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# ON THE USE OF ACTIVE FLOW CONTROL FOR AEROFOIL NOISE REDUCTION

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The possibility of trailing edge noise reduction using active flow control is addressed in this paper. The boundary layer is altered with the help of flow injection and suction on a long flat plate upstream of a sharp trailing edge. To study the effects of active flow control on the trailing edge noise generation mechanisms, simultaneous measurements have been taken for the streamwise velocity component using hot-wire anemometry and surface pressure fluctuations with flush mounted microphones. It has been shown that the proposed flow injection and suction methods are capable of reducing the noise over a wide range of frequencies. It has also been revealed that the blowing is effective in shifting the energy containing turbulent structures farther away from the wall, resulting in a significant reduction of measured surface pressure spectra. The boundary layer suction control method was shown to be effective in the reduction of pressure fluctuations in the mid frequency regions, which quickly moves to the lower frequencies at further downstream locations. It has also been observed that the blowing can lead to a significant reduction of trailing edge noise when located close to the trailing edge, and the favourable effects of the flow suction case can be exploited by placing the trailing edge farther from the flow control section.
Keywords: active flow control, trailing edge noise

## 1. Introduction

The trailing edge (TE) noise is one of the most significant contributor to the overall noise emitted by rotating machines such as fans, turbo-engines, wind turbines, and also high-lift devices. The broadband TE noise is generated by the scattering of the boundary layer pressure fluctuations into acoustic waves at the trailing edge of any lifting surface. The TE noise is often the dominant component in the absence of incoming turbulence interaction. The continuously increasing air traffic, the spread of wind farms and the rising number of turbo-engine operated (or assisted) machines have all contributed to the increase of our environmental noise. The high level of environmental noise pollution resulted in stringent regulations which lead to engineering challenges in order to meet the desired low noise emission levels.

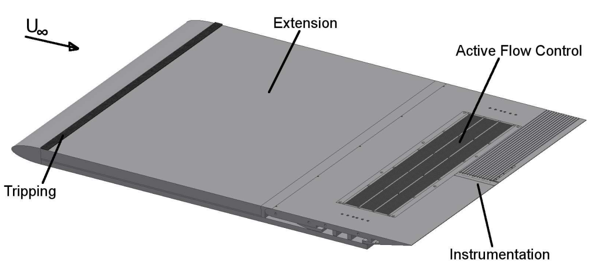
The currently available TE noise reduction approaches can be categorized as *passive* and *active* methods. The examples of the former one include the application of TE serrations [1–3], TE brushes [4,5], porous materials [6,7], surface treatments [8,9], shape optimization and morphing, [10], etc. The passive methods are known to be effective over a range of operating conditions and outside this range they might introduce undesired losses. The active flow control (AFC) methods intend to overcome these limitations and push the boundaries of the achievable noise reductions. They can be adjusted according to the external conditions, but they also require external power input. This requirement needs to be kept low enough to achieve a desirable overall efficiency. Prior research have shown that the energy demand of the AFC methods are usually too high for aerodynamic performance tailored applications, as their power intake requirement scales with approximately $10^{-3}$ of the flow total energy. As the turbulence generated noise scales approximately with $10^{-6}$ portion of the flow total energy, it is expected that AFC methods tailored for aeroacoustic noise reduction will require significantly lower power input than those intended for aerodynamic purposes, making AFC a much more applicable candidate for noise reduction.

The active reduction of TE noise can be performed by boundary layer flow control. The effect of BL injection and suction, from turbulence point of view, has already been studied by Antonia *et al.* [11], Park and Choi [12] and Oyewola *et al.* [13, 14], etc. It was found that even with a low amount of BL suction or injection (10 % of free stream velocity), the boundary layer structure can be significantly altered. Park and Choi [12] reported that uniform blowing leads to the uplift of near-wall vortices and they become stronger downstream of the AFC section due to reduced viscous diffusion. This results in the increase of the turbulence intensity as the flow advances downstream. They showed that the streamwise vortices were brought closer to the wall for the suction case, resulting in increased viscous diffusion. The increased diffusion leads to decrease in the turbulence intensity and Reynolds shear stresses downstream of the AFC section. Additionally, Antonia *et al.* [11] made similar investigations as Park and Choi [12], but their study was limited to suction with an increased flow rate. They reported that with the increased amount of suction, they experienced partial or total relaminarisation. Their study also revealed that below a threshold suction rate, suction has a negligible effect on the structure of the boundary layer.

