to proprietary reasons but, since all of them consisted of a three element (slat, wing main element and flap) 2-D wing, the particularities of each geometry were not relevant. All wing models have pressure taps at center chord and the first model tested had also taps at the main element near the top and the bottom walls as well as in the spanwise direction at 0.25c and at 0.75c. Figure 3 shows the set-up of the first wing model.

Pressure measurements were carried out using a Scanivalve® ZOC system with a pressure transducer of ±20-inchH_2O and accuracy of ±0,15% of the full scale. The slat and flap had each one 27 pressure taps distributed on both surfaces and the main element had 57 and 53 on the upper surface and bottom surface respectively.

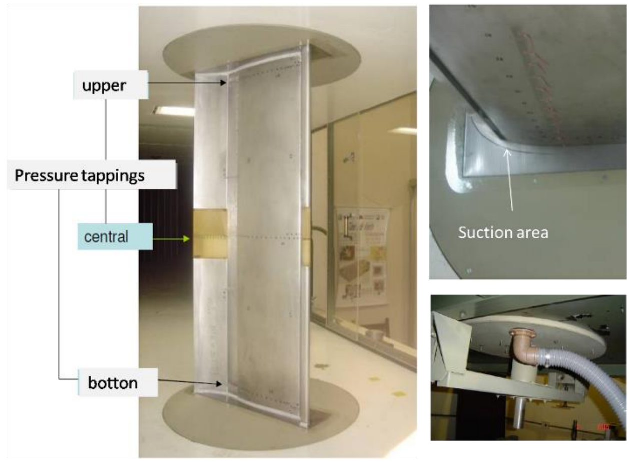

Fig. 3 High-lift experimental set-up with wind tunnel wall boundary layer suction.

Surveys of the wing wake were performed with a seven holes Pitot probe developed at the laboratory, using piezoresistive pressure transducers by sensortechnics HCLA 12X5B with ±12,5mBar range and 0.05% accuracy to 0,25%FS. This probe was calibrated with neural networks to measure flows with high angularity and it is especially suitable to obtain the flow field characteristics of the flap side edge vortices. Mapping was performed using a Dantec traverse gear with ±0,1mm accuracy.

Recently, the LAE-1 wind tunnel passed through an upgrade to reduce the background noise in order to carry-out beamforming noise measurements. Details of this upgrade and characterization can be found in [8] and Fig. 4 shows the final results for the wind tunnel background noise after the modifications, in terms of the Overall Sound Pressure Level (OSPL) variation with the flow speed.

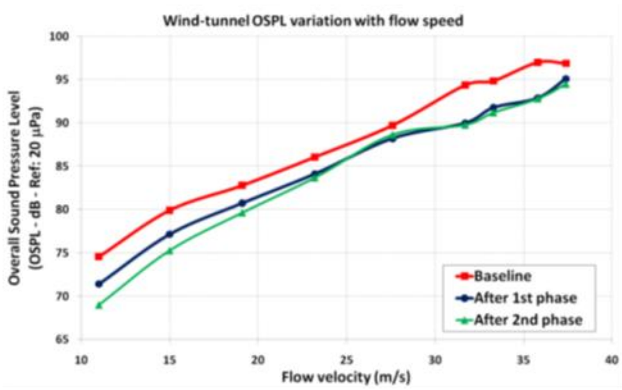

Fig. 4 OSPL variation with the wind tunnel flow speed [8].

For aeroacoustic tests, an array with 61 microphones was employed to measure noise intensity and localization by applying the the beamforming technique. The antenna has 61 G.R.A.S. 46BD high frequency microphones suitable for acoustic measurements up to 70 kHz. Phased array signal processing using Conventional Beamforming algorithm is used to create the source maps and the Source Power Integration technique to create the noise spectrum at a given grid location.

3 Results and Discussion

3.1 Aerodynamic results

The first results are for the model with the following list of pressure taps: one central which included flap and slat; two in the main element only located near the roof and floor of the wind tunnel; and one distribute in the spanwise and located at 1/4chord. Those pressure taps were strategic located for checking the effect of the suction system on sustaining two-dimensional flow over the wing. Also, a near field wake survey was carried-out to evaluate the spanwise wake distribution including the effect of slat brackets on the main element and flap separation. All the aerodynamic and aeroacoustic testing were conducted at an average Reynolds number of $1x10^6$. Figs. 5 and 6 show results for the main element pressure distribution at incidence angle of 18 degrees, note that the labels mean the frequency at the centrifugal pump inverter, following Fig 7. It is clear that the effect of the wall boundary layer interaction with the wing flow must be controlled and this control can be carry-out by discrete suction although its effect is highly dependent on the suction mass flow. From Fig 6 the pressure distribution closed to the wall with suction off show a huge separation at x/c= 0.15 and when the suction equalizes the pressure field this separation tends to disappear. This "V" shape separation at both wing model ends is confirmed by flow visualization.

