EXPERIMENTAL INVESTIGATION OF ISOLATED AEROFOIL NOISE

Stefan Pröbsting, Fulvio Scarano

Department of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands,
e-mail: s.probsting@tudelft.nl

Over the past 40 years the tones generated by isolated aerofoils at moderate Reynolds numbers
have been subject to scientific discourse and are often related to boundary layer instabilities.
An experimental study is conducted on a NACA 0012 aerofoil profile using far field microphone
and high-speed particle image velocimetry (PIV) measurements.
Acoustic measurements have been performed in an anechoic open jet wind tunnel facility
for various angles of attack between $0^\circ$ and $8^\circ$ and Reynolds numbers between $33,000$ and
$233,000$. PIV measurements have been performed to assess the flow structure in the source
region at these flow conditions, revealing the significance of flow separation and instability
growth for the noise generation process.
Results indicate that both frequency and magnitude of the tones emitted at moderate Reynolds
numbers are highly dependent on these parameters. Forcing transition on both sides of the
aerofoil alternatively shows that various regimes can be identified within which noise gen-
eration is dominated by the flow on pressure side, suction side, or by an interaction of the
two. The flow structure around the trailing edge confirms this hypothesis. Coherent vortical
structures convecting past the trailing edge on the respective side are present in the cases with
strong tones.
Moreover, the influence of upstream traveling acoustic waves produced by a speaker located
downstream of the aerofoil on the noise generation process is investigated and significant effect
is observed, confirming the possibility of acoustic feedback as a frequency selection mecha-
nism.

1. Introduction

In 1973 [1] reported the observation of tonal noise occurring for isolated aerofoils in an airflow.
The authors commented on the particular nature of the spectrum of acoustic pressure, which showed
variations of discrete tones with $f_n$ proportional to a power of the free stream velocity $u^{0.8}$. However,
the dominant tone $f_{n_{max}}$ followed this variation with $u^{0.8}$ only over a finite range of Reynolds numbers
before a transition (or “jump”) of the maximum to a different tone occurred. On average [1] found an
approximation of the main tone frequency $f_s$ described by Eq. 1, where $c$ is the chord length of the
aerofoil and $\nu$ the kinematic viscosity. This particular structure of the spectrum with multiple discrete
tones $f_n$ and transitions of the main tone $f_{n_{max}}$ was termed “ladder” type structure.

$$f_s \approx 0.011u^{3/2}/(c\nu)^{1/2}$$ (1)
Since this observation the topic has received much attention and recent publications show the sustained interest and ongoing debate [2, 3, 4]. Explanations for the generation of tonal noise were proposed by [5], who proposed an acoustic feedback between a noise source in the wake and the trailing edge, and [6], who explained the phenomenon by the scattering of convective surface pressure perturbations induced by instability waves developing in the boundary layer upstream of the trailing edge. In a PIV experiment on a NACA 0018 profile [7] observed periodic structures passing the trailing edge, which were attributed to instability waves and associated to tonal noise generation. These experimental findings are consistent with the results of numerical simulations reported by [2] and [8].

Various researchers [9, 1] have investigated tonal noise generation under the condition of turbulent flow on one side, for instance forcing transition by the application of tripping devices. They reported that no tonal noise was observed when the flow on the pressure side was turbulent. Turbulent flow on the suction side was reported to have a minor influence, leading to the conclusion that tonal noise emission in this case is due to instabilities on the pressure side. Other studies report that events on the suction side dominate noise emission [8].

As also pointed out by [3] results available in literature show differences in the details of the “ladder” structure and explanation of related mechanisms. A large number of studies, especially numerical investigations of the topic, are limited to a small number of flow conditions and the influence of Reynolds number and angle of attack is often not discussed. Therefore, to obtain a better understanding of the differences in the observation of tonal noise emission due to laminar boundary layer instabilities, a more differentiated discussion taking into account the boundary conditions of the problem is required.

