

# Trailing Edge Noise Production, Prediction and Control



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*An original refereed contribution to New Zealand Acoustics.*

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## Abstract

This paper describes the airfoil trailing edge noise generation mechanism and how flow over an airfoil can create tonal or broadband noise. Examples of vortex shedding as well as tonal and broadband noise spectra are presented. A brief review of how trailing edge noise can be predicted computationally is given and some results shown using a new industrially friendly computational methodology that couples with conventional steady flow simulation software. The paper concludes with a discussion of passive trailing edge noise control devices and their effectiveness.

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## INTRODUCTION

Unsteady fluid flow and sharp edges are common partners in industry and nature that often create loud and unwanted sound, which is known as airfoil trailing edge noise. The most common form of unsteady flow is turbulent, and as turbulent flow passes the trailing edge of an airfoil, strong broadband noise is generated, which can be annoying to people. Less common, but equally annoying, is tonal noise generated by vortex shedding (laminar or turbulent) or a self-supported aeroacoustic feedback loop at low flow speeds. Airfoil trailing edge noise can be created by wind turbines, helicopter rotors, aircraft wings, gas-turbine blades, cooling fans, propellers and submarine control surfaces. As unwanted noise reduces quality of life and can be a public health issue, it is necessary for engineers to be able to understand, predict and control airfoil trailing edge.

In this paper, some current research results concerning trailing edge noise from the University of Adelaide are reviewed and presented. The aim of the paper is to inform the acoustics community of the physics controlling the generation of trailing edge noise, how it can be predicted and controlled along with some avenues for further research.

## NOISE PRODUCTION

Unsteady fluid motion, or turbulence, is a weak source of sound, associated with the so-called “stresses” that are generated by the fluctuating fluid transporting momentum in time and space. Lighthill (1952) showed that these stresses radiate acoustic energy in a similar manner to a quadrupole source. The weak nature of turbulent quadrupole sources at low Mach number ( $M = U/c_0 < 0.2$ , where  $M$  is the Mach number,  $U$  is the mean fluid velocity and  $c_0$  is the speed of sound in the ambient, surrounding fluid) means that normally, turbulence is not considered a significant noise source. However, the addition of a sharp trailing edge in close proximity to the turbulent flow introduces a scattering surface that improves the acoustic radiation efficiency of turbulent flow (Howe 1999). In effect, the edge supports a source that creates noise that has a higher intensity than would be expected for isolated turbulence.

The speed of the flow ( $U$ ) approaching the airfoil, its size (chord,  $c$ ) and fluid viscosity ( $\nu$ ) will determine if the noise generated is predominately tonal or broadband in nature.

Tonal noise usually occurs when there is some kind of vortex shedding from, or concentrated fluid energy (as an eddy) passes, the trailing edge. Vortex shedding can either be laminar or turbulent (depending on the flow Reynolds number,  $Re = Uc/\nu$  (Blake 1986)); however, different flow mechanisms are present in each case.

### Tonal Noise

We will first consider vortex shedding which is illustrated in Figs. 1 and 2. These figures are results obtained from computer simulations of laminar flow over a flat-plate airfoil with an elliptical leading edge and bevelled trailing edge. Full details of the simulation and work can be found in Doolan et al. (2012). Experimental data for the same case can be found in Moreau et al. (2012a). Figure 1 shows the flow over the entire plate, which is from left to right, and shows that laminar boundary layers (indicated by the blue and red vorticity regions on the upper and lower surfaces respectively) form and approach the trailing edge. Further, unsteady eddies form in the upper surface boundary layer and these are due to a mild separation near the leading edge. Ignoring this secondary effect, the laminar boundary layer on the upper surface separates when it reaches the bevel and forms coherent vortex structures, thus starting the vortex shedding process.

Figure 2 shows a series of snapshots of the flow at the trailing edge at sequential instants of time over one vortex shedding cycle. Further, Fig. 3 shows how the lift coefficient varies during the same vortex shedding cycle. The cycle starts near the minimum point in the cycle, which corresponds to Fig. 2(a) and point (a) on Fig. 3. At this point of the lift cycle, the main shed vortex from the upper surface has just passed into the wake and a small intense vortex is being created over the trailing edge via a process where the lower boundary layer is entrained upwards by the low pressure field of the upper surface shed vortex. As time progresses to point (b), lift is generated rapidly on the plate and this is due to the formation of the intense lower surface shed vortex as well as another shed vortex on the upper surface. When time reaches point (c), the rate of lift production has slowed because the lower surface vortex has moved away from the trailing edge, leaving lift production to the low pressure core of the upper surface vortex. Lift increases further to point (d),

as another upper surface vortex forms while the previous vortex exists over the trailing edge. After this point, lift is quickly destroyed (point (e)) as the upper surface shed vortex moves over the trailing edge. By point (f), the lift is at a minimum again and subsequently, a new cycle begins. Thus, the repeated shedding of vortices causes a periodic variation of force on the airfoil. This variation of force is responsible for tonal noise generation by vortex shedding.