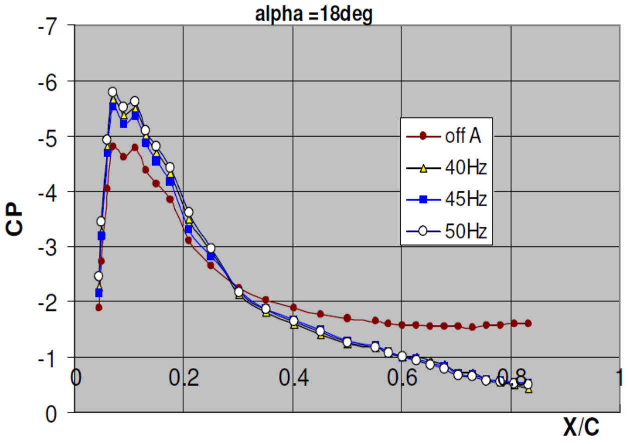

Fig. 5 Pressure distribution at center of the wing.

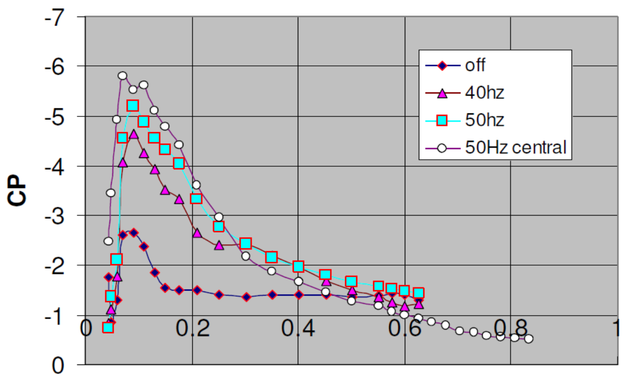

Fig. 6 Pressure distribution near the wind tunnel wall.

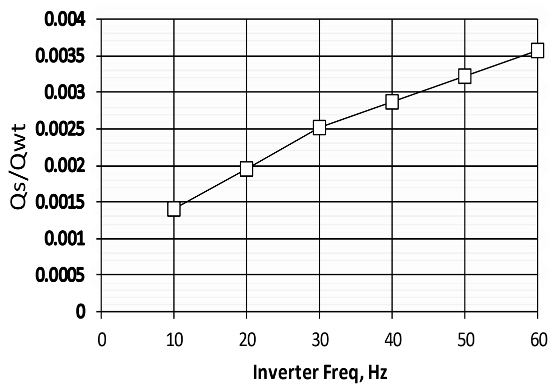

Fig. 7 Suction mass flow rate Qs/Qwt as function of the inverter frequency

Figures 8 and 9 show the effect of suction on the pressure distribution of the slat and the flap. From the slat results of Fig 8, it is clear that the variation of mass flow suction does not affect significantly the slat pressure distribution and the increase of circulation is more like to be a result of increase of incidence due the less tri-

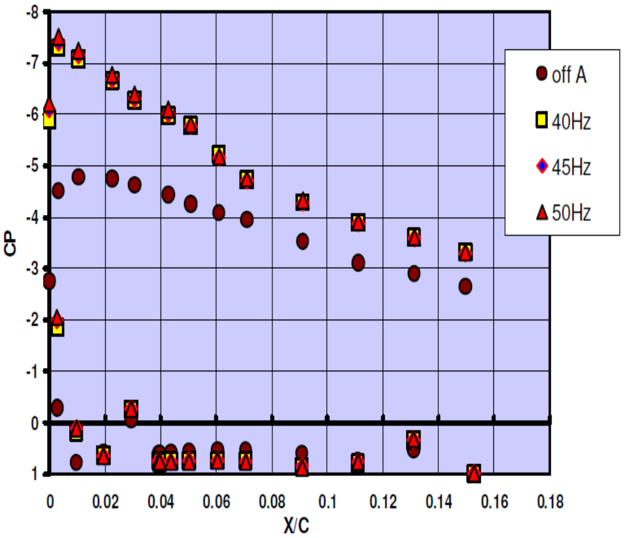

Fig. 8 Pressure distribution at center of the slat.