In the present study, the noise generation on an aerofoil profile is investigated for a wider range of Reynolds numbers and angles of attack. Through a parametric study it is intended to identify the relative contribution of events on pressure and suction side to overall noise generation. In conjunction with visualizations of the flow field through PIV experiments this approach is expected to provide a more complete picture of noise generation on isolate aerofoils.

2. Experimental set-up

A NACA 0012 profile is selected, since a large part of the available literature is based on this aerofoil. The chord of the model, manufactured from acrylic glass, is $100\,\text{mm}$ and the span $400\,\text{mm}$. Randomly distributed 3D roughness elements (carborundum, nominal grain size $0.58\,\text{mm}$) on a $5\,\text{mm}$ wide strip are attached to the aerofoil at 25% chord to force transition. Measurements are performed with roughness elements on pressure side only, suction side only, both sides, and with a clean configuration.

2.1 Acoustic measurements

Acoustic measurements have been performed in the anechoic open jet wind tunnel facility at the University of Notre Dame (test section $2 \times 2\,\text{ft}^2$). The walls of the room containing the test section are covered with anechoic foam wedges, rated to absorb 99% of the acoustic power above $100\,\text{Hz}$.

An ACO Pacific Type 7016 microphone with pre-amplifier was located in the mid-span plane at a distance of $2\,\text{m}$ perpendicular to the chord at the streamwise position of the trailing edge with the aerofoil at zero incidence. The analogue signal was amplified, high-pass (cut-off frequency $30\,\text{Hz}$) and sampled at a frequency of $40\,\text{kHz}$. Due to the flat response of the microphone, a B&K 4228 piston phone was used for calibration at a single frequency.

Measurements were performed over a large range of angles of attack ($\alpha = 0^\circ - 8^\circ \pm 0.15^\circ$) and velocities between $5 - 35\,\text{m/s}$, resulting in Reynolds numbers based on the chord and free stream velocity between about $Re = 33,000$ and $233,000$. The increments in free stream velocity between
Figure 1: Power spectral density of acoustic pressure for $\alpha = 1^\circ$ (a), $2^\circ$ (b), and $4^\circ$ (c). Clean aerofoil.

the measurements were approximately $0.35m/s$. At each measurement point (combination of angle of attack and velocity) data was acquired over a measurement period of $30s$. Between two measurement points a period of $15s$ was allowed for adaptation of the airflow.

Spectral analysis is performed based on the modified periodogram method of [10] with segments of $16,384$ samples, windowed using a Hamming window, and an overlap of $50\%$. The procedure results in a frequency resolution of $2.44Hz$ for an average over $145$ segments.

For acoustic excitation a speaker facing upstream was positioned on the suction side of the aerofoil, outside the open jet and approximately $25mm$ downstream of the trailing edge.

2.2 Particle image velocimetry

PIV measurements were performed on the same aerofoil model in a low speed open jet facility at Delft University of Technology (test section $0.4 \times 0.4m^2$). Due to the amount of data produced in PIV experiments, the parameter space was limited to three angles of attack ($0^\circ, 2^\circ, \text{and } 4^\circ$) and five free stream velocities ($16 - 32m/s$).

A measurement system consisting of a Litron Nd:YLF laser (dual cavity) and a Photron Fastcam SA 1.1 ($20\mu m$ pixel pitch, $5.4kHz$ at $1024 \times 1024px^2$) equipped with Nikon Micro-Nikkor $200mm$ lens was used. The field of view entailed an area of $32mm \times 16mm$ around the trailing edge, resulting in a resolution of $0.5mm$. The light sheet was positioned in the mid span plane, illuminating the field of view from the side. Due to the transparency of the acrylic glass, particles on both sides could be imaged. The acquisition frequency was $6kHz$. A more detailed description of the experiment can be found in [11].

