Aerodynamic Noise Reduction Using Active Flow Control Techniques

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AERODYNAMIC NOISE REDUCTION USING ACTIVE FLOW CONTROL TECHNIQUES

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KEYWORD:

Active flow control, turbulent boundary layer, suction, blowing, sweeping jet, trailing edge noise.

ABSTRACT:

Experimental studies using active flow control techniques for trailing edge noise reduction have been carried out. The experiments were performed for a flat plate test rig, equipped with different types of active flow control devices, namely steady boundary layer suction, steady blowing and unsteady blowing using sweeping jet actuators. The results of the boundary layer surface pressure energy spectra show that the proposed active flow control methods can offer significant reduction in the trailing edge noise, particularly at low frequencies, where passive noise control techniques, such as serrations, are not particularly effective. Further experiments are planned to study the aerodynamic benefits of the proposed methods and also their effects on flow mixing and lateral coherence of the turbulent structures within the boundary layer and wake.

1 INTRODUCTION

Airfoil self-noise is considered as one of the most challenging noise sources in different engineering applications. Airfoil self-noise comprises of both broadband and tonal components. Most of the broadband noise sources can be attributed to trailing edge noise, tip noise or stall/separation noise, which are more difficult to control [1]. The tonal noise components are caused by blunt trailing edge vortex shedding or laminar instability waves, which can be avoided by removing the bluntness or creating geometrical disturbances on the surface of the airfoil. One of the dominant factors of the broadband noise component can be attributed to trailing edge noise. At high Reynolds number a turbulent boundary layer is generated over the majority of the airfoil surface, creating broadband noise that radiates as a dipole noise source, due to the interaction with the trailing edge. Turbulent structures in the turbulent boundary layer radiate in the form of quadrupole sources just before interacting with the trailing edge [2].

Trailing edge noise can be reduced using both active and passive flow control methods. Passive flow control (PFC) methods, such as altering the blade shape to reduce boundary layer turbulence [3, 4] using porous surfaces [5–10], trailing edge serrations [11–15] or trailing edge brushes [16, 17], can be used to eliminate these aerodynamic noise sources. Among the mentioned passive control techniques, serrations have received much attention. The studies have shown that trailing edge serrations can produce significant noise reductions with the least aerodynamic penalties, relative to the other PFC methods. Moreover, it was shown that a deterministic correlation could be obtained between the serrations geometry, spacing and the optimum noise reductions. However, these optimum reductions are highly dependent on the operating conditions and can be only optimized for a certain inflow and angle of attack (AoA). Furthermore, significant noise reductions were only limited to low AoA.

Meanwhile, active flow control (AFC) methods provide a potential technique that can push the limits of the current aerodynamic noise control technology used in different applications. To cope with the ever increasing restrictions in the global aircraft noise regulations, ACARE (the Advisory Council for Aeronautics Research in Europe) suggested developing what is called Generation 2 Noise Reduction Technologies [18]. These technologies mainly focus on using multidisciplinary aeroacoustic designs and implementing active noise reduction techniques. Thus, there is a global research trend that seeks to evaluate some of these active control techniques, understand the physics behind their attenuation mechanisms and to implement them in a suitable way to target major aerodynamic noise sources. The AFC techniques can be implemented to reduce trailing edge noise in different ways. Suction AFC methods have been considered in previous studies. Gregory [19, 20] recently conducted an extensive experimental investigation on the aerodynamic performance of different AFC parameters such as location, operation type, shape, flow rate etc. However, such study on these parameters have not been considered from the aeroacoustic performance point of view. Some practical considerations, such as the suction systems weakness toward blockage or high negative pressure requirements, might challenge the implementation of suction AFC for some industrial applications. As the noise generated by turbulence scales with 10^{-6} portion of the flow total energy, it is expected that AFC methods tailored for aeroacoustic performance require significantly lower power intake than those intended for aerodynamic performance. In [21], Wolf conducted an experimental study to investigate the use of surface distributed suction through a perforated plate on trailing edge noise reduction. It was shown that noise reductions up to 5 dB were possible to obtain for suction mass flow coefficients rates of 0.1 $\sim$ 0.2. It can be easily inferred that removing the boundary layer turbulence would reduce the airfoil self-noise, by reducing the intensity of the turbulent structures interacting with the trailing edge. Moreover, delaying separation would also prevent the self-noise generated due to the interaction of the separated bubbles with the airfoil surface.