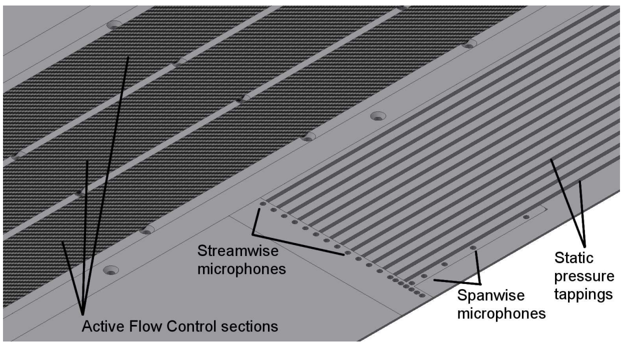
Active flow control methods for aeroacoustic purposes have not yet been widely studied, unlike the passive noise control methods, which has received reasonably high research attention over the past few years. The limited number of studies published on the application of AFC reported a few decibels of far-field noise reduction [15–18]. The majority of these studies focus on fluid injection from the TE into the wake or flow suction from the boundary layer upstream of the TE. Many of them are either limited to low Reynolds numbers with the help of computational fluid dynamics or based on experiments, but limited to only the far-field noise. An in-depth detailed study is required to reveal the effect of AFC methods on turbulence and therefore on the generated TE noise.

Our aim is to address the effect of blowing and suction on the driving parameters of trailing edge noise. Experiments have been conducted on a flat plate to measure and investigate the turbulence properties of the boundary layer and the exerted surface pressure fluctuations on the plate. The measured changes in these parameters can be brought into relation with the far-field noise through Amiet's TE noise model [19]. We aim to find answers and directions for an effective and efficient way to control the TE noise with the help of the currently proposed AFC methods.

## 2. Experimental Set-up




(a) Overall view of the rig




(b) Detailed view of the instrumented and active flow control area

Figure 1: Schematic view of the test rig

Experiments have been conducted in the open jet closed-circuit wind tunnel facility of the University of Bristol. A long ($L$ =1000 mm), zero pressure gradient flat plate with a sharp ($12°$) trailing edge has been built to achieve a well developed boundary layer. The overall view of the test rig is depicted in Fig. 1(a). The applied wind tunnel speeds were $u_\infty = 10$ and $15$ m/s with a corresponding Reynolds number of 0.67 and 1.0 million based on the length of the plate. The turbulence intensity of the flow in the test section was 1 %.

Flush mounted electret microphones were used for the measurement of unsteady surface pressure fluctuations. A total number of 21 transducers were distributed both in the streamwise and spanwise directions close to the TE, see Fig. 1(b). The miniature FG-23329-P07 type Knowles microphones have been calibrated prior to the measurements and their uncertainty was found to be ±0.5 dB within the investigated frequency range. The microphones were mounted below a pinhole with a diameter of $d = 0.4$ mm. Schewe [20] reported that by keeping the dimensionless pinhole diameter ($d^+ = du_\tau/\nu$) below $d^+ = 19$, the attenuation of the pressure signal will be negligible and the discontinuity introduced on the surface will not affect the boundary layer. The current configuration resulted in $d^+$ values ranging between 8 and 12. Additionally, the corrections proposed by Corcos [21] were applied during the post processing of the microphone signals. Results will be shown at two particular microphone locations along the centreline ($z = 0$) referred to as $m1$ and $m2$ located at 99 mm and 4.5 mm upstream of the TE, respectively (see Fig. 2).