The vortex shedding process described above was based on the laminar case. Similar vortex shedding can occur when turbulent boundary layers are present and the trailing edge is sufficiently blunt to achieve significant flow separation and hence vortex roll-up (Blake 1986).

A different form of tonal noise can occur at low Reynolds numbers ( $Re < 200,000$ ) for airfoils with sharp trailing edges. This type of noise is characterised by a primary tone and a number of sidebands, as can be seen in Fig. 4, which is the noise spectrum measured from a NACA 0012 airfoil at zero angle of attack and a Reynolds number of  $Re = 75,000$  (Arcondoulis et al. 2012). It is widely believed that this type of tonal noise is due to an aeroacoustic feedback loop between the trailing edge (source of sound) and a point on the airfoil where convective disturbances (eddies) are created (Arcondoulis et al. 2010).

At present, the exact source of the convective disturbances is unknown and probably depends on the precise aerodynamic environment about the airfoil. One model for the feedback loop has been suggested by Arcondoulis et al. (2012) and is summarised in Fig. 5. In this model, acoustic waves generated at or near the trailing edge travel upstream and interact with the separation process near the leading edge where the shear layer is most receptive to acoustic disturbances. There is some empirical evidence to suggest that this model may hold (Arcondoulis et al. 2012), but numerical work (Jones et al. 2010) suggests that convective disturbances are generated at the leading edge. Further research is needed to resolve the exact mechanics of the feedback loop.

### Broadband Noise

When the Reynolds number is sufficiently high ( $Re > 300,000$ ), the boundary layers on the surfaces of the airfoil become turbulent. Turbulent flow consists of a random number of eddies of various sizes and speed (or scales) and thus creates a broadband fluctuating surface pressure near the trailing edge of the airfoil. This broadband surface pressure is scattered by the trailing edge (Amiet 1976) and creates broadband acoustic waves that can in some cases be intense and annoying to the human ear. This form of trailing edge noise is responsible for most of the aerodynamic noise from wind turbines above 300 Hz (Oerlemans et al. 2007, Doolan 2012) as well as significant amounts of noise from aircraft wings (Lockard & Lilley 2004), propellers and rotors (Paterson & Amiet 1982) and hydrofoils (Blake 1986).

To illustrate the nature of broadband trailing edge noise, results from an experimental study by Moreau et al. (2011) are reviewed. The airfoil used in this study is a flat plate model, similar to a hydrofoil, that has a circular leading edge with a radius of 2.5 mm and the trailing edge is symmetric with an apex angle of  $12^\circ$ , as shown in Fig. 6.

Figure 7 shows experimental noise spectra generated by the flat plate model when placed in an anechoic wind tunnel at various Reynolds numbers (see caption of Fig. 7 for actual test Reynolds numbers). The tests were conducted at a range of Reynolds numbers that extend below the natural transition point and hence turbulent boundary layers would not normally be present for cases (e) and (f). However, this model has a circular leading edge, which acts as a type of boundary layer trip, that ensures turbulent flow by creating a region of separated flow just downstream of the leading edge. The free shear layer associated with this separation is very unstable and reattaches to the airfoil surface as a turbulent boundary layer.

In contrast to the tonal noise, turbulent trailing edge noise is broadband in nature and has peak acoustic energy at typically lower frequencies than tonal noise, despite the flow velocity being usually higher. This is because in turbulent boundary layer flow, turbulent energy resides in the larger scales (or lower frequencies) and in the tonal noise case, flow energy is concentrated into higher frequency (small scale) eddies. It should be noted that a practical way to control tonal noise is to disrupt the formation of these concentrated high energy vortices by placing roughness element or trips on the surface of the airfoil.

## PREDICTION

Predicting airfoil trailing edge noise has many challenges, the most difficult of which is modelling the turbulence in the boundary layer. Exact analytical solutions are available to predict trailing edge noise (Ffowcs-Williams & Hall 1970, Amiet 1976, Howe 1999); however, each solution requires an estimate of the turbulent velocity or surface pressure spectrum.

