

# On the noise reduction mechanisms of porous aerofoil leading edges

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## Abstract

This paper is predominantly an experimental study into the reduction of turbulence - aerofoil interaction noise by the introduction of aerofoil porosity. In this paper we study three scenarios applied to flat plates: (a) when the flat plate is fully porous, (b) when the flat plate is partially porous from the leading edge and (c) when porosity is introduced downstream of the leading edge. This paper shows that the noise reduction spectra collapse when plotted against non-dimensional frequency  $fl/U$ , where  $l$  is the length of porous section and  $U$  is the flow velocity. Narrow band measurements on a partially porous aerofoil have shown that its noise reduction spectra is characterised by a number of narrow peaks. This paper proposes two main mechanisms for explaining this behaviour. The noise reduction mechanisms are validated against noise reductions measured on a realistic aerofoil at relatively low angles of attack. One of the key findings of this paper is that, by using only a single row of holes downstream of the aerofoil leading edge one can obtain significant levels of noise reduction. This use of downstream porosity is specifically shown to be capable of providing low-frequency noise reductions without increasing the radiated noise at higher frequencies.

*Keywords:* Turbulence-aerofoil interaction noise, Fan Broadband noise, Porous leading edges, Noise reduction mechanisms.

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## 1. Introduction

The broadband noise produced by the fan wake interacting with the outlet guide vanes (OGV's) is one of the dominant noise sources in a turbofan engine. This form of leading edge interaction noise is also known to be important in wind  
5 turbines at low frequencies when the blades interact with large-scale atmospheric turbulence. Serrations (undulations) introduced onto the leading edge have been shown to be a highly effective method for reducing broadband interaction noise [1-7]. Reductions of up to 18dB at some particular frequencies and up to 6dB in  
10 overall noise have been reported. However, at chord based Reynolds numbers of  $2 \times 10^5 - 6 \times 10^5$  and low angles of attacks ( $\text{AoA} = 0^\circ - 3^\circ$ ), a clear disadvantage with these leading edge geometries is their negative impact on aerodynamic performance and structural integrity ([6]).

This paper deals with an alternative approach for reducing broadband interaction noise that involves introducing porosity at the leading edge. This control  
15 principle has previously been investigated experimentally [3, 8-11] and theoretically [12], where significant reductions in broadband interaction noise of up to 10dB were reported at some frequencies.

The reduction in turbulence interaction noise obtained by using a fully porous SD7003 aerofoil was previously investigated by [8]. Commercially avail-  
20 able porous materials such as polyurethane foams, metal foams and felts were used in this study. They showed that open-porous materials with low air flow resistivity (high permeability) lead to greater noise reductions, which are attributed to the suppression of pressure fluctuations at the porous leading edge. The authors also observed at chord based Reynolds numbers of  $4 \times 10^5 - 7.8 \times 10^5$   
25 and zero angle of attack, a significant decrease in lift and increase in drag compared to the baseline impermeable aerofoil. One of the main reasons for this poor aerodynamic performance is because the entire aerofoil was made porous.

Roger et al [3] also investigated the use of porosity for reducing interaction noise by filling the shell of a hollow NACA-0012 aerofoil with steel wool. Noise  
30 reductions of up to 5 dB were reported, even though there was no attempt at optimising of the material parameters.

Sarradj and Geyer[9] further extended the work of [8] by applying symbolic regression to the noise reduction data to establish models for the noise generation of fully porous aerofoils. They showed that leading edge noise radiation due to  
35 porous aerofoils depends on the square of the turbulence intensity and shows a dependency on the fifth to sixth power of the flow velocity. More critically, the spectrum of radiated noise was shown to be highly sensitive to the flow resistivity of the porous material.

More recently, Geyer et al. [11] investigated the noise reductions due to  
40 porosity introduced by the use of narrow channels of uniform cross section that were run between the suction and pressure sides of the aerofoil. These channels were only applied to about 5% of leading edge in an attempt to reduce aerodynamic losses. At low geometric angles of attack from  $0^\circ - 8^\circ$  and chord based Reynolds numbers of  $6.5 \times 10^5$ , noise reductions of up to 8 dB were reported  
45 at some frequencies, while the noise was found to increase by between 4 and 5 dB at high frequencies. Reasons for the reduction of noise are investigated in their paper; they attribute the reduction to a number of mechanisms such as, 1) hydrodynamic absorption in which turbulence kinetic energy is dissipated in the holes, 2) an increase in the effective aerofoil thickness in which the mean flow  
50 through the pores increases the boundary layer thickness leading to an effective increase in the aerofoil leading edge, which is well known to reduce interaction noise, 3) displaced turbulence in which the turbulence structures impinging on the aerofoil are displaced away from the surface, leading to a reduction in the pressure fluctuations on the surface, and hence, far-field noise.

55 Another attempt to explain the noise reduction mechanism was proposed by [10] who evaluated the effectiveness of porous materials on a relatively thick NACA-0024 aerofoil for reducing aerofoil interaction noise. Their experimental results show that the use of porous leading edges leads to a reduction in in-

teraction noise in the low-frequency range and an increase at high-frequencies,  
60 mostly due to surface roughness noise. From their hot-wire analysis they also  
showed that the root-mean-square velocity fluctuations in the close vicinity of  
the leading edge was reduced due to a weaker flow distortion by the porous  
leading edge, leading to a reduction in radiated noise.