Dantec 55P16 type single-sensor hot-wires were used to measure the turbulence properties of the streamwise velocity component along the $y$-axis above the microphones $m1$ and $m2$, as shown in Fig. 2. The probes were operated by a Dantec StreamWare Pro CTA91C10 module at an overheat ratio of 1.8. They were calibrated in advance of the measurements and their uncertainty was found to be less then 0.5 %. The data was captured from the microphones and the hot-wire simultaneously by a National Instruments PXIe-4499 system at a sampling rate of 65,536 Hz ($2^{16}$ Hz) for a time period of 8 seconds. The frequency resolution was set to 64 Hz during the post processing of the captured data.

The applied active flow control method involved fluid injection (blowing) and suction through a 2 mm thick and $b = 30$ mm long porous aluminium sheet with 90 pores per inch (PPI), ending 110 mm upstream of the TE. The direction of the flow, therefore, was perpendicular to the plate. The AFC flow severity is defined after [11] as $\sigma = u_\perp b u_\infty^{-1} \Theta^{-1}$, where $u_\perp$ is the AFC flow velocity, and $\Theta$ is the boundary layer momentum thickness for the baseline case, i.e. it relates the momentum of the boundary layer to the momentum of the AFC. Initial wind tunnel tests have shown that the two investigated active flow control methods are effective on different boundary layers. The flow suction has been found to be efficient on a thinner, and the blowing on a thicker boundary layer. This has been achieved by applying different trippings on the plate, such as mounting (a) an 80 grit 40 mm long sandpaper to achieve a thinner boundary layer ($\delta \approx 20$ mm) and (b) a 25 PPI 10 mm thick, 20 mm long porous aluminium block resulting in a thick boundary layer ($\delta \approx 100$ mm).

## 3. Results

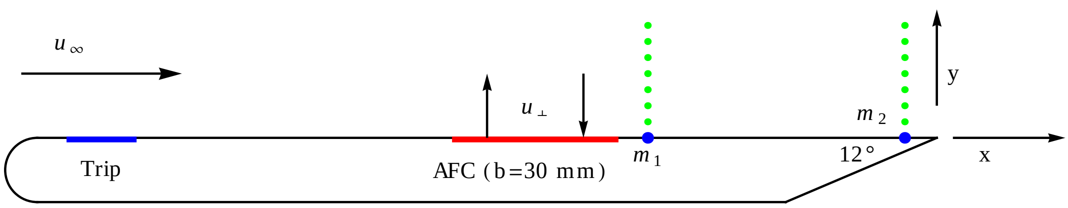
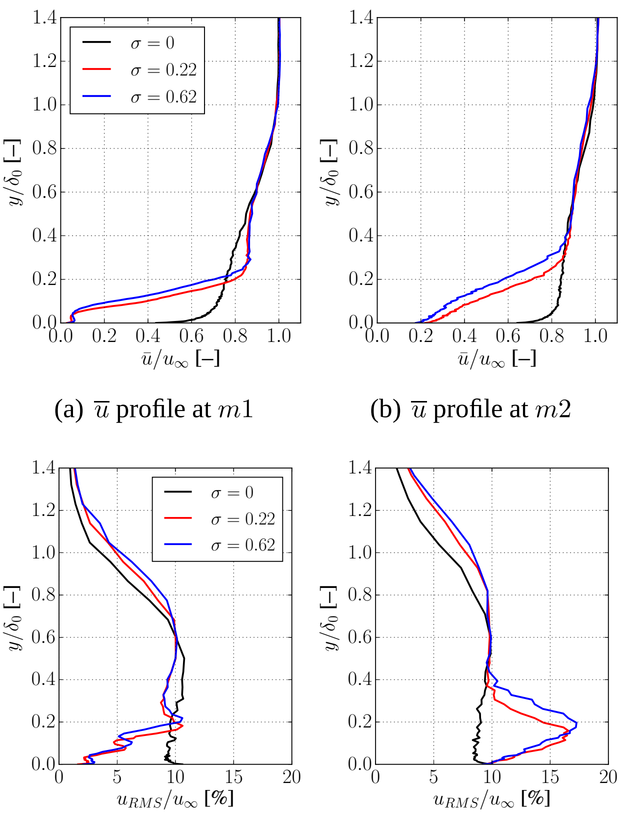



Figure 2: The cross-section of the test rig (●, flush mounted microphones; ●: hot-wire measurement locations)

In this section the measured data will be presented and discussed. The effects of the proposed AFC techniques will be shown and highlighted through the measured quantities and the physical causes of any significant reductions observed will be analysed. In what follows, we shall first present the results of the steady blowing, followed by the steady suction results.