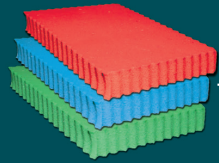
Turbulence is a random, complex and highly non-linear process with no closed form solution. In an attempt to resolve this problem, turbulence models have been developed (Wilcox 2006) to avoid the computational cost of directly resolving all the scales of turbulent flow, which for typical high Reynolds number flows over airfoils, is impossible using today's computers.

Large eddy simulation (LES) is becoming increasingly popular for modelling airfoil trailing edge turbulent flow and noise (Wang et al. 2009). LES resolves only the largest, energy containing scales of turbulence, while using an analytical model to describe the smaller, dissipative scales. While this technique is able to provide accurate descriptions of the turbulent field, computational costs are still high and for many engineering design situations where multiple iterations and calculations are needed, it is prohibitive.

The normal engineering approach to turbulent flow modelling remains the steady solution of the Reynolds averaged Navier Stokes (RANS) equations with an analytical turbulence model to describe all scales of turbulence. Such a modelling methodology does not include the time-varying properties of the turbulence, instead replacing them with mean quantities of velocity, turbulent kinetic energy and dissipation. Thus, by itself, RANS simulations are not able to model the turbulent noise sources near the trailing edge of an airfoil. However, there is a need to be able to use RANS simulations for noise prediction to increase productivity during engineering design.

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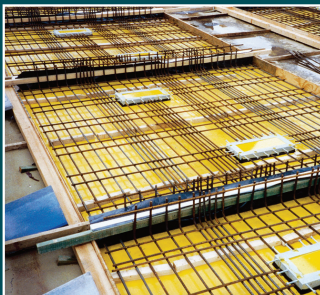
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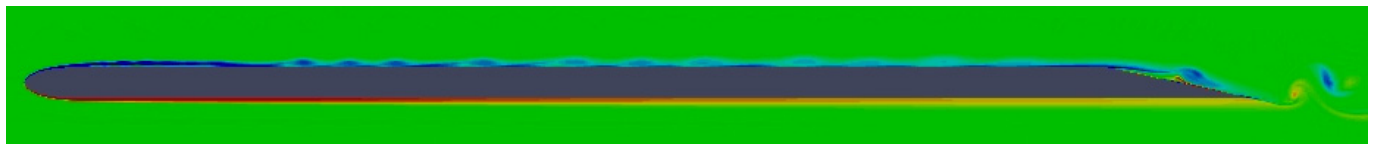


Figure 1. Contours of instantaneous spanwise vorticity about a flat plate (32 equispaced contours  $-7 \leq \omega_z H/U_\infty \leq 7$ , where  $\omega_z$  is flow vorticity and  $H$  is the thickness of the plate).