3. Isolated aerofoil noise

In general, over a large range of Reynolds numbers and angles of attack the acoustic spectrum of the NACA 0012 shows tonal noise (Fig. 1). At low Reynolds numbers a single tone is present, most prominently at low angle of attack (Fig. 1a), as reported for a numerical study in similar conditions by [3]. With increasing Reynolds number and angle of attack multiple tones appear in the spectrum; a condition which has been described often in literature [7, 2, 12, 4]. At high Reynolds numbers again a single tone tends to dominate the spectrum, albeit a strong upper harmonic and several weaker tones at lower frequencies are present. In all cases the frequency of the discrete tones increases with velocity, which will be discussed later.

Forcing transition on pressure and suction side, alternatively, reveals the contribution of events on each side to overall noise generation. Fig. 2 shows the power spectral density of acoustic pressure for the case of $\alpha = 2^\circ$ and should be compared to the clean case in Fig. 1b). For forced transition
on the pressure side (Fig. 2a), multiple tones are present at 10 m/s and above. In particular the comparatively symmetric arrangement of side peaks with respect to the dominating tone below 25 m/s should be noted, which closely resembles the spectrum observed for the clean aerofoil, and has been related previously to a periodic amplitude modulation of the signal [2, 11]. Forcing transition on the suction side (Fig. 2b) shows a strong, dominating tone and a set of weaker tones at lower frequencies, reminiscent of the clean case above 25 m/s. The absence of any tones above 10 m/s for the case where tripping devices are applied on both sides of the aerofoil (Fig. 2c) confirms that transition occurs sufficiently far upstream to allow for turbulent breakdown upstream of the trailing edge.

The frequency of the dominating tone $f_{\text{max}}$ (Fig. 3) confirms this behaviour. The dominating tone is defined by the maximum power spectral density above 25 dB. Additionally the slope corresponding to the scaling of the discrete tones with $u^{0.8}$ and the mean trend of the dominating tone scaling with $u^{1.5}$ [1] is indicated. Overall, the agreement with these trends is good, in particular the slope of the discrete tones matches well. The right column of Fig. 3 shows the dominant tone frequency relative to the approximation (Eq. 1) against Reynolds number. In general, at low Reynolds numbers this frequency coincides with the that observed when the pressure side is tripped, thus relating noise generation to events on the suction side of the aerofoil. This is contrasted by the situation at high Reynolds numbers where the dominant tone frequency shows to be related to pressure side events. In particular, towards high Reynolds numbers the tripped cases show different slopes and diverging trends. For the clean case a very good agreement with the case of forced transition on the suction side is observed, which underlines the dominance of pressure side events at high Reynolds numbers. Furthermore, it should be noted that the dominant tones at higher Reynolds numbers can be interpreted as and upper harmonic showing frequency doubling. The transition between the harmonics occurs at an intermediate Reynolds number that decreases with increasing angle of attack. Overall, it appears that the transition Reynolds number range between the two regimes, where the dominant tone frequency does not match that of the clean case, becomes broader with increasing angle of attack.

Fig. 4 shows the power spectral density of the dominating tones identified in Fig. 3. The striking agreement between the results for the clean and pressure / suction side tripped case at low / high Reynolds numbers, respectively, confirms that events on a single side of the aerofoil are dominating the noise generation in the respective regimes. The Reynolds number at which noise related to the pressure side supersedes that related to the suction side is close to the values that can be identified in Fig. 3. In summary, it is possible to identify a regime at low Reynolds numbers dominated by suction side events, and one at high Reynolds numbers dominated by pressure side events. Furthermore, the data shows evidence of an intermediate regime, where the dominating tone frequency shows differences with respect to the tripped cases.
Figure 3: Dominating tone frequency $f_{n_{\text{max}}}$ against free stream velocity (left column) and dominating tone frequency relative to $f_s$ defined in Eq. 1 (right column) for $\alpha = 1^\circ$ (a,b), $2^\circ$ (c,d), and $4^\circ$ (e,f). Solid line indicates approximation of dominant tone frequency (Eq. 1) by [1].
To understand this behaviour, the relation between acoustic emissions and flow structure has to be considered. For the case of a sharp trailing edge and under the assumption of frozen turbulence in its vicinity, [13] and more recently [14] give an expression for the relation between the power spectrum of the acoustic pressure in the far field and the statistics of the unsteady surface pressure field. Under the given assumptions the relevant parameters related to the flow field are the spectral density of the surface pressure, induced by vortices in the boundary layer, and its spanwise coherence length. An increase in any of these quantities will lead to an increase in noise level at a given frequency.