## 3.1 Steady Uniform Blowing




(a) $\overline{u}$ profile at $m1$ (b) $\overline{u}$ profile at $m2$

(c) $u_{RMS}$ profile at $m1$ (d) $u_{RMS}$ profile at $m2$

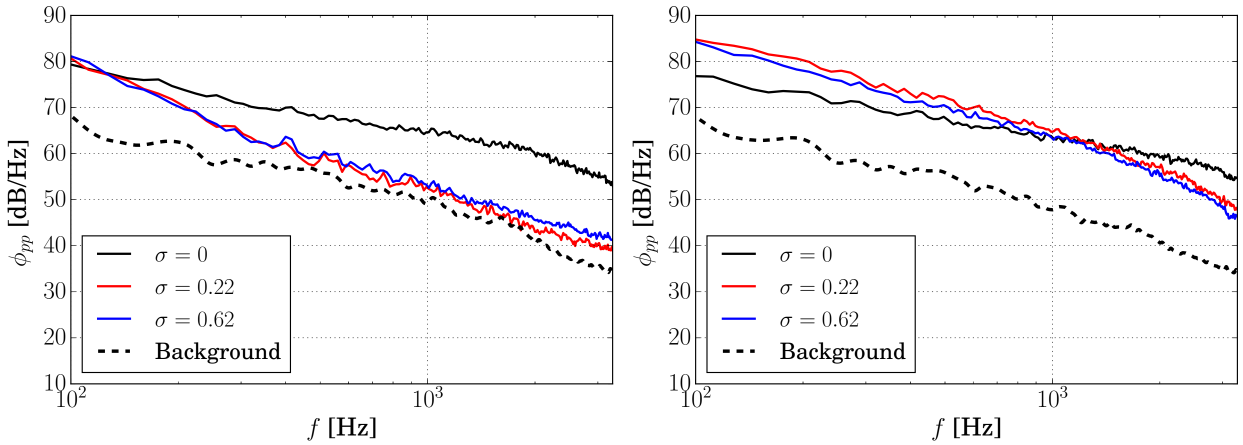
Figure 3: Mean (a, b) and RMS (c, d) velocity profiles downstream of the active flow control section at two locations ($m1$ and $m2$) for the blowing flow control cases

Figure 3 presents the boundary layer behaviour upstream of the TE for two different blowing rates ($\sigma = 0.22$ and 0.62) and for the baseline case ($\sigma = 0$). Figures 3(a) and 3(b) show the measured mean velocity ($\overline{u}$) profiles, while Figs. 3(c) and 3(d) show the root mean square (RMS) velocity profiles. Concerning the mean velocity profiles, the newly introduced fluid layer within the BL results in a significant momentum deficit below $y/\delta_0 = 0.2$, while it increases the flow velocity at the $m1$ location between $y/\delta_0 = 0.2 - 0.6$. This effect on the BL profiles, similarly to what Park and Choi [12] reported, is the uplift of the turbulent structures. We can find an inflexion at location $m1$ close to the surface ($y/\delta_0 < 0.1$) in the blown BL $\overline{u}$ profiles indicating separated flow. This inflexion was not experienced at the TE, suggesting attached flow. We can conclude from the $\overline{u}$ profiles that the introduced fluid has a local near-wall effect on the boundary layer structure which exerts its effect as the flow advances downstream.