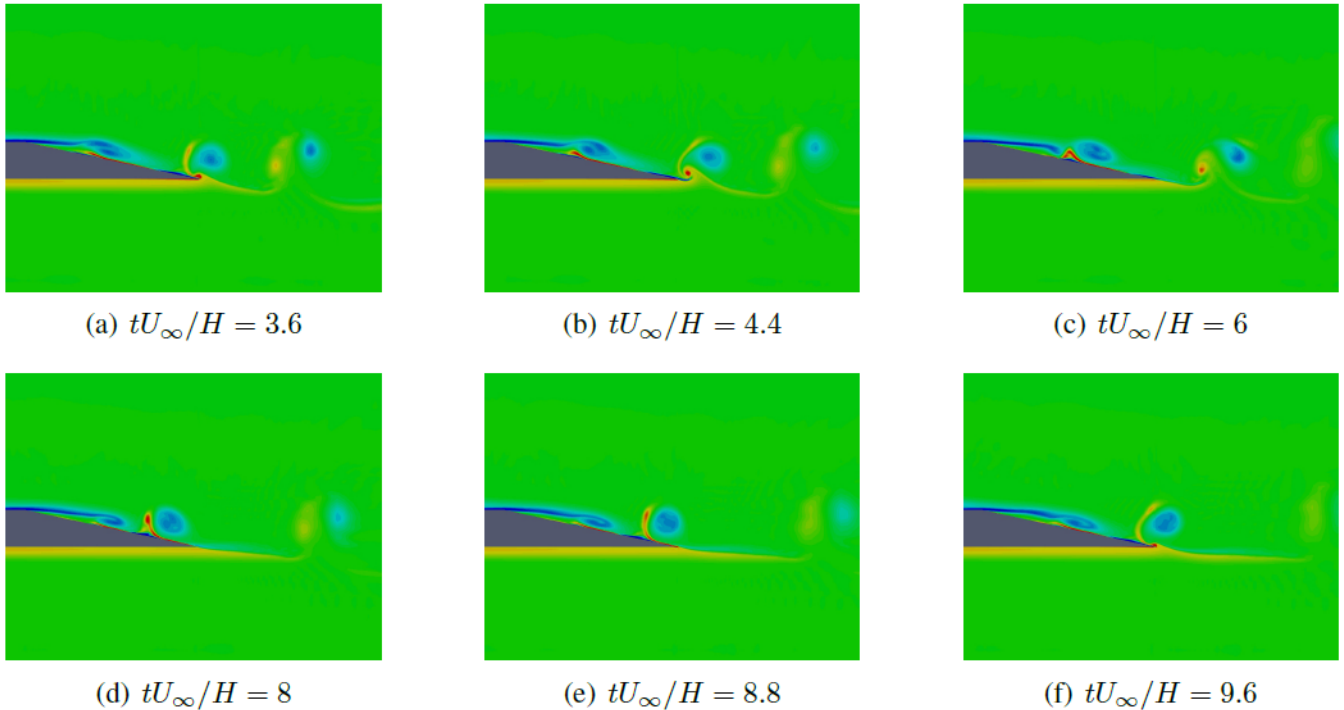


Figure 2. Contours of instantaneous non-dimensional spanwise vorticity: mode II (32 equispaced contours over  $-7 \leq \omega_z H/ U_\infty \leq 7$ , where  $\omega_z$  is flow vorticity and  $H$  is the thickness of the plate).

Recently, there has been some new ideas on how to use RANS modelling for noise prediction. One such approach is the RANS based Statistical Noise Model or RSNM (Doolan et al.

2010). In this approach, data provided by the RANS solution (specifically, mean velocity, turbulent kinetic energy and dissipation) are used with a statistical model of the two-point

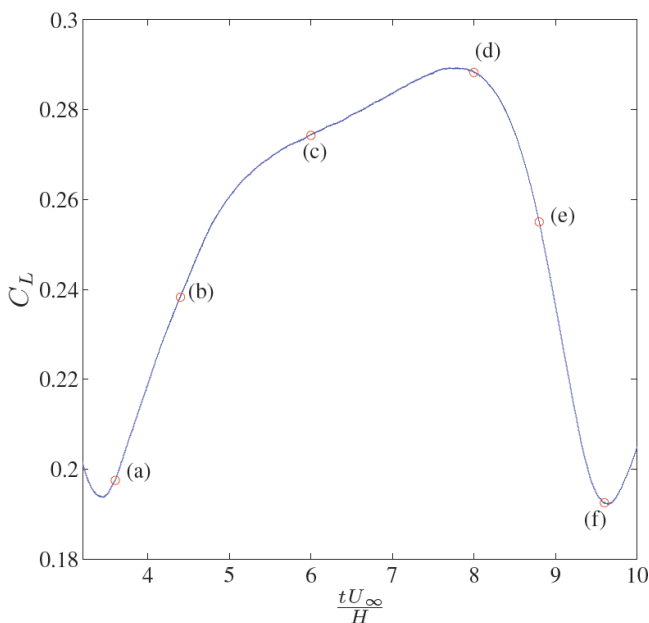


Figure 3. Unsteady lift cycle corresponding to Figure 2 (mode II), where  $C_L$  is the lift coefficient,  $t$  is time and  $H$  is the thickness of the plate.

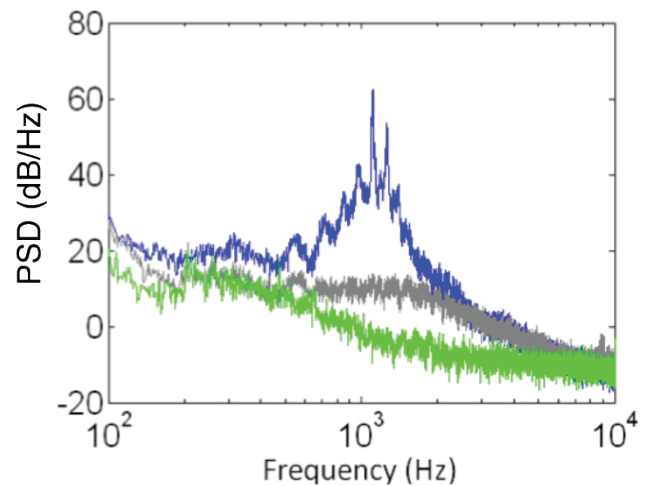


Figure 4: Acoustic spectra of a NACA 0012 airfoil at a Reynolds number of (a) 50,000 and (b) 75,000. The green, grey and blue lines represent the background noise with flow, the tripped (both surfaces) NACA 0012 airfoil and the untripped NACA 0012 airfoil, respectively. (Arcondoulis et al. 2012).