Priddin *et. al.* [12] have predicted analytically the noise radiation from a  
65 flat plate comprising a number of circular holes interacting with a harmonic  
vortical gust. The Wiener-Hopf method was used to provide the solution and  
a homogenised impedance-type boundary condition was applied in which the  
mass flow rate through the holes was related to the jump in velocity potential  
across the holes via an impedance term related to the Rayleigh conductivity.  
70 We note that in this formulation the effects due to viscous dissipation, by vortex  
shedding for example, are not included and only the real value of the impedance  
is considered. Predictions were compared against the measured noise reduction  
spectra from a flat plate comprising of a number of regularly spaced circular  
holes distributed between the leading edge and some downstream location. In  
75 [12] the noise reduction spectra were predicted to peak at the non-dimensional  
frequencies of  $fl/U=0.5$  and  $1.5$ , where  $l$  is the length of the porous section.  
Narrow band peaks of very similar spectral shape were also observed in the mea-  
sured data but at the slightly different frequencies of  $fl/U=0.7$  and  $1.4$ . More  
critically, the predicted frequencies are in the ratio of 1:3, while the peaks in the  
80 experimental noise reduction spectra are in the ratio 1:2. The reasons for the  
existence of these peaks and the difference in the predicted and measured ratios  
are discussed in this paper, and will be shown to be important in explaining the  
fundamental noise reduction mechanism.

In this paper we demonstrate that, in addition to the dissipative mecha-  
85 nisms proposed by [10, 11] there are two other potentially more important noise  
reduction mechanisms. These mechanisms are particularly important for thin  
aerofoils typical of OGV's, that are non-dissipative but essentially involve in-  
terference effects along the chord. In the present paper, the fundamental noise  
reduction principles are investigated experimentally on a porous flat plate and

90 later extended to a 10% thick aerofoil.

A simple noise reduction model is proposed to explain the basic characteristics of the noise reduction spectra that is entirely consistent with the experimental data. In section 4 of this paper we demonstrate that simply introducing a single row of holes downstream of the leading edge provides similar noise reduction characteristics to that when the aerofoil is fully porous. Naturally, the  
95 advantage of this approach is that it requires a much smaller modification to the leading edge and is therefore beneficial for the aerodynamic performance.

## 2. Noise reduction mechanisms for a fully porous, and partially porous aerofoils

100 In this section we present a simple and highly idealised model aimed at explaining the dominant noise reduction mechanisms on partially and fully porous aerofoil leading edges. We propose two principal noise reduction mechanisms:

The first mechanism, which is pertinent to fully or partially porous aerofoils, is based on the assumption that by allowing the upper and lower aerofoil surfaces to 'communicate', the unsteady pressure difference  $\Delta p$  across the aerofoil  
105 is forced to propagate along the aerofoil chord at the boundary layer convection flow speed  $U_c$ . By contrast  $\Delta p$  across a rigid aerofoil propagates at the supersonic speed  $a + U_c$ , corresponding to the sound speed  $a$  in the reference frame moving at  $U_c$  in the boundary layer. The important consequence of this phenomenon is that, at subsonic flow speeds  $U_c < a$ , the surface pressure response  
110 by the porous aerofoil radiates with considerably less efficiency compared to the corresponding rigid aerofoil. In this idealised model, zero radiation is predicted when there is an integer number of whole hydrodynamic wavelengths  $U_c/f$  across the porous section of length  $l$ , i.e., when  $fl/U_c = n$ , where  $n$  is any integer.  
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The second mechanism is relevant only to partially porous aerofoils in which the noise is reduced through destructive interference between sound generated at the edge discontinuity between the porous section and the downstream rigid

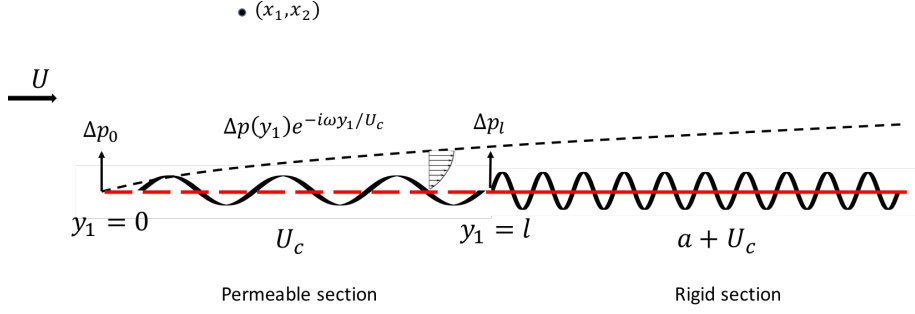


Figure 1: Schematic of the source regions for a partially porous flat plate leading edge.

section, and the sound radiated from the leading edge.

### 2.1. Simple analytical model

Consider a flat plate aligned along the  $y_1$ -direction in the direction of the mean flow with leading edge at  $y_1=0$ , as shown in Fig. 1. The flat plate is assumed to be porous over the section  $0 \leq y_1 \leq l$ , and perfectly rigid for  $y_1 \geq l$ , assumed to extend to infinitely in the streamwise direction. Turbulent flow impinging on the flat plate leading edge at the flow speed  $U$  is assumed to generate three distinct sources. The first occurs when the vortical flow impinges on the leading edge at  $y_1 = 0$ , which we assume generates a localised compact pressure jump at the leading edge equal to  $\Delta p_0 \delta(y_1)$ , where  $\delta$  is the Dirac delta function. The second source is assumed to be of the form of a wave propagating across the porous section  $0 < y_1 < l$  at the convection speed  $U_c$ . At a single frequency, this source is of the form  $\Delta p(y_1)e^{-i\omega y_1/U_c}$ . Finally, a source is generated at the edge discontinuity  $y_1 = l$  between the porous and non-porous (rigid) sections, which, at a single frequency, we represent as a localised compact source of the form,  $\Delta p_l \delta(y_1 - l)e^{-i\omega l/U}$ , whose phase difference compared with the leading edge source at  $y_1 = 0$  arises from the time taken  $l/U$  for the vortical gust to convect across the porous section of distance  $l$ . A schematic of these assumed source distributions is shown in Fig. 1.

