Empirical study of the tonal noise radiated by a sharp-edged flat plate at low-to-moderate Reynolds number

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ABSTRACT

Airfoils operating at low-to-moderate Reynolds number may produce noise that contains one or more high amplitude tonal components. Many previous researchers have attributed airfoil tonal noise to a feedback loop between instabilities in the laminar boundary layer and the acoustic waves produced at the trailing edge. There is, however, limited experimental evidence to verify this proposed hypothesis. This paper presents results of an empirical study on the tonal noise produced by a sharp-edged flat plate at low-to-moderate Reynolds number ($0.7 \times 10^5 \leq Re_c \leq 2.3 \times 10^5$, based on chord). Simultaneous measurements of the far-field noise and flow about the plate's trailing edge have been acquired in an anechoic wind tunnel at the University of Adelaide. An empirical formula is derived to estimate the tonal frequencies produced by flow past the flat plate. A feedback model based on that developed by Tam (1974) is applied to the experimental data to demonstrate that the characteristics of the flat plate tonal noise and flow fields do not support an aeroacoustic feedback mechanism. The vortex shedding model developed by Moreau et al. (2011) is reviewed to show that in this particular case, the tonal noise appears to be governed by vortex shedding processes at the trailing edge.

INTRODUCTION

Tonal noise is produced by airfoils operating at low-to-moderate Reynolds number ($Re_c < 5 \times 10^5$, based on chord) and low angles of attack. It is commonly created by micro-wind turbines, fans, unmanned aircraft and underwater vehicles. Given its practical importance, airfoil tonal noise at low-to-moderate Reynolds number has been a subject of much interest over the years with past research focusing on understanding the tonal noise generation mechanism (Paterson et al., 1973; Tam, 1974; Arbey and Bataille, 1983).

Aerodynamic tonal noise is traditionally associated with vortex shedding. In the first experimental study dedicated to airfoil tonal noise at low-to-moderate Reynolds number, Paterson et al. (1973) considered the tonal noise emitted by NACA 0012 and NACA 0018 airfoils to be the consequence of vortex shedding from the trailing edge. Tam (1974) analysed the measurements of Paterson et al. (1973) and disagreed with this hypothesis arguing that being streamlined, an airfoil does not approximate a bluff body, with which vortex shedding is normally associated. Tam (1974) instead proposed that airfoil tonal noise is produced by an aeroacoustic feedback loop between laminar boundary layer instabilities (known as Tollmien-Schlichting or T-S waves) that originate at the sharp trailing edge and a point in the wake which acts as the acoustic source. Wright (1976), Longhouse (1977), Fink (1978) and Arbey and Bataille (1983) later modified the feedback mechanism proposed by Tam (1974) to suggest that the airfoil tonal noise is produced by an aeroacoustic feedback loop between aerodynamic instabilities in the laminar boundary layer and the acoustic waves produced as these instabilities convect past the trailing edge. Nash et al. (1999) and Mc Alpine et al. (1999) examined the acoustic and flow fields of a NACA 0012 airfoil and suggested that the feedback process is not a necessary condition for the generation of acoustic tones. They proposed that airfoil tonal noise is generated by the trailing edge diffraction of boundary layer T-S waves that are strongly amplified by the inflectional mean velocity profile in the separated shear layer at the trailing edge. Recently, Jones et al. (2010) identified a feedback mechanism that involves the generation of boundary layer disturbances at the leading edge through acoustic excitation from the trailing edge. This feedback loop was shown to exist only in certain flow conditions (Jones and Sandberg, 2010).

While Kingan and Pearse (2009) have created a theoretical laminar boundary layer instability noise model that combines the work of Arbey and Bataille (1983) and Nash et al. (1999), there is no general consensus on the tonal noise generation mechanism amongst researchers in the field. Moreover, no experimental studies have confirmed any of the mechanisms proposed in the past. The present paper thus presents an experimental investigation of the flow and noise produced by a flat plate at low-to-moderate Reynolds number ($0.7 \times 10^5 \leq Re_c \leq 2.3 \times 10^5$) in an effort to aid understanding of the tonal noise mechanism. The aims of this paper are (1) to present aeroacoustic test data for a sharp-edged flat plate that produces tonal noise at low-to-moderate Reynolds number; (2) to show that the flat plate experimental data do not support an aeroacoustic feedback mechanism and (3) to review the vortex shedding model developed by Moreau et al. (2011), which suggests the flat plate tonal noise is governed by vortex shedding processes at the trailing edge.

EXPERIMENTAL METHOD

Testing was conducted in the anechoic wind tunnel at the University of Adelaide. The anechoic wind tunnel test chamber is 1.4 m × 1.4 m × 1.6 m (internal dimensions) and has walls that are acoustically treated with foam wedges to provide a reflection-free environment (ideally) above 200 Hz. The facility contains a rectangular contraction with a height of 75 mm and a width of 275 mm. The maximum flow velocity of the free jet is 40 m/s and the free-stream turbulence intensity is low at 0.3% (Moreau et al., 2010a).

The flat plate model used in this study has a chord of 200 mm, a span of 450 mm and a thickness of 5 mm. The flat plate leading edge is elliptical with a semi-major axis of 8 mm and a semi-minor axis of 2.5 mm while the trailing edge is asymmetrically beveled at an angle of 12° as shown in Fig. 1. The flat plate was held between two side plates attached to the contraction flange at zero angle of attack, as shown in Fig. 2. The span of the flat plate models extends beyond the width of the contraction to eliminate the noise produced by the interaction of the side plate boundary layers with the model leading edge. As shown in Fig. 2, two extension plates made from 75 × 75 mm steel equal angle were attached to the contraction flange and aligned with the top and bottom edges of the contraction outlet. These extension plates extend the contraction past the leading edge of the plate, reducing the distance between the plane of the contraction outlet and the trailing edge. These extension plates were