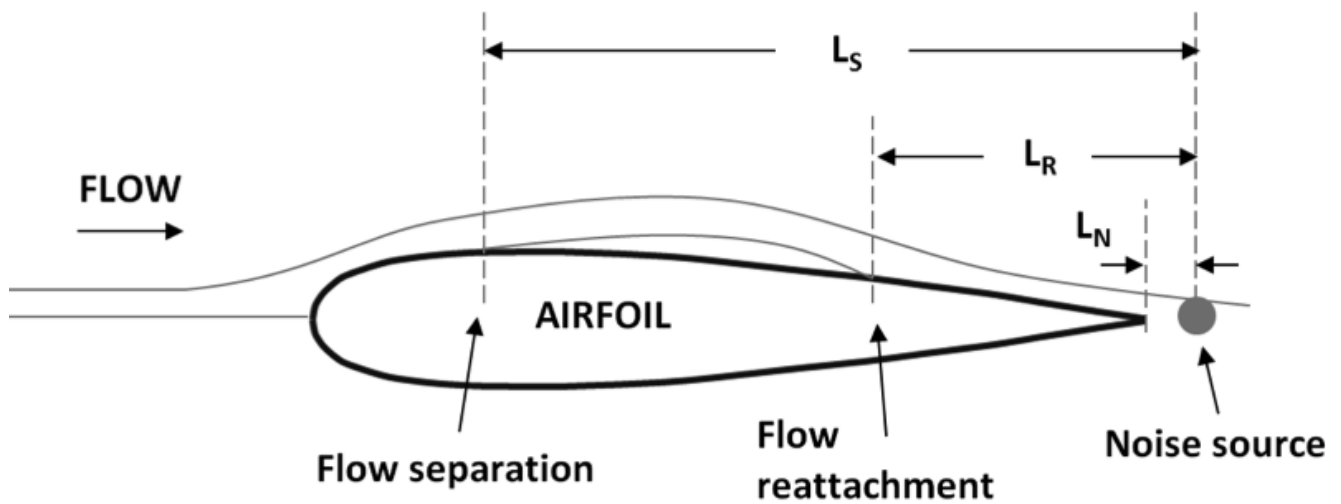


Figure 5. Suggested feedback loop of Arcondoulis et al. (2012).  $L_S$  is the distance from the noise source to the point of boundary layer separation,  $L_R$  is the distance from the noise source to the point of boundary layer reattachment and  $L_N$  is the distance from the noise source to the trailing edge.

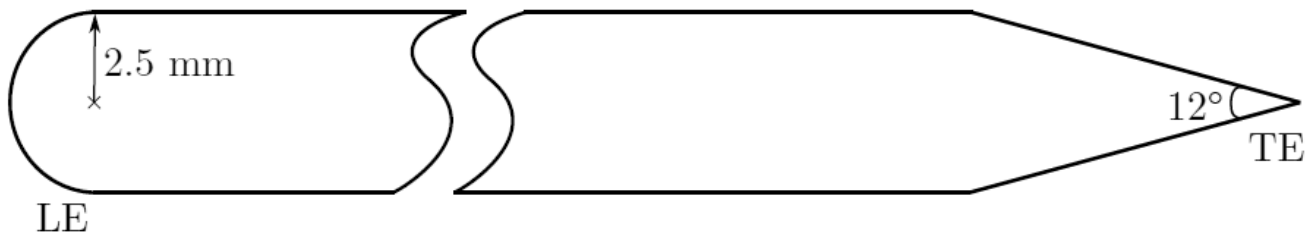


Figure 6. Schematic diagram of the flat plate airfoil model (Moreau et al. 2011). LE = leading edge, TE = trailing edge.

velocity correlation to construct noise sources in the boundary layer. Such a methodology is an accurate way to predict trailing edge noise using a fraction of the computational requirements of a LES solution. To illustrate the performance of RSNM, a comparison against some experimental data is shown in Fig. 8 (Albarracin et al. 2012).