Substituting the sum of the two contributions to  $\Delta p(y_1)$  discussed above into the chord-wise radiation integral due to Amiet [13] and integrating over the porous

140 section of the aerofoil gives the following expression for the far-field acoustic pressure  $p(x_1, x_2, \omega)$ ,

$$p(x_1, x_2, \omega) \approx \frac{x_2}{4\pi a \sigma^2} \int_0^l \left[ \Delta p_0 \delta(y_1) + \Delta p(y_1) e^{-i\omega y_1/U_c} + \Delta p_l \delta(y_1 - l) e^{-i\omega l/U} \right] e^{-i\frac{\omega}{a\beta^2} \left(M - \frac{x_1}{\sigma}\right) y_1} dy_1 \quad (1)$$

where  $(x_1, x_2)$  is the observer position relative to the leading edge with stream-wise distance  $x_1$ , and transverse distance  $x_2$ ,  $\sigma^2 = x_1^2 + \beta^2 x_2^2$ ,  $\beta^2 = 1 - M^2$  and  $M = U/a$ .

## 145 2.2. Cutoff radiation from porous section

We first consider the radiation from a porous flat plate section of length  $l$ , with pressure jump characterised by a wave response convecting with the boundary layer convection speed  $U_c$ ,  $\Delta p(y_1) e^{-i\omega y_1/U_c}$ . Putting  $\Delta p_0 = \Delta p_l = 0$ , and for simplicity assuming  $\Delta p(y_1) = \Delta p_s$  (i.e., the pressure amplitude of  $\Delta p$  is assumed independent of  $y_1$ ) in Eq. (1), and after integration, yields

$$p(x_1, x_2, \omega) \approx \frac{x_2 \Delta p_s}{4\pi a \sigma^2} \left[ \frac{1 - e^{-i\omega l/U_c (1 + [M/\beta^2](M - x_1/\sigma))}}{\omega l/U_c (1 + [M/\beta^2](M - x_1/\sigma))} \right] \quad (2)$$

The radiated sound power  $W$  is related to the mean square far-field pressure integrated over some suitable closed surface:

$$W(\omega) \propto \overline{p^2}(\omega) \propto \mathbf{E}[p^*(\omega)p(\omega)],$$

Comparing this expression to the mean square radiated pressure  $\overline{p_{bl}^2}(x_1, x_2)$  in the absence of porous treatment obtained by putting  $l=0$  in Eq. (2), the corresponding reduction in the radiated sound power obtained through cutoff radiation is of the form,

$$\frac{W}{W_{bl}} \propto \frac{\overline{p^2}}{\overline{p_{bl}^2}} = \text{sinc}^2 \left\{ \frac{\omega l}{2U_c} \left[ 1 + \frac{M}{\beta^2} \left( M - \frac{x_1}{\sigma} \right) \right] \right\} \quad (3)$$

where  $\text{sinc}(X) = \sin(X)/X$ . We emphasise that  $\Delta p_s$  for the porous and baseline cases will of course differ significantly and Eq. (3) therefore cannot provide a

prediction of the absolute noise reduction but is sufficient to predict the main  
 160 characteristics of the noise reduction spectra.

One of the most significant features of Eq. (3) for the acoustic radiation due  
 to cutoff effects is that the noise reduction spectra are predicted to collapse on  
 $fl/U_c$  and that zero far-field radiation is predicted at frequencies  $f_n l/U_c \approx n$   
 ( $n = 1, 2, 3, 4, \dots$ ). Note that the radiated field due to cutoff effects is predicted  
 165 to oscillate around the general frequency decay  $\overline{p^2}(x_1, x_2) \approx (\omega l/U_c)^{-2}$  and  
 therefore the radiation is predicted to tend to zero as frequency increases.

### 2.3. Edge-to-edge interference

In addition to the cutoff radiation from the porous section, destructive in-  
 terference will also occur between sound generated at the edge discontinuity  
 170 between the porous section and the downstream rigid section, and the sound  
 radiated from the leading edge. This is described by the remaining two terms  
 in Eq. (1).

The far-field pressure due to interference from these two sources may be  
 obtained by putting  $\Delta p(y_1) = 0$  in Eq. (1) and for simplicity assuming identical  
 175 edge source strengths  $\Delta p_0 = \Delta p_l$ . After performing the integration over  $y_1$ , the  
 acoustic pressure due to edge-to-edge interference is of the form,

$$p(x_1, x_2, \omega) \approx \frac{x_2 \Delta p_0}{4\pi a \sigma^2} \left( 1 + e^{-i\omega l/U} \right) e^{-i \frac{\omega}{a\beta^2} \left( M - \frac{x_1}{\sigma} \right) l} \quad (4)$$

The two edge sources therefore differ in phase by an amount equal to the  
 time taken  $l/U$  for the surface pressure response to travel between the leading  
 edge and the end of the porous section plus the difference in propagation times  
 180  $l/(a\beta^2) (M - x_1/\sigma)$ . We note that turbulence is convected between the edges  
 at the free stream velocity  $U$ . The corresponding reduction in radiated sound  
 power is therefore given by,

$$\frac{W}{W_{bl}} \propto \frac{\overline{p^2}}{p_{bl}^2} = \cos^2 \left\{ \frac{\omega l}{2U} \left[ 1 + \frac{M}{\beta^2} \left( M - \frac{x_1}{\sigma} \right) \right] \right\} \quad (5)$$



As in Eq. (5) for the radiation due to cutoff effects the noise radiation due to the edge-to-edge interference is also predicted to collapse on the non-dimensional frequency  $fl/U$ , although it is now defined with respect to the free stream velocity  $U$ . At sufficiently small values of  $M$ , therefore, or when the average pressure is taken over a number of microphones, perfect cancellation of the far-field pressure is predicted at frequencies,  $f_n l/U \approx n-1/2$ , ( $n=1, 2, 3, \dots$ ). We note that these frequencies differ from those due to source cutoff given by  $f_n l/U_c \approx n$ , thereby allowing the effects due to the two different mechanisms to be separated.