Figures 3(c) and 3(d) show the velocity root mean square (RMS) of the streamwise velocity component ($u_{RMS}$) along the boundary layer at the $m1$ and $m2$ locations. We can see a significant reduction achieved in $u_{RMS}$ at location $m1$ and as we move downstream, the reduction fades away and an increase in the RMS profiles is observed. The point $y/\delta_0 \approx 0.6$ separates two regions in the flow at locations $m1$ and $m2$: below $0.6\delta_0$ the effect of blowing on $u_{RMS}$ is originated from the newly introduced fluid, while above $y/\delta_0 \approx 0.6$ the increase in $u_{RMS}$ is the result of the uplifted BL flow. The presence of a shear layer is indicated by the shape of the RMS profiles. They have a pointed shape below $y/\delta_0 \approx 0.4$ with a peak located at $y/\delta_0 \approx 0.2$. This statement can be confirmed by the fact that there is a lower momentum fluid located closer to the wall, and one finds a higher momentum fluid above the peak location. This layout, being a clear effect of blowing, encourages the flow to develop larger, higher energy containing turbulent structures as the flow moves downstream. Similarly, Park and Choi [12] reported growth in the turbulence intensity downstream of the blowing section and they related this effect to the reduced viscous diffusion. The increase in the streamwise turbulence experienced here is indicating that as we move downstream of the AFC section, more streamwise fluctuations are present in the flow. One can also see that the existence of separation at the first location ($m1$) is confirmed by the first RMS profile, where two peaks below $y/\delta_0 = 0.2$ are indicating the separation. These findings will be further investigated using PIV measurements.

Table 1: Boundary layer properties for the blowing cases above microphone $m1$

| | $\sigma$ | $u_\infty$ | $\delta$ | $\delta^*$ | $\theta$ | $u_\tau$ | $Re_\theta$ |
|---|---|---|---|---|---|---|---|
| $m1$ | $[-]$ | [m/s] | [mm] | [mm] | [mm] | [m/s] | $[-]$ |
| | 0 | 15 | 109.75 | 16.54 | 12.89 | 0.555 | 13,032 |
| | 0.22 | | 111.22 | 22.08 | 10.98 | 0.540 | 11,075 |
| | 0.62 | | 107.04 | 24.07 | 10.91 | 0.525 | 11,006 |




(a) measurement at $m1$ (b) measurement at $m2$

Figure 4: Surface pressure fluctuation spectra $\phi_{pp}$ downstream of the active flow control section at locations $m1$ and $m2$ for the blowing flow control cases

Figure 4 presents the effect of the blowing on surface pressure fluctuations ($\phi_{pp}$) at the $m1$ and $m2$ locations. The AFC has a broadband effect on the measured spectra. Immediately downstream of the flow control section, at location $m1$, we find a significant (up to 10 dB) broadband reduction in $\phi_{pp}$. This originates from the formerly seen complex effect of blowing, such that it can shift the energy containing eddies farther from the wall, reducing their contribution to the surface pressure fluctuations, and introducing a lower energy containing fluid layer close to the wall. As we approach the TE, the reduction in $\phi_{pp}$ becomes less obvious, its amount decreases and alongside with this, we see an energy increase at the low frequencies. The energy increase at downstream locations is due to the emergence of larger structures originating from the shear induced vortices. As observed in Figs. 3 and 4, to exploit the advantages of the BL blowing for TE noise reduction purposes, the position of flow blowing should be located close to the trailing edge.