1989) are compared with RSNM and a semi-empirical model (the so-called BPM model described in Brooks et al. (1989)). RSNM is able to accurately predict trailing edge noise over most frequencies.

### TRAILING EDGE NOISE CONTROL

Here, experimental one-third band noise data (Brooks et al.

While turbulent flow is the physical source of trailing edge



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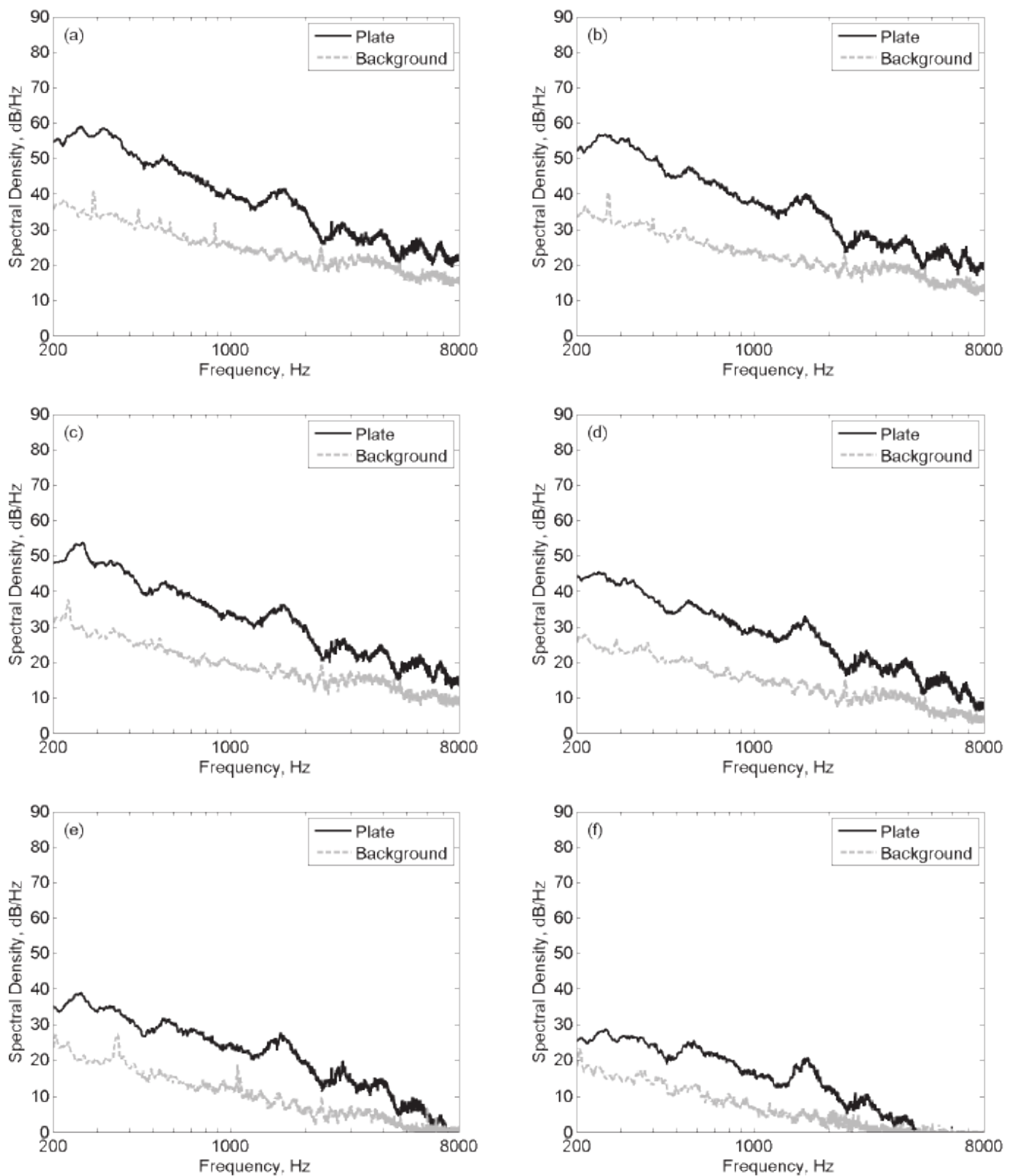


Figure 7: Far-field acoustic spectra for the flat plate model for  $Re =$  (a)  $5.0 \times 10^5$ , (b)  $4.6 \times 10^5$ , (c)  $4.0 \times 10^5$ , (d)  $3.3 \times 10^5$ , (e)  $2.6 \times 10^5$  and (f)  $2.0 \times 10^5$  (Moreau et al. 2011).

noise, the edge diffraction process is often the focus of noise control methodologies. Specifically, by reducing the severity of the sharp impedance change across the trailing edge, it is hoped that the mechanism whereby acoustic sources near the edge are reinforced can be diminished. Such techniques include porous trailing edges (Geyer et al. 2010) and brush attachments (Herr & Dobrzynski 2005).