This assumption of compact sources at the two edge discontinuities cannot be justified from the classical rigid flat plate theory. The edge-to-edge interference condition of Eq. (5) when expressed in terms of non-dimensional acoustic frequency is given by  $f_n l/a = (n - 1/2)M$  so that the first interference peak in the noise reduction spectra is  $f_1 l/a = M/2$ , which at the Mach number  $M = U/a$  of the experimental data presented below is  $f_1 l/a = 0.075$ . The source distribution  $\Delta p(y_1)$  for a rigid flat plate is therefore predicted to be uniformly distributed across the porous flat plate and not concentrated at the edges as assumed in the simple model. However, from the measured noise reduction spectra we must assume that the source distribution across the porous section is significantly different compared to a rigid plate. This difference may be explained by a reduction in  $\Delta p(y_1)$  downstream of the leading edges, when the unsteady pressures on the upper and lower sides are equalised through communication of the upper and lower pressures across holes. As a result the sources are concentrated at the leading edges, as assumed in the simple theoretical model.

We emphasise that in making the assumption of compact source and equal source strength at either ends of the porous section we are concerned with capturing the general behaviour of the noise reduction spectra and not the absolute levels of the noise reduction that would require more detailed information about the source strength distribution over the porous section.

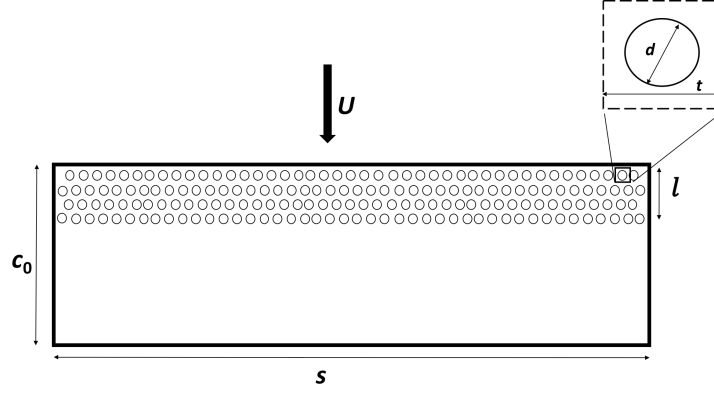


Figure 2: A schematic sketch of porous leading edge profile.

### 3. Noise reduction mechanism validation

#### 3.1. Porous flat plate and aerofoil configurations

By way of validation of the noise reduction principles outlined above a simple  
 215 experimental study was undertaken using porous flat plates placed within a  
 turbulent stream. The effect on the radiated noise due to variations in porous  
 leading edge length  $l$  and flow velocity  $U$  were investigated. A partially porous  
 leading edge on a 3D aerofoil was also investigated to establish whether the  
 same noise reduction principles can be extended to relatively thick aerofoils.

220 A schematic of the porous flat plate is shown in Fig. 2. Here, a regular  
 pattern of circular holes of diameter  $d$ , separated by a distance  $t$  are introduced  
 onto a flat plate of 2 mm thickness, span 450 mm and chord  $c_0$ , which is varied  
 in the experiment. The length of the porous section from the leading edge  
 is  $l$ . In this preliminary study two different configurations were investigated.  
 225 The first was a fully porous flat plate (i.e.,  $l = c_0$ ) with  $d = 3$  mm,  $t = 5$  mm  
 (representing a 32% porosity) with  $c_0 = 100$  mm and 150 mm. The second was  
 a partially porous flat plates comprising of varying porous length sections, in  
 the range  $l/c_0 = 0.2$  to 1, as shown in Fig. 3a.

To verify the same basic noise reduction principles observed in the simple  
 230 flat plate experiment, porous treatments were also applied to the leading edge of

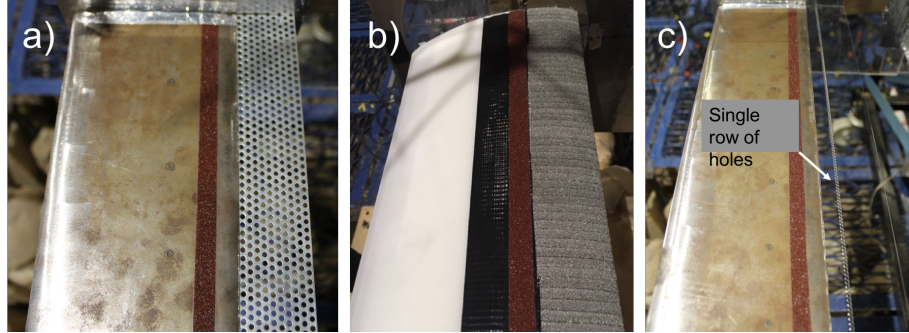


Figure 3: A photograph of the porous LE aerofoil in anechoic wind tunnel a) Partially porous flat plate b) 3D porous leading edge c) Single-row of holes on leading edge (discussed in section 4).

a realistic aerofoil of 10% thickness. Here, the first 50 mm of a NACA 65(12)-10 aerofoil of 150 mm total chord and was replaced by a porous section of identical geometry cut from a metal foam with 90% porosity, as shown in Fig. 3b. The pore diameter of the porous section was in the range of 0.2 to 0.4 mm. The main body was fabricated using a 3-D printer from the durable acrylonitrile butadiene styrene (ABS) photo polymer that has a high-quality surface finish.

### 3.2. Experimental procedure and instrumentation

Far-field noise measurements were carried out at the Institute of Sound and Vibration Research's open-jet wind tunnel facility. The wind tunnel is located within the anechoic chamber, of dimension 8 m x 8 m x 8 m. The nozzle has dimensions of 150 mm and 450 mm and provides a maximum flow speed of 100 ms<sup>-1</sup>. A detailed description of the wind tunnel, including its characteristics, is presented by [14].