Other studies also investigated the use of AFC blowing for reducing rotors wake deficit and wake turbulence that would lead to rotor/stator interaction noise [22–26]. All these studies agreed on showing reductions in both the tonal and broadband components of the noise. However, higher reductions were obtained for the tonal noise components as it was mainly linked to the filling of the mean velocity deficit in the wakes. On the other hand, the broadband part is still challenging to mitigate as it is linked to the wake turbulent structure of the wake. To be able to improve the broadband noise reductions, more studies are required to understand the wake turbulent structures and their interaction mechanism with the stators downstream.

A great potential also arises from the possibility of using sweeping jets for AFC. Several studies investigated the use of these jet actuators [27–30] for enhancing the aerodynamic performance of different airfoils.These studies reported that the application of sweeping jet actuators delay the separation of the boundary layer over the airfoil which results in the increase of aerodynamic performance. This was achieved by blowing air into the boundary layer through a discrete spanwise distribution of sweeping jets. Although all the previous studies showed positive results regarding aerodynamic performance only, results have indicated that such method could potentially be used for noise control purposes. The sweeping nature of the jet could be used to break the coherence between the structures interacting with solid boundaries that would lead to the generation of self-noise. Moreover, enhancing the mixing within the turbulent boundary layer would also lead to potential reduction in the self-noise associated with separation and vortex shedding (stall, instability waves, etc.).

According to Amiet's trailing edge noise model [31], for an arifoil with a span of d and chord length b, Eq. 1 can be used for the prediction of the far-field noise, as

$$S_{pp}(x,0,z,\omega) = \left(\frac{\omega b z}{2\pi c_0 \sigma^2}\right)^2 d|\mathcal{L}|^2 l_y(\omega)\phi_{pp}(\omega,0). \quad (1)$$

Equation 1 shows that the far-field noise S_{pp} can be defined in terms of several variables that are experimentally measurable. The value $|\mathcal{L}|$ represents the integral of the airfoil pressure distribution, $l_y(\omega)$ is the spanwise correlation length, c_0 is the speed of sound, $\sigma^2 = x^2 + \beta^2 z^2$, $\beta^2 = 1 - M^2$ and M is the far-field Mach number. Finally, $\phi_{pp}(\omega,0)$ is the surface pressure fluctuations spectrum. As shown in the equation, the value of S_{pp} directly correlates to $\phi_{pp}(\omega,0)$. Thus, in this study the reduction in $\phi_{pp}(\omega,0)$ is used as an indication for the effectiveness of the proposed AFC methods for the reduction of the far-field noise.

2 EXPERIMENTAL SET-UP

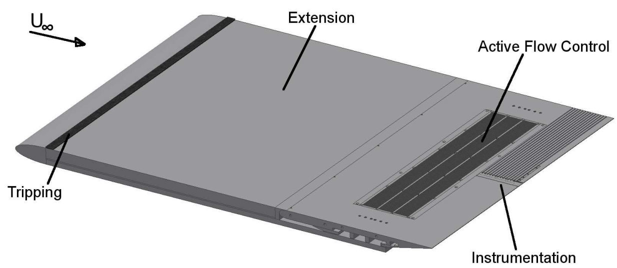

Figure 1: Flat plate test rig overview

A long flat plate with the chord-length of $1m$ was used for this experiment, see Fig. 1. The flat plate test rig has an elliptical leading edge and sharp 12° trailing edge, equipped with several slots for fitting different types of active flow control modules. The trailing-edge section is instrumented with an L-shaped array of flush mounted surface pressure transducers, see Fig. 2. In order to achieve a range of boundary layer thicknesses, two types of flow tripping were used shortly after the leading edge: an 80 grit 20 mm wide sandpaper to create a thin but very well developed boundary layer, and a 25 PPI (pores per inch) 10 mm thick 20 mm long porous aluminium block to achieve a much thicker boundary layer.