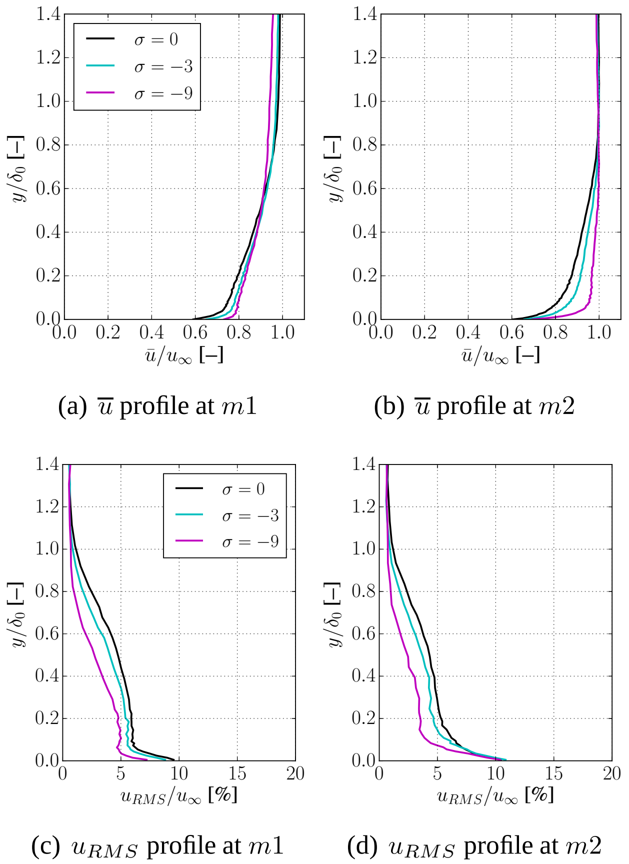
## 3.2 Steady Uniform Suction

The same flow quantities are investigated for the flow suction case as were for the blowing case. The boundary layer properties for locations $m1$ and $m2$ are listed in Table 2 with and without flow suction. Figure 5 shows the BL mean ($\overline{u}$) and RMS ($u_{RMS}$) profiles. The suction affects the shear in the BL, especially at $m2$, by splitting it up into two distinct regions: a high velocity gradient region below $0.1\delta_0$ and a low velocity gradient region above this point. The boundary layer thickness is more significantly affected for this treatment than for the blowing cases. Table 2 indicate that the BL thickness first increases and as the flow advances, the boundary layer thickness decreases to $\delta \approx 0.6 \ldots 0.7\delta_0$. This is shown in Fig. 5(a) by the fact that the treated profiles do not reach the free-stream velocity even at $1.4\delta_0$, indicating an increased BL thickness. Similar findings were observed by Park and Choi [12], where jump in the boundary layer momentum thickness was reported just downstream of the AFC slit, followed by a decrease further downstream. The boundary layer momentum thickness ($\theta$) has been significantly reduced for the $\sigma = -9$ case by 70 % of its original value. The flow suction results in increased momentum in the BL, which decreases the momentum in the near-wall region.

Table 2: Boundary layer properties at microphone $m1$ and $m2$ for the suction cases

| | $\sigma$ [$-$] | $u_\infty$ [m/s] | $\delta$ [mm] | $\delta^*$ [mm] | $\theta$ [mm] | $u_\tau$ [m/s] | $Re_\theta$ [$-$] |
|---|---|---|---|---|---|---|---|
| $m1$ | 0 | 10 | 19.55 | 1.51 | 1.29 | 0.530 | 860 |
| | $-3$ | | 29.01 | 2.49 | 2.12 | 0.480 | 1,430 |
| | $-9$ | | 51.03 | 3.47 | 3.10 | 0.475 | 2,100 |
| $m2$ | 0 | 10 | 20.33 | 1.53 | 1.30 | 0.525 | 920 |
| | $-3$ | | 17.77 | 1.04 | 0.92 | 0.550 | 630 |
| | $-9$ | | 12.44 | 0.41 | 0.37 | 0.650 | 258 |

The RMS profiles are presented in Figs. 5(c) and 5(d). A significant reduction in flow energy content is observed over the entire BL for both locations. We can not see clearly from Fig. 5 if laminarization was achieved, hence further hot-wire and hot-film measurements are planned to find the suction rate that can relaminarize the flow. Total recovery to the baseline conditions in the investigated streamwise distance has not been achieved, as the profiles after $5\delta_0$ downstream of the treatment are still significantly different from the baseline. This is in agreement with the findings of Antonia *et al.* [11], who reported that for $\sigma = 2.6$ the flow required approximately $40\delta_0$ to return to its original state ($x = 0$, $\sigma = 0$). The treated profiles partially return to their original values in the near-wall region above location $m2$, which agrees with the findings of Park and Choi [12], where the near-wall energy content of the streamwise velocity component was shown to return to its original value in a short distance. The study also reported that as the turbulent structures were brought closer to the wall, the viscous dissipation increased downstream of the treatment. This effect is going to be investigated with the help of PIV measurements.