Far-field noise measurements were made using 16, half-inch condenser microphones (B&K type 4189) located at a constant radial distance of 1.2 m from the mid span of the flat plate leading edge. These microphones were placed at emission angles of between 40° and 130° measured relative to the downstream jet axis. Noise reductions are presented in terms of the Sound Power Level spectra  $PWL(f)$  calculated by integrating the pressure spectra over the polar

array of 16 microphones using the procedure described in [15]. Measurements  
 were carried for 20 s duration at a sampling frequency of 40 kHz, and the noise  
 spectra were calculated with a window size of 1024 data points corresponding  
 to a frequency resolution of 19.5312 Hz and a bandwidth–time (BT) product  
 of approximately 400, which is sufficient to ensure negligible variance in the  
 spectra estimated at this frequency resolution.

In an attempt to produce turbulence that is approximately homogeneous  
 and isotropic at the aerofoil leading edge, a bi-planar rectangular grid ([16])  
 of wooden bars of 12 mm width separated by 34 mm was used to generate  
 turbulent inflow. A comparison of the streamwise velocity spectra measured at  
 145 mm from the nozzle exit plotted against  $f/U$  is compared in Fig. 3 of [6]  
 to the theoretical Liepmann velocity spectrum, where the mean square velocity  
 and integral length scale are chosen to give the best fit to the measured data.  
 Close agreement is observed at an inflow condition of 2.5% turbulence intensity  
 and a 7.5 mm streamwise integral length-scale.

### 3.3. Fully porous flat plates

The validity of the "source cutoff" hypothesis proposed in Section 2.2 and the  
 derivation of Eq. (3) to predict the noise reduction spectra by a fully porous flat  
 plate was investigated by introducing porosity over the entire flat plate. Edge-  
 to-edge interference effects proposed in Section 2.3 were therefore absent in  
 this experiment. The noise reduction spectra were measured by comparing the  
 measured radiation spectra with that obtained from a non-porous flat plate of  
 the same dimensions. Two fully porous flat plates of chord lengths  $c_0 = 100$  and  
 150 mm were investigated at the two different flow velocities of 40 and 60  $\text{ms}^{-1}$ .  
 The sound power level reduction spectra for the three cases of  $(c_0, U) = (100$   
 mm, 40  $\text{ms}^{-1}$ ), (150 mm, 40  $\text{ms}^{-1}$ ) and (150 mm, 60  $\text{ms}^{-1}$ ) are plotted against  
 the non-dimensional frequency  $fl/U_c$ , where  $l = c_0$  in this case. Also shown in  
 Fig. 4 is the theoretical curve of Eq. (3) for the noise reduction spectra due to  
 cutoff effects, where we have assumed  $U_c = 0.7U$  ([17]).

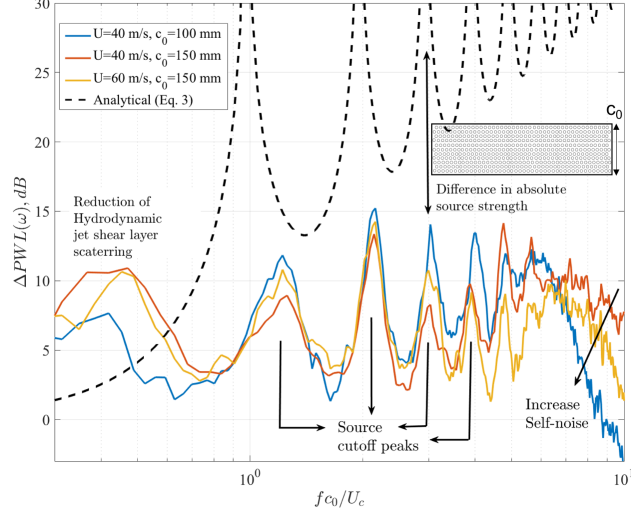


Figure 4: Sound pressure level reduction spectra versus non-dimensional frequency  $f c_0 / U_c$  measured flow speeds of 40 and 60  $\text{ms}^{-1}$  for a fully porous leading edge of length 100 mm and 150 mm. Also shown is the theoretical curves for the source cutoff noise reduction mechanism.

280      Excellent collapse of the three measured spectra are observed with each spectra clearly showing evidence of multiple peaks of maximum noise reduction of up to 15dB at  $f l / U_c = 1.2, 2.1, 3.0, 3.9, 4.8, \dots$ . These peak frequencies are entirely consistent with the hypothesis of source cutoff proposed in Eq. (3) where peak noise reductions corresponding to  $f l / U_c \approx n$  are predicted. The small  
285      difference between the measured and predicted frequencies can be attributed to variations in convection velocity and its frequency dependence where variations of up to 20% can be observed on aerofoil geometry. [18]. Naturally, the simple theory considerably over-estimates the measured noise reductions owing to the idealised assumptions made regarding their relative source strengths. Moreover,  
290      the predictions do not include the effects of additional noise sources generated by the porous plate, such as roughness noise and the noise due to the cross-flow effects. Nevertheless, the agreement is sufficiently close to provide confidence in the proposed noise reduction mechanism. Note that the levels of noise reductions appear to diminish as the chord length  $c_0$  is increased. This may be due to

295 reduction in the coherence of  $\Delta p$  along the chord with the increase of chord  
length.