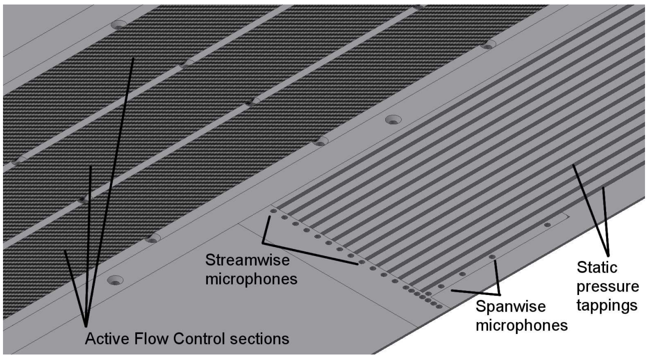

Figure 2: Instrumentation of the flat plate test rig

Measurements were carried out in the open test section return-type wind tunnel of the University of Bristol, and the free-stream flow velocity was set to $u_\infty = 10, 15,$ and 20 m/s with a typical turbulence intensity of less than 1 %. The properties of the boundary layer was measured with a Dantec 55P16 type miniature hot-wire, which was operated by Dantec 91C10 CTA modules at an overheat ratio of 1.8. The uncertainty of the hot-wire measurements was found to be less than ± 0.5 %. Surface pressure fluctuations were measured at different streamwise and spanwise locations on the test rig with Knowles FG-23329-P07 type miniature electret condenser microphones (see Fig. 2), which were calibrated in advance of the measurements. The microphones were placed in an L-shaped arrangement that would allow the measurement of the streamwise and the spanwise correlations of the pressure fluctuations. The uncertainty of the pressure fluctuation measurements were found to be within ± 0.5 dB with 99 % confidence level assuming normal deviation of pressure fluctuations. The data acquisition system was National Instruments PXIe-4499 type operated with a sampling frequency and measurement time of $65536 = 2^{16}$ Hz and 16 seconds. During the post processing of the measured quantities, the frequency resolution was set to 64 Hz.

As shown in Figs. 1 and 2, the test rig incorporates three AFC sections, each 30 mm long in the streamwise direction and 500 mm in the spanwise direction. The first two AFC sections were covered

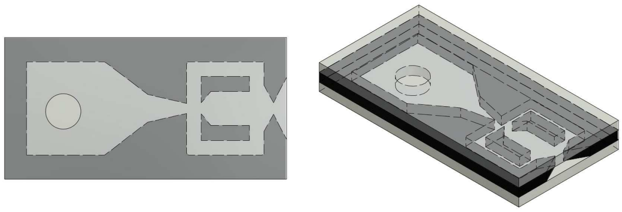

Figure 3: The cross section of the applied sweeping jet (left) and the schematic of the actuators with the laser cut layers (right)

with acrylic sheet and were not used in the current study and the flow control was applied in the last section only (145 mm upstream of the TE). Three different active flow control methods have been tested: (a) steady homogeneous suction, (b) steady homogeneous blowing, and (c) a number of unsteady sweeping jet actuators. The steady suction case was performed through an angled ($60°$) honeycomb structure whose orientation was chosen such that it was favourable for the flow to enter the material. The steady blowing was performed through a 2 mm thick 90 PPI aluminium porous material. The unsteady sweeping jets were located at 5 different spanwise locations and the actuators were built with laser-cutting technology out of perspex sheets. The cross section and the schematic of the actuators are shown in Fig. 3. The layout of the test rig with the sweeping jet actuators installed is presented in Fig. 4.

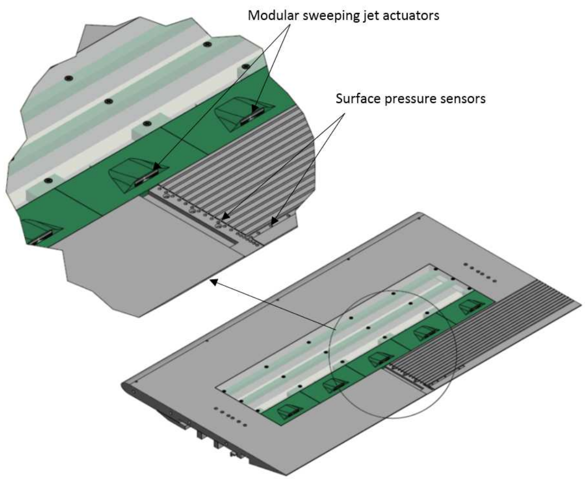

Figure 4: Sweeping jet actuators installed on the test rig

The severity of the AFC for the steady suction and blowing cases was defined after Antonia *et al.* [32] as