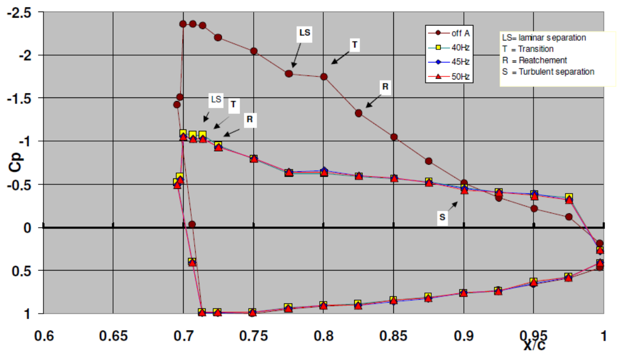

Fig. 9 Pressure distribution at the center of the flap.

dimensional wing main element and flap flow. Also, the horseshoe like vortex is just initiating at slat and, due its small chord the effect on the pressure distribution is very small. The effect of highly loaded wing main element is also observed at the flap as its circulation gets smaller as the suction is applied. These observations are in accordance with the expected behaviors of a 2-D three element high-lift wing model.

Fig.10 shows the effect of the suction mass flow over the spanwise pressure distribution at 1/4chord position. It can be seen that there is a minimum suction quantity that guarantees two-dimensionality and excess of suction may lead to an over load towards the wing model ends. In Fig. 11 it is possible to observe the effects of suction on the wing wake, with two-dimensional flow confirmed by a wake with less downwash. Figure 12 shows CDxα from the wake integration and it can be seen that the model with suction has a drag coefficient that rises with the increasing angle of attack, while the model without suction behaves more like a finite wing with low aspect-ratio, sustaining an almost constant drag coefficient.

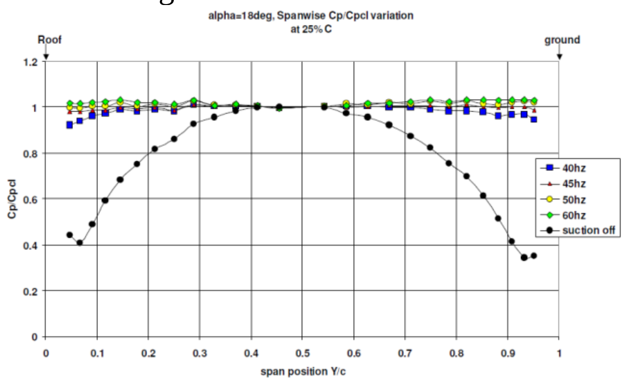

Fig. 10 Cp/Cpcl spanwise distribution at 0.25% chord.

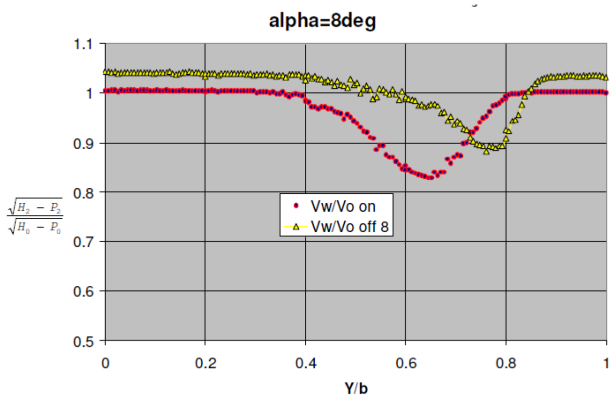

Fig. 11 Wake total head rate at one chord distance.

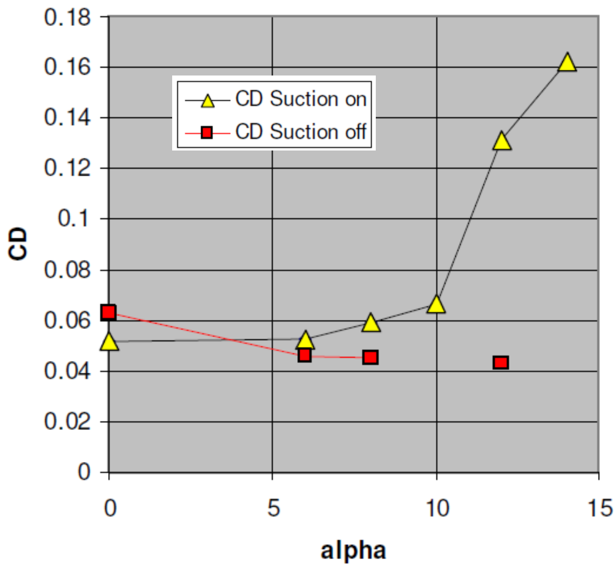

Fig. 12 Drag coefficient from wake integration.