### 3.4. Partially porous leading edges

We now investigate experimentally the noise reduction spectra due to par-  
tially porous flat plates in which, according to our hypotheses in Section 2,  
300 two distinct noise reduction mechanisms are involved. In Section 2.3 we argue  
that edge-to-edge interference is also present when the aerofoil is only partially  
porous. To validate this hypothesis the noise reduction spectra were measured  
for a range of different porous section lengths  $l/c_0=0.2, 0.32, 0.49$  on a flat plate  
at  $U = 60 \text{ ms}^{-1}$ . Sound power level reduction spectra are plotted in Fig. 5  
305 versus  $fl/U$  for a fixed chord length of 150 mm. It is clear from this figure  
that introducing porosity on only the leading edge section of the aerofoil intro-  
duces additional peaks compared to that when it is fully porous. Now present  
in figure are the peaks  $fl/U=0.5$  and  $1.5$  in addition to the source cutoff peaks  
of  $fl/U_c=1.2, 2.1$  (equivalent to  $fl/U=0.85, 1.4$  based on the assumption of  
310  $U_c = 0.7U$ ). These additional peak frequencies are in excellent agreement with  
the predicted peaks from Eq. (5) based on the assumption of destructive in-  
terference between the two edge discontinuities at  $y_1 = 0$  and  $l$ . Moreover, a  
good collapse is observed when the measured noise reduction peaks are plotted  
against  $fl/U$ . Considerably better agreement with the measured noise spectra  
315 may be obtained by allowing the source strengths at the ends of the porous sec-  
tion to vary by a non-dimensional frequency-dependent complex factor  $\eta$  whose  
phase will cause a shift in the peak frequencies and whose magnitude will affect  
the noise reduction peaks, i.e.,  $\Delta p_0 = \eta \Delta p_l$ . Infinitely large noise reductions  
are predicted for  $\eta=1$  which then reduces as  $\eta$  deviates from 1. This ability  
320 to shift noise reduction peaks is also possible in the more complicated Wiener-  
Hopf model of Priddin *et. al.* [12], whereby a complex impedance parameter  
would result in an additional phase term which would also allow for a shift in  
peak frequencies. However, this effect is a comparatively minor effect and for  
simplicity we consider  $\eta=1$ .

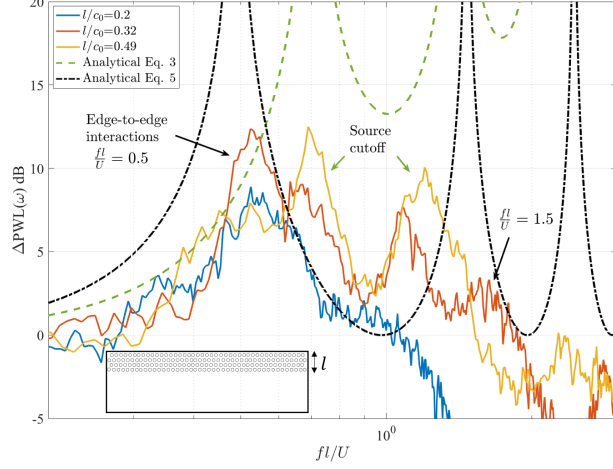


Figure 5: Sound pressure level noise reductions versus non-dimensional frequency  $fl/U$  for partially porous flat plates of varying porous length of  $l/c_0=0.2, 0.32$  and  $0.49$  at the flow velocity of  $60 \text{ ms}^{-1}$ . Also shown are the theoretical curves for the two noise reduction mechanisms.

Figures 4 and 5 showing the noise reduction spectra for both fully and partially porous flat plates, and their collapse on  $fl/U$ , have provided strong validation of the two noise reduction mechanisms proposed above. The level of noise reductions appear to improve as  $l$  is increased which may be related to the sources being more localised at the edges  $y_1 = 0$  and  $y_1 = l$ .

We conclude this section by demonstrating that the same fundamental noise reduction principles observed in the simple flat plate measurements are also present in a realistic and relatively thick, aerofoil with porous leading edges. Porosity was introduced into the first 5 cm of a NACA65 aerofoil of 150 mm total chord and 10% thickness (see Fig. 3b). The variation in noise reductions due to changes in the porous section length  $l$  was investigated by the use of thin metal tape to cover both the upper and lower surfaces of the porous section. Three values of  $l$  were investigated corresponding to 10, 20 and 30% of the chord ( $l=1.5, 3.0$  and  $4.5 \text{ cm}$ ). The sound power level reduction spectra plotted against  $fl/U$  at a flow speed of  $40 \text{ ms}^{-1}$  and  $\text{AoA}=0^\circ$  for the three section lengths of

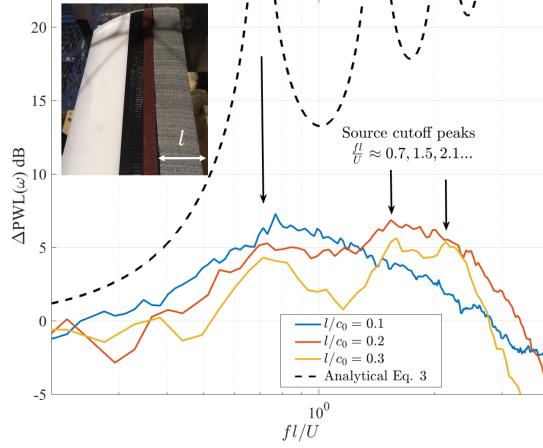


Figure 6: Sound power level reduction spectrum for a NACA65 aerofoil with 5cm, 10cm and 15cm of porous leading edge versus non-dimensional frequency  $fl/U$  measured at  $40 \text{ ms}^{-1}$  and  $\text{AoA}=0^\circ$ . Also shown is the theoretical curves for the dominant noise reduction mechanism.

340  $l/c_0$  of 0.1, 0.2 and 0.3 are shown in Fig. 6. Also shown in this figure is the theoretical curve of Eq. (3).

The noise reduction spectra are observed to have similar behaviour to the flat plate spectra in Fig. 5 and collapse reasonably well on  $fl/U$ . Peaks at  $fl/U \approx 0.7, 1.4$  and  $2.1$  (corresponding to  $fl/U_c = 1, 2, 3 \dots$  assuming  $U_c =$   
 345  $0.7U$ ) are also observed in the noise reduction spectra for the two largest porous sections. The second peak in the measured noise reduction spectra is absent for the shortest porous section due to masking by self-noise source at this relatively high (absolute) frequency. For the two largest porous sections, the second peak is marginally greater than the first peak by about 1dB suggesting that the cutoff  
 350 effect is the dominant noise reduction mechanism for this choice of geometry and porosity.