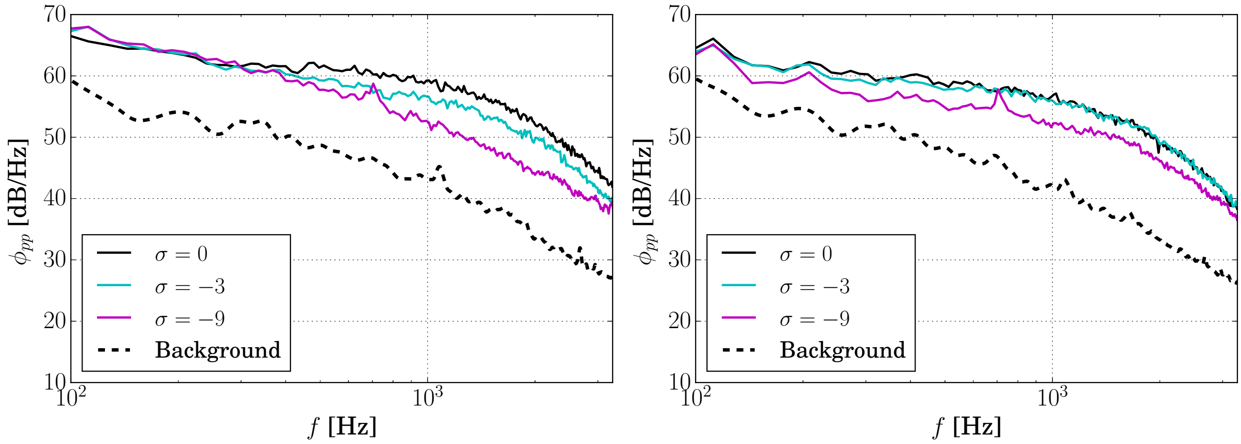



(a) $\overline{u}$ profile at $m1$ (b) $\overline{u}$ profile at $m2$

(c) $u_{RMS}$ profile at $m1$ (d) $u_{RMS}$ profile at $m2$

Figure 5: Mean (a, b) and RMS (c, d) velocity profiles downstream of the active flow control section at two locations ($m1$ and $m2$) for the suction flow control cases

The effect of the flow suction downstream of the AFC section on the measured surface pressure fluctuations is presented in Fig. 6. Results have shown that the BL suction can result in broadband reduction of $\phi_{pp}$. Immediately downstream of the AFC section, at $m1$, there is a slight increase at low frequencies in the measured pressure spectra, but as the flow advances, this increase is quickly eliminated. Approximately 8 dB reduction is achieved in the mid frequency region at the $m1$ location (Fig. 6(a)). The amplitude of the achieved energy reduction decreases downstream and it spreads to the lower frequencies. The earlier discus-




(a) measurement at location $m1$

(b) measurement at location $m2$

Figure 6: The measured surface pressure fluctuations ($\phi_{pp}$ [dB]) in the boundary layer downstream of the active flow control section at location $m1$ and $m2$ for the suction flow control cases

sion on the flow behaviour downstream of the AFC can be brought in relation with the experienced changes of measured surface pressure spectra. It was shown in the boundary layer studies that the highest reduction is experienced aft the AFC section but it shortly recovers in the near-wall region downstream. Park and Choi [12] reported the break-up of larger structures after the AFC section. Based on the discussion provided in [12], the experienced increase at $m1$ at low frequencies can be related to the presence of larger structures, while by reaching the TE ($m2$) these vortices can be expected to split up, resulting in the decrease of $\phi_{pp}$. Further PIV and hot-wire tests are planned in order to better understand this behaviour and to resolve the components of the turbulent energy.

## 4. Summary

The use of active flow control methods for the reduction of trailing edge noise is investigated. A comprehensive study is performed upstream of the sharp trailing edge of a flat plate to simultaneously measure the surface pressure fluctuations and the streamwise velocity component. Two flow control scenarios are investigated: fluid injection with low flow rate and flow suction with moderate flow rate. Both has been shown to be effective in reducing the measured surface pressure spectra up to 10 dB/Hz over a wide range of frequencies. The blowing is effective in shifting the energy containing turbulent structures farther from the wall, resulting in the experienced decrease in the surface pressure fluctuations. The suction was capable of reducing the energy containing eddies, resulting in the decrease of the turbulence properties both in the space and frequency domain. Our future work will involve the investigation of turbulent length scales, studying the flow structures using PIV measurements and additional BL correlation studies.

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