The pressure distribution showed in the following figures were carried out in order to check that the test conditions could be reproduced by CFD/CAA codes and used as validation data for those codes. The minimum suction rate at the wind tunnel wall boundary layer control to assure two-dimensional flow at the model was assessed prior to the final measurements. Figs 13 and 14 show the final results for the 30P30N model pressure distribution with suction on and off and compared to the CFD results at 4°.

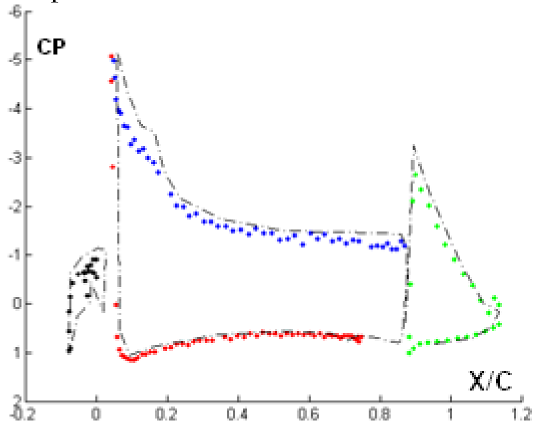

Fig. 13 Comparison with CFD alpha=4 deg suction off.

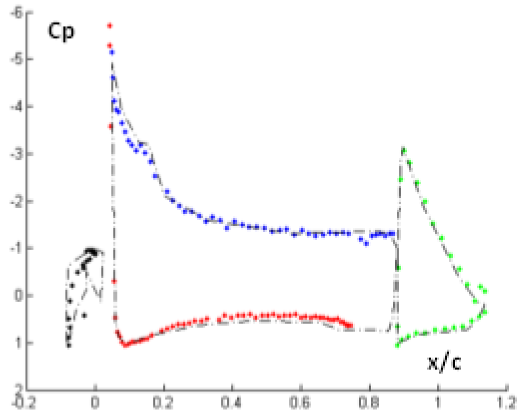

Fig. 14 Comparison with CFD α= 4o suction on.

The following figures 15 and 16 show the same results but for an incidence angle of 16°. It can be seen from Figs. 13 to 16 that the suction is more important for 16° than for 4° as the high suction peak more strongly interacts with the wind tunnel wall boundary layer.

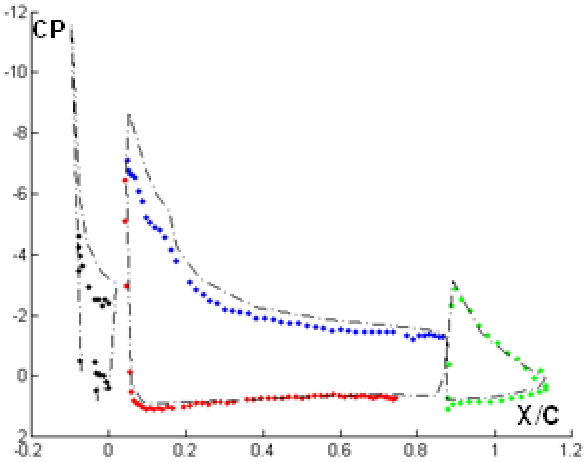

Fig. 15 Pressure distribution alpha=16°, suction off.

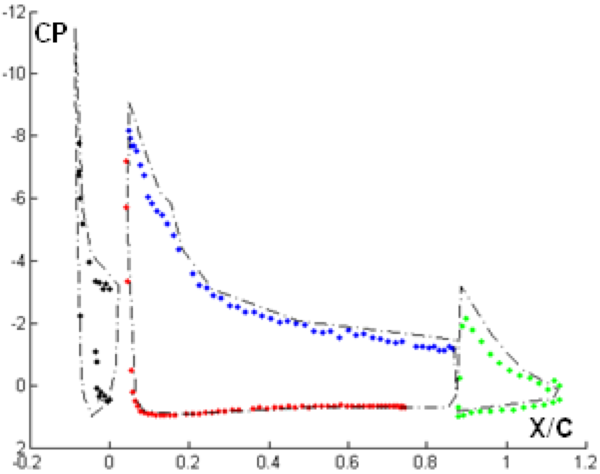

Fig. 16 Pressure distribution α=16o, suction on.