It is important to note the absence of peaks at  $fl/U = n - 1/2$  resulting from the edge-to-edge interaction noise for this 3D aerofoil. We can conclude therefore that the sources at  $y_1 = 0$  and  $y_1 = l$  are sufficiently different in level,  
 355 or sufficiently weak, so that their level of destructive interference is negligible.



Edge-to-edge interference is therefore not a dominant noise reduction mechanism for this relatively thick aerofoil and porosity but may be more significant in other configurations. Another possible noise reduction mechanism is the Helmholtz-type resonance created by the mass of tape acting against the stiffness of the air trapped by the tape on both sides of the porous leading edge. However, it is not clear at the present time how this type of resonance can lead to noise reductions and occur at harmonic frequencies.

Finally, we investigate the effect on the noise reductions due to changes in angle of attack of the NACA65 aerofoil. Fig. 6 shows the sound power level reduction spectra plotted against  $fl/U$  for a fixed porous length of  $l/c_0 = 0.3$  at three different geometric AoA=0°, 5°, 10° and a flow speed of 40 ms<sup>-1</sup>. The noise reduction spectra are observed to have similar behaviour to the AoA=0° spectra in Fig. 6 and collapse reasonably well on  $fl/U$  except at high frequencies  $fl/U \geq 1.5$ . With the increase of AoA, a significant increase in the radiated noise is observed and may be attributed to the increase in self-noise due to cross-flow through the porous section. This cross-flow effect can be avoided by the introduction of a solid plates passing through mid-camber line as demonstrated by [10]. Note that in this study the effective angles of attack are very small due to jet deflection from the open-jet wind tunnel measurements.

In the next section we propose an alternative porosity distribution for the reduction of broadband leading edge interaction noise. The innovative feature of this porous configuration is that the porous section is located well downstream of the leading edge and is therefore predicted to have much smaller effect on the aerodynamic performance. We now demonstrate that this new porosity configuration is able to reproduce the same cutoff radiation effects demonstrated previously for the partially porous aerofoils.

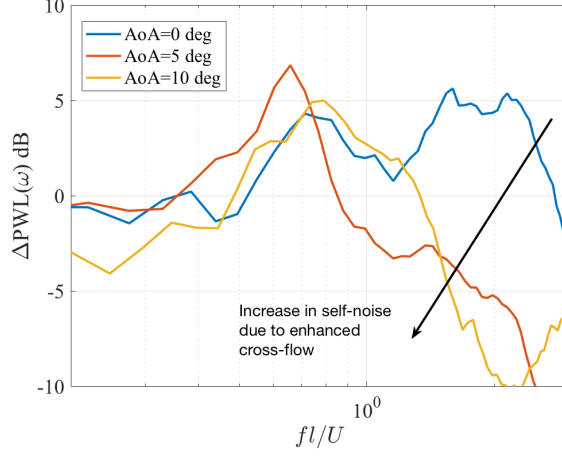


Figure 7: Sound power level reduction spectrum for a NACA65 aerofoil with 15cm of porous leading edge versus non-dimensional frequency  $fl/U$  measured at  $40 \text{ ms}^{-1}$  at  $\text{AoA}=0^\circ, 5^\circ, 10^\circ$ .

#### 4. Porosity downstream of the leading edge

##### 4.1. Flat plate configurations

In this section we explore the effect on noise reduction performance obtained when holes are introduced downstream of the leading edge of a flat plate. In the general case a porous section of length  $l$  is located at a distance of  $l_0$  from the leading edge of the flat plate, as shown in Fig. 2 and Fig. 3c. A total of 40 different porous plates of varying hole diameters  $d$ , hole spacing  $t$ , number of porous rows, rectangular slot geometry and distance from the leading edge  $l_0$  were tested. Table 1 provides a summary of the flat plate configurations tested in this study.

Configuration	Hole diameter, $d$ (in mm)	Spacing ( $t/d$ )	Distances (in mm)
Single row	1, 2, 3 and 4	1.5, 2, 2.5 and 3	$l_0=40, 60, l = d, c_0=150$
2 rows	2	2	$l_0=40, 60, l = 2d + t, c_0=150$
3 rows	2	2	$l_0=40, 60, l = 3d + 2t, c_0=150$

Table 1: A summary of flat plate experiments performed in the current study.

#### 4.2. Noise reduction performance

Figure 8 shows the typical noise reduction spectra plotted against  $fl_0/U$  for a single row of holes of  $d = 2$  mm and  $t = 4$  mm at the four different locations of  $l_0/c_0 = 0.13, 0.2$  and  $0.27$  and  $0.4$  at a fixed velocity of  $40 \text{ ms}^{-1}$ .

Even though only a single row of holes are introduced well downstream of the leading edge, the noise reduction spectra exhibit similar characteristics, but at a lower level, to that obtained when an entire porous section of length  $l$  is introduced. Good collapse of the spectra is obtained when plotting against  $fl_0/U$ . Unexpectedly, peak frequencies at  $fl_0/U \approx 0.7, 1.4$  and  $2.1$  are observed which are identical to that obtained for partially porous sections of length  $l$  as shown in Fig. 5.