The coherent vortex core of convecting instability waves (Fig. 5) before turbulent breakdown is reminiscent of two-dimensional vortical structures with relatively large spanwise extent. This implies an increase in the coherence length of flow field quantities, and in particular of the unsteady surface pressure, at the passing frequency of these vortices.

The relation between the presence of different regimes of tonal noise generation can now be understood when considering the changes with Reynolds number and angle of attack. For a given Reynolds number, separation on the suction side tends to occur further upstream on the suction side with increasing angle of attack due to a less favourable pressure gradient. For the pressure side the opposite holds true and the separation point moves downstream. In turn, for a given angle of attack the separation and transition point tends to move upstream on both sides with increasing Reynolds number. Therefore, at low Reynolds numbers (Fig. 5a) transition on the pressure side occurs late, while roll-up on the suction side occurs upstream, causing coherent vortices to pass the trailing edge. Increasing the Reynolds number (Fig. 5b) the transition points move upstream, leading to a roll-up and coherent vortical structures on the pressure side and initial stages of turbulent breakdown on the suction side. This behaviour causes a shift of the contribution to overall noise generation from events on the suction side towards the pressure side. Increasing the Reynolds number (Fig. 5c) even further amplifies this effect and the boundary layer on the suction side reaches a turbulent state before reaching the trailing edge. Therefore, the strong tonal noise emission is dominated by pressure side
Figure 6: Effect of acoustic excitation. Power spectral density of acoustic pressure. Pressure side tripped, $\alpha = 2^\circ$.

events in this regime, as corroborated by [1]. With increasing angle of attack the difference in pressure gradient between the two sides becomes larger and pressure side instabilities start to dominate only at higher Reynolds numbers (see Fig. 4).

It is known that strong acoustic waves can have an influence on the transition process over aerofoils. Therefore, acoustic feedback loops have been suggested as a frequency selection mechanism for multiple tones in the acoustics spectrum [6]. In the present experiment a speaker has been placed downstream of the aerofoil, outside the airflow and pointing upstream. Measurements are performed for the clean configuration without and consecutively with a coustic excitation at the frequency of the dominant tone. In a number of cases this excitation causes discrete tones to decrease in intensity 6, showing that acoustic feedback might indeed be a possible explanation for the particular structure of the acoustic spectrum.

4. Conclusion

The present study shows that noise emission of an isolated aerofoil with a given profile is highly dependent on both Reynolds number and angle of attack.

In particular for the NACA 0012 profile it is shown that laminar boundary layer instabilities on the suction side prevail in the noise generation at lower Reynolds numbers, while instabilities on the pressure side are the dominant contributor at higher Reynolds numbers. The dividing Reynolds number for the two regimes increases with increasing angle of attack, which can be attributed to the more favourable pressure gradient on the pressure side and thus later transition compared to the suction side.

Furthermore, results show that the side peaks of the dominating tone frequency can be attenuated by acoustic excitation at the dominant tone frequency, supporting the hypothesis of an acoustic feedback loop as frequency selection mechanism.

The authors would like to thank Dr. S. C. Morris and Y. Guan for the support provided with the acoustic measurements in the Anechoic Wind Tunnel at the University of Notre Dame.
REFERENCES