3.2 Aeroacoustics Results

The difference between the spectra of the slat sources of the high-lift 2D model measured with a microphone phased array and predicted with conventional beamforming and source power integration at three different suction quantities are shown in Fig. 17. The figure indicates how the suction system affects the predicted slat noise, mostly the slat mid-frequency tones, that decrease with the increasing suction quantities. This is in accordance with the observed pressure distribution improvements obtained with the suction system since higher induced angles of attack are followed by smaller tonal contents, as discussed in [9].

Despite such improvements in the mid-frequency tonal levels, the broadband levels in high Strouhal numbers are affected by the system self-noise and therefore suction values should be controlled in order to provide good pressure distribution allied with minimum broadband influence.

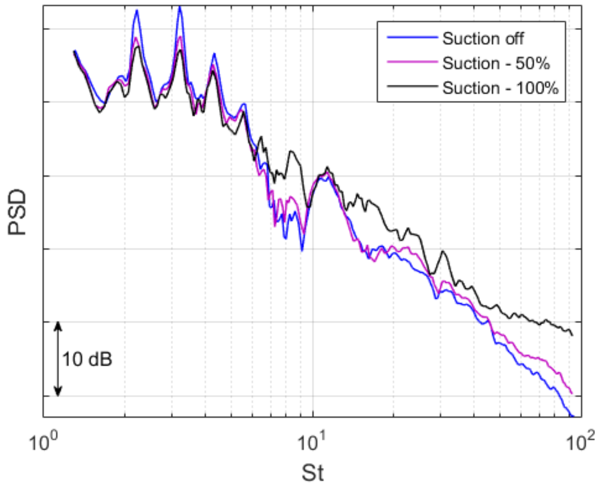

Fig. 17 Effects of the suction system on the slat beamforming noise spectrum [9].

The beamforming maps (Figure 18) also reveal how the distribution of the sources is improved by the use of the suction system, with more distributed sources observed even in the broadband range. However, sources at the model borders and higher sources upstream from the slat are observed, indicating the system self-noise contamination in the measurements. This system self-noise could contaminate the spectrum predictions even when integrating the sources at the center of the slat due to its high frequency content and the effects of side lobes in the spectrum.

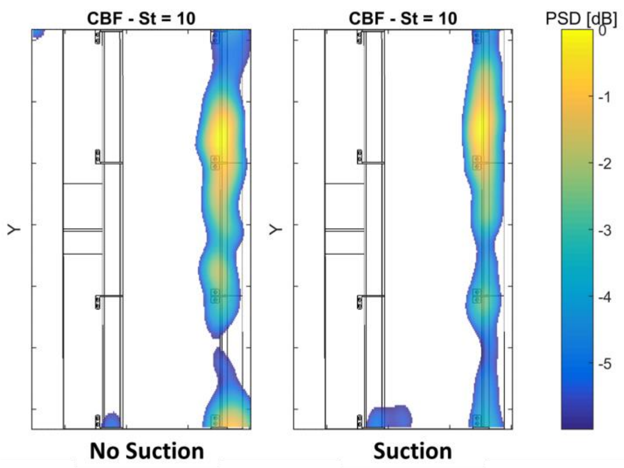

Fig. 18 Variation of the beamforming maps by the suction system.

4 Conclusions

A study evaluating the effects of a suction system on the aerodynamic and aeroacoustic performance of high-lift airfoils was carried out. Based on previous results the best suction pattern for the porous area turn-table was applied and results were presented comparing suction on and off for both aerodynamic and aeroacoustic applications. The following conclusions can be drawn from the presented tests:

1 For the high-lift configurations tested, the suction system was able to effectively control sidewall boundary-layer separation and maintain a uniform spanwise flow field up to the stall condition for the Reynolds number tested.

2. Concentrated suction in the junction region between the tunnel sidewall and the upper surface of the model was required for spanwise uniform flow on all HLW 2-D model elements.

3. Accurate experimental determination of airfoil optimization for maximum lift are difficult to assess without adequate wind tunnel wall boundary layer control.

4. Due the good quality of the two-dimensional data obtained with the suction system the data are considered acceptable for validation of computational fluid dynamics prediction codes.

5. Aeroacoustic testing using microphone array and beamforming technique revealed that accurate suction can impact the flow distribution and, consequently, the predicted model noise.

6. The noise produced by the suction system can also impact the acoustic measurements and therefore a study with the minimum suction quantity necessary for 2-D flow must be taken before any final acoustic measurements.

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