$$\sigma = \frac{u_\perp}{u_\infty}\frac{t}{\theta}, \tag{2}$$

where $u_\perp$ is the normal component of the suction velocity, u_∞ is the far field flow velocity, t is the streamwise length of the AFC treatment and θ is the momentum thickness of the boundary layer. The momentum thickness of the boundary layer was found with the help of a hot wire sensor, and the applied σ rates are listed in Table 1.

For the sweeping jet case a separate coefficient (C_μ) was used after Schmidt *et al.* [27] as

$$C_\mu = 2\frac{A_{noz}}{A_{plate}}\left(\frac{u_{jet}}{u_\infty}\right)^2, \tag{3}$$

where A_{noz} is the cross-section area of the nozzles (2 mm $\times$ 2 mm), A_{plate} is the area of the plate where the sweeping jets were applied (1 m $\times$ 0.5 m) and u_{jet} is the mean velocity at the throat of the jets. The applied C_μ values are listed in Table 1.

Case	u_∞ [m/s]	θ [mm]	σ [–]	C_μ [%]
Steady suction	10	2	6,9	-
Steady blowing	15	9	0.22,0.62	-
Sweeping jets	15 20	- -	- -	0.02,0.05,0.082 0.02,0.05,0.082

Table 1: Properties of the boundary layer and the applied active flow control methods

3 RESULTS AND DISCUSSION

In this section the energy spectra of the surface pressure fluctuations are presented for the three different AFC methods proposed in this study. The discussion focuses on the effects of the proposed AFC techniques on the surface pressure fluctuations and the physical causes of any significant reductions observed. In what follows, we shall first present the results of the steady suction, followed by the steady blowing results, and finally, the results of the sweeping jet actuators.

Steady suction: The first investigated case was the uniform steady suction through an angled (60°) honeycomb structure. The free-stream flow velocity was set to 10 m/s and the sandpaper tripping was applied on the flat plate. The surface pressure spectra presented in Fig. 5 was measured by a microphone flush mounted Δx = 50 mm downstream of the AFC section and Δx = 60 mm from the TE. Results are presented for the baseline ($\sigma = 0$), two different suction rates ($\sigma = 6, 9$), and background noise. The background noise was measured by covering the whole surface of the flat plate rig with a thick acoustic foam to eliminate the BL related noises. The tonal peaks at frequencies above 3 kHz are originated from the wind tunnel fan.

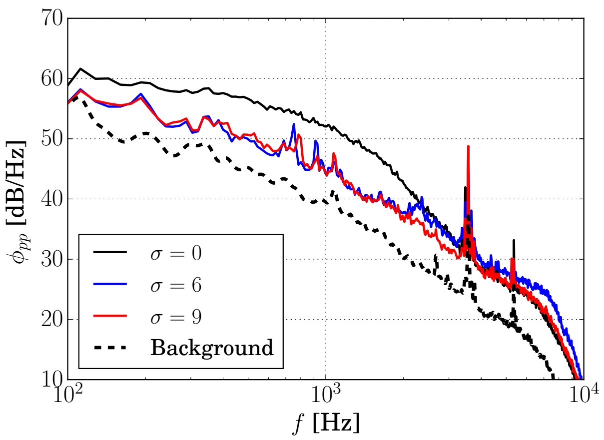

Figure 5: Surface pressure fluctuation spectrum (ϕ_{pp}) for different uniform suction rates at u_∞ = 10 m/s

We can see that both suction rates give a broadband noise reduction of up to 10 dB, which is an indication of that the suction has successfully removed a wide range of turbulent structures from the boundary layer. The peaks in the curves at around 700 Hz is originated from the fans that deliver the suction. The other effect of these fans is also visible above 4 kHz, where the blue curve exceeds the baseline solid black curve. We can see that at frequencies above the tonal peaks of the wind tunnel fan, the background noise begins to contaminate the measurements, therefore the measured changes in ϕ_{pp} in this range is not reliable.