Clearly, therefore, a single row of holes located downstream of the leading edge provides a noise reduction mechanism similar in principle to that when the aerofoil is partially porous. We argue above that this mechanism is mainly due to the unsteady aerofoil response now convecting with the flow speed rather than the sound speed for rigid aerofoils. The reasons for this behaviour is currently unknown but we speculate that introducing downstream porosity creates a local low-pressure boundary condition  $\Delta p(l_0) \approx 0$  which has a significant effect on  $\Delta p(y_1)$  upstream. It is possible that forcing  $\Delta p(y_1)$  to be small at  $y_1 = l_0$  forces a slowing of  $\Delta p(y_1)$  to that of the flow speed. Clearly, more work is needed to confirm this hypothesis, although at the present time we are unable to provide an alternative explanation behind these peak frequencies. We note that another benefit in relocating the porosity downstream of the leading edge is a reduction in the noise increase at high frequencies. The precise reason for this finding is also not known but may be related to reduced roughness noise or a thinner boundary layer associated with holes introduced further downstream.

The influence of the hole diameter was also investigated where a very small hole of just  $d = 1$  mm in diameter was found to achieve similar noise reductions to within 1dB at most frequencies and up to 3dB at the peak frequencies. An increase in hole diameter was also found to increase self-noise at high frequencies, which may be related to increased roughness. Varying the hole, spacing and

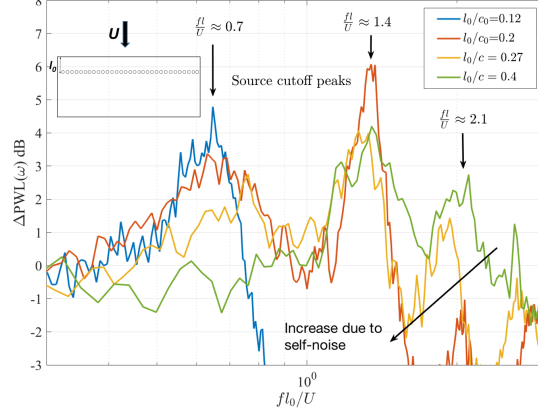


Figure 8: Sound pressure level reduction spectra versus non-dimensional frequency  $fl_0/U$  measured at a flow speed of  $40 \text{ ms}^{-1}$  for a single row of holes located at distances  $l_0/c_0 = 0.12, 0.2, 0.27$  and  $0.4$  from the leading edge.

replacing the circular holes with rectangular slots was found to have a negligible effect ( $\leq 1.5\text{dB}$ ) on the noise reduction levels.

425 Finally, we investigate the most general configuration in which a porous section of length  $l$  is introduced at a distance of  $l_0$  downstream of the leading edge. Figure 9 shows the comparison of the sound power reduction spectra obtained using 5 rows of holes of  $d=3 \text{ mm}$  and  $t=5 \text{ mm}$  located at  $l_0/c_0 = 0$  and  $l_0/c_0 = 0.32$  whose length of porous section is  $l/c_0 = 0.32$  at a flow velocity of  
430  $40 \text{ ms}^{-1}$ . The effect of relocating the holes downstream can be seen to provide a significant reduction (of up  $5\text{dB}$ ) in noise over a same band of frequencies to that obtained when the holes are introduced at the leading edge. These reductions are superior to those in Fig. 4 where only a single row of holes are used. However, the significant difference now is that the two spectral peaks are absent. Clearly,  
435 the introduction of an additional edge discontinuity at  $y_1 = l + l_0$  has the effect of modifying the source balance and weakening the effects of destructive interference such that strong interference peaks no longer occur. However, the important difference between the two cases is that at the leading edge, where most of the lift is generated, does not require significant modification, which

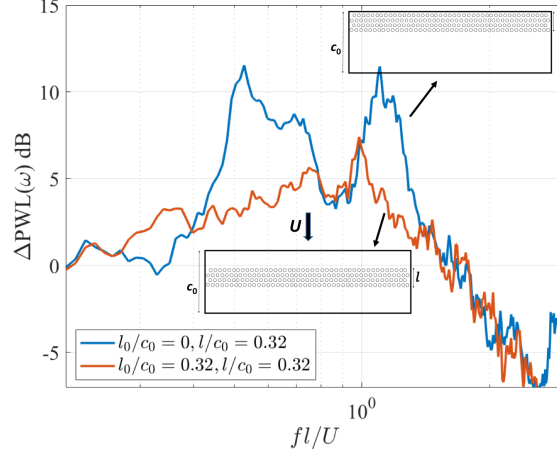


Figure 9: Sound pressure level reduction spectrum versus non-dimensional frequency  $fl/U$  measured at a flow speed of  $40 \text{ ms}^{-1}$  to demonstrate the influence of porous section introduced downstream of the leading edge.

440 should have significant benefit in terms of aerodynamic performance.

## 5. Conclusion

This paper has investigated in detail the reductions in the broadband aerofoil interaction noise due to the introduction of porosity over the entire chord, over a short section from the leading edge and a short section located downstream  
 445 of the leading edge. Consistent with the results from the previous work, porous leading edges have been shown to provide substantial reductions in turbulence-aerofoil interaction noise. This paper has shown experimentally and through a simple analytic model that noise reduction spectra strongly collapse when plotted against non-dimensional frequency  $fl/U$ . Narrow band measurements  
 450 for a partially porous aerofoil have shown that its noise reduction spectrum is characterised by a number of narrow peaks at approximately  $fl/U_c \approx n$  and  $fl/U \approx n - 1/2$ , where  $n$  is any integer. This paper has proposed two main mechanisms for explaining this behaviour. The first is a 'Source cutoff' effect in which the unsteady aerofoil response is assumed to convect at the flow con-

455 vection speed and therefore radiates with much lower efficiency than for a rigid  
aerofoil whose unsteady response is at supersonic speeds. The second mechanism  
invoked to explain the observed noise reduction spectrum is related to the  
'Edge-to-edge interference' in which compact sources at the edge discontinuities  
interfere destructively.

460 An intriguing finding of this paper is that just a row of holes downstream  
of the aerofoil leading edge can provide a similar effect on the noise radiation  
spectra as when the aerofoil is made partially porous from the leading edge. The  
cutoff radiation effects have been proposed to explain this behaviour but more  
work is needed to establish more definitely the noise reduction mechanism.

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