Porous trailing edges can produce up to 10 dB reduction in sound pressure level at low to mid frequencies; however, an increase in noise at higher frequencies was observed and this was attributed to surface roughness effects. Similarly, brushes were found to produce up to 14 dB noise reduction (Herr & Dobrzynski 2005) but with no high frequency increase in noise level.

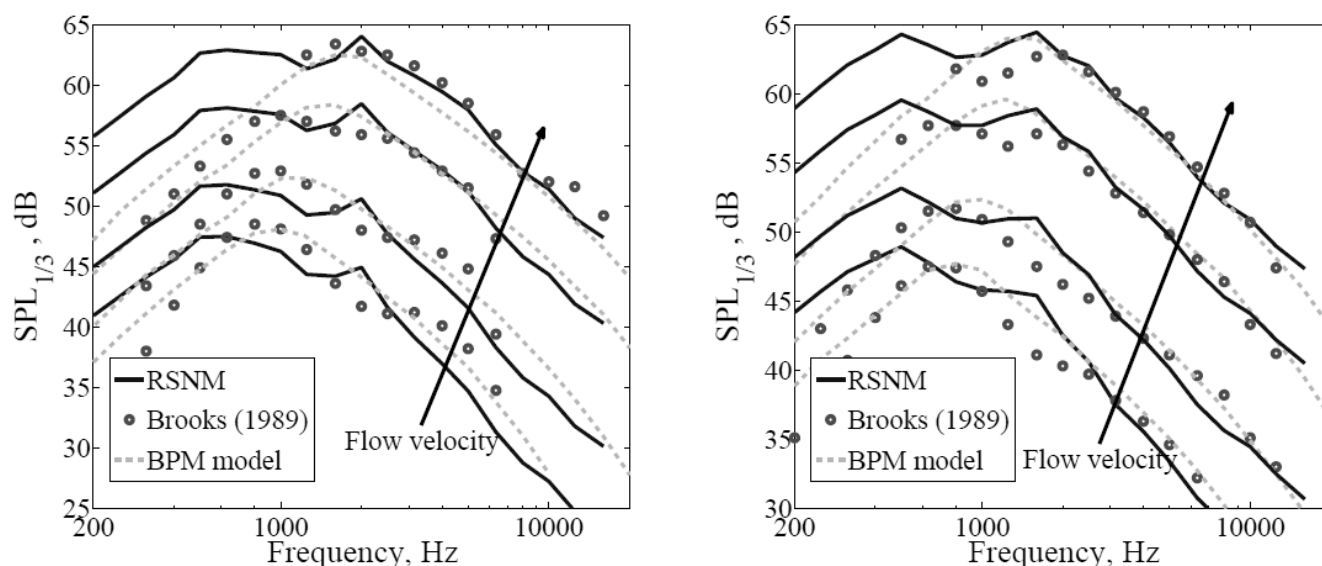


Figure 8: Noise spectra in one-third octave bands for two different chord NACA 0012 airfoils, calculated with RSNM (solid line) compared with experimental data of Brooks et al. (1989) (circles) and the BPM empirical model (Brooks et al. 1989) (dashed line) for flow velocities of 31.7, 39.6, 55.5 and 71.3 m/s; (Albarracin et al. 2012).

While effective, porous edges and brush attachments may have practical limitations, namely the fine pores or spaces between brushes are prone to collect dirt and insects making them ineffective. Thus significant effort will be required for cleaning which may not be attractive to airline operators or even possible for large wind turbines.

Another method for controlling trailing edge noise is the serrated edge (see Fig. 9), that may be easier to implement in industrial situations. Here the impedance change across the trailing edge is distributed over the serrations, which according to theory (Howe 1999), will reduce radiated trailing edge noise.

Recent measurements (Moreau et al. 2012b) of flow and noise from serrated trailing edges attached to a flat plate show that experimental noise reduction is much less than that predicted by theory and, in some frequency bands, noise may increase. In fact, it was concluded that the noise reducing effects of the serrations are mainly due to a rearrangement of the flow field by the serrations, rather than an effect on the acoustic edge diffraction mechanism.