Steady blowing: The second investigated case was the uniform steady blowing whose results are presented in Fig. 6. The free-stream flow velocity in this case was 15 m/s and the applied tripping was the porous material strip which resulted in a thick (δ = 90 mm, θ = 9 mm) boundary layer. The results in Fig. 6 are measured using a surface pressure microphone at Δx = 17 mm downstream of the AFC section. The results for the background noise, the baseline case and two different blowing rates are presented.

The uniform blowing approach can also result in the broadband reduction of the surface pressure fluctuations. One can see that the lower blowing rate, which is presented by the red line, gives larger reduction in the energy content of the surface pressure fluctuations than the higher blowing rate. This suggests that a low momentum fluid injected into the lower region of the boundary layer can lead to a

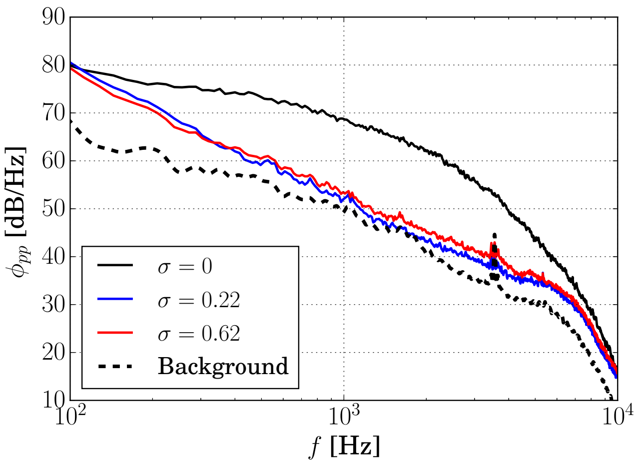

Figure 6: Surface pressure fluctuation spectrum (ϕ_{pp}) for different uniform blowing rates at u_∞ = 15 m/s

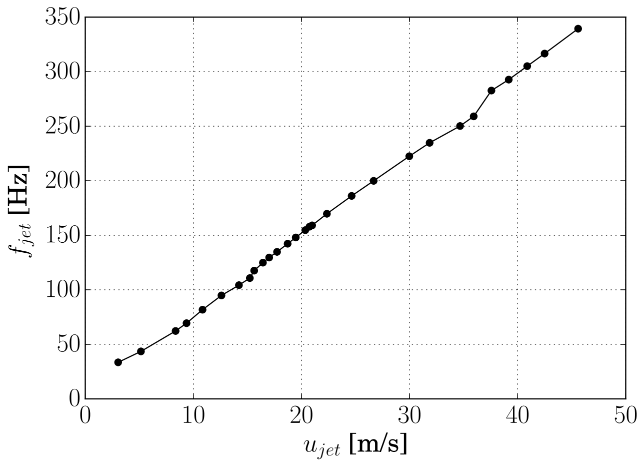

Figure 7: Relation between the jet mean velocity and the oscillation frequency for each sweeping jet

significant reduction in ϕ_{pp}.

Sweeping jet: The final case investigated is the use of blowing through sweeping jet actuators. The behaviour of the actuators have been investigated in isolation. A single hot wire anemometer was placed at a distance of 5 mm from the centre of the outlet of one of the sweeping jet actuators to record flow velocity variations. By linking the mean outlet jet velocity to the variation in the maximum tonal component of the velocity variation, the relation shown in Fig. 7 was obtained. The results show a sinusoidal variation in time that can be related to the sweeping motion of the jet. Both the mean injection rate and the sweeping oscillation of the jets can be utilized to disturb the the coherence of the surface pressure fluctuations near the trailing edge. Figure 8 shows the energy spectra of the surface pressure fluctuations measured using a microphone flush mounted at Δx = 51 mm downstream of the jets.