The latest hypothesis is that the serrated edge affects the turbulent flow sources to such an extent that it overwhelms any noise reducing effects. Experiments are needed to examine in much closer detail how serrations affect turbulent flow and how these changes interact with acoustic theory in order to better explain acoustic measurements.

## CONCLUSIONS & OUTLOOK

This paper has given a brief introduction to the physical mechanisms of tonal and broadband trailing edge noise generation. Tonal noise can be generated by either vortex shedding, a feedback mechanism, or both. More research is needed to identify the exact path a feedback loop takes around an airfoil. Specifically, how the upstream running acoustic wave interacts with the airfoil and boundary layer to create convective

disturbances is still not clear.

Broadband noise is usually generated by turbulent flow travelling past the sharp trailing edge, acting to increase the radiating efficiency of the random, turbulent eddies as they pass.

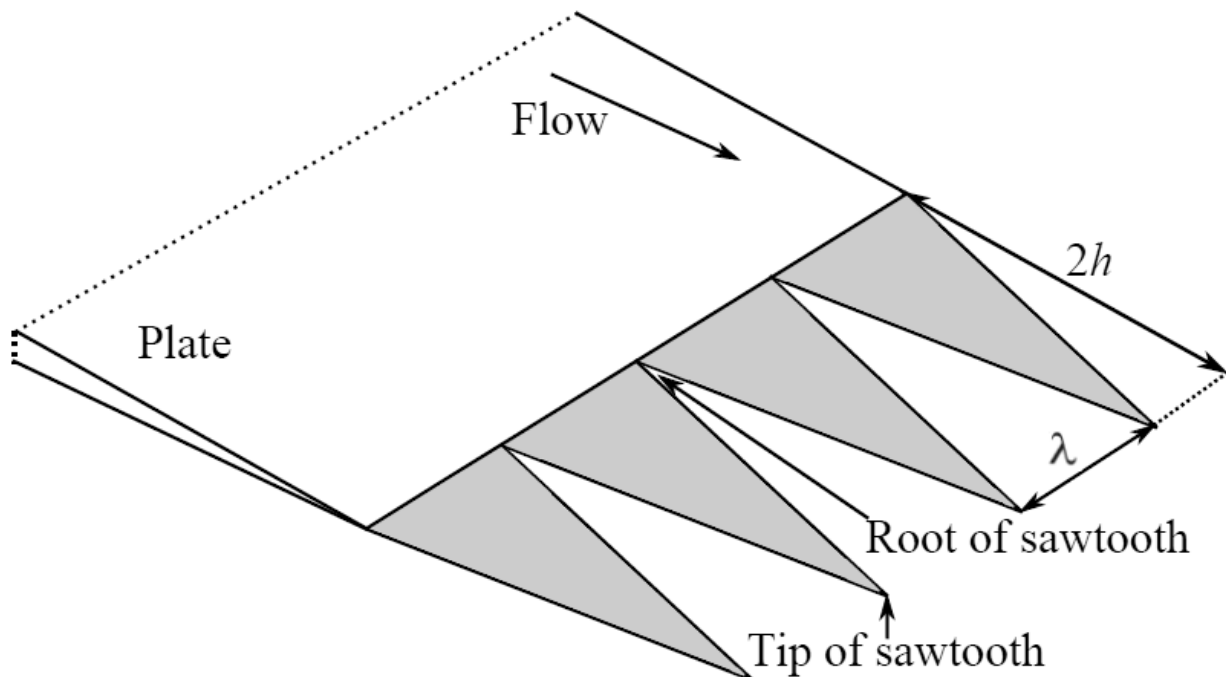
Methodologies to predict broadband trailing edge noise were reviewed and results using the RANS based Statistical Noise Model (RSNM) were shown. RANS based noise calculation methods are the only practical way industry can accurately predict trailing edge noise during the design process, as other computational techniques (such as LES or DNS) are too computationally expensive in terms of computer infrastructure and time.

Some passive methods of controlling trailing edge noise were reviewed. While effective, porous trailing edges and brush attachments may require too much cleaning to be practicable. Serrations, on the other hand, are larger and hence will have a lower tendency to clog with dirt, but experiments show they are not as effective as theory suggests.

More research is needed to understand why this is the case and see if there are ways to improve the performance of serrated trailing edges.

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**Figure 9: Sawtooth serrations at the trailing edge of a flat plate with root-to-tip amplitude of  $2h$  and wavelength of  $\lambda$ ; (Moreau et al. 2012b).**

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