The porous material tripping was used to create the boundary layer for this case and $C_\mu = 0\%$ corresponds to the baseline case. This figure shows the results obtained at 15 m/s free-stream velocity. For the lowest blowing rate $C_\mu = 0.02\%$, noise reduction can be noticed in the low frequency range. The extent of this reduction is limited to a range of frequencies up to about 4 kHz. At the same blowing rate a tonal component generated from the jet can be noticed around 8 kHz. The noise reduction increases with increasing the blowing rate to $C_\mu = 0.05\%$. At the highest blowing rate $C_\mu = 0.082\%$ the reduction in the surface pressure fluctuations is only achieved at very low frequencies below 300 Hz. The high frequency region is dominated by the broadband self-noise generated by the jet actuators, even masking the tonal component at higher frequencies that was generated at the lowest blowing rate. This shows the importance of understanding the jet actuator self-noise for aerodynamic noise control purposes.

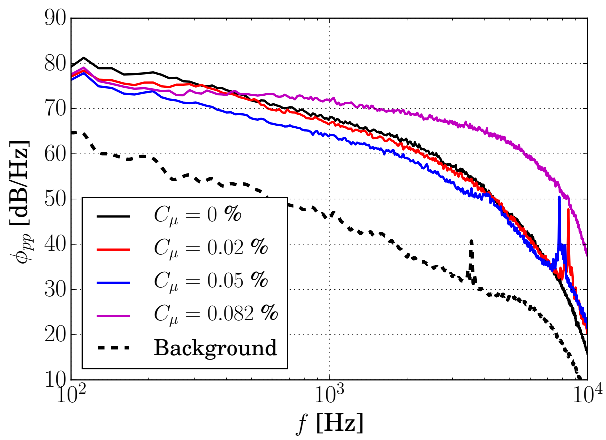

Figure 8: Surface pressure fluctuation spectrum (ϕ_{pp}) for sweeping jet actuators at different flow rates at u_∞ = 15 m/s

Figure 9 shows the results obtained for the free-stream velocity 20 m/s case. Noise reductions can be achieved at all blowing rates. The range of these reductions was extended to higher frequencies even covering the whole frequency range for the two lower blowing rate cases (C_μ = 0.02 and 0.05 %). The limit of this frequency range decreases with the increase in the blowing rate. This can be related to the increase in the high frequency broadband noise generated by the jets. One can notice that the low frequency broadband noise reduction correlates to the increase in the blowing rate. This was also visible for the two first blowing rates in the previous case (see Fig. 8). For this case, the tonal component generated by the jet was totally masked by the broadband noise for all blowing rates.

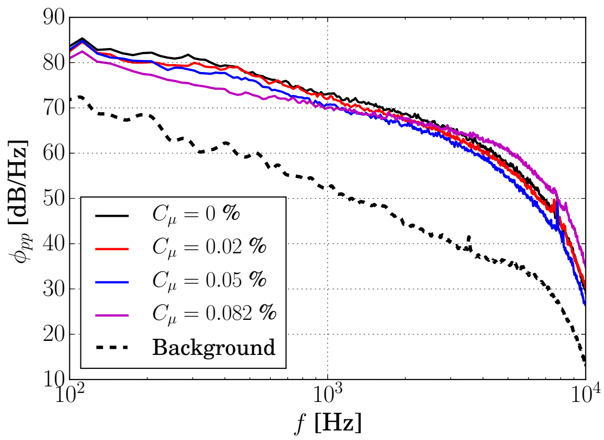

Figure 9: Surface pressure fluctuation spectrum (ϕ_{pp}) for sweeping jet actuators at different flow rates at $u_\infty = 20$ m/s

4 CONCLUSIONS AND FUTURE WORK

The effect of different active flow control methods on the trailing edge noise and surface pressure fluctuations have been studied. The proposed active flow control methods consisted of uniform suction, uniform blowing and localized sweeping-jet injection. It was found that the applied treatments can lead to significant reduction of the surface pressure fluctuations over a wide range of frequencies, particularly at low frequencies. The effectiveness of the suction approach is believed to be due to the elimination of the large coherent turbulent structures within the boundary layer and this method was proven to be more effective at higher suction rates. The blowing resulted in broadband noise reduction as well, but the best results were achieved at significantly lower blowing rates. The sweeping jets were also shown to be effective at low injection rates. To better understand the effects of the proposed flow control methods on the structure of the boundary layer, and therefore the noise generation mechanism, further measurements are planned for the measurement of the spanwise coherence, turbulence length-scales, and pressure-velocity correlations within the boundary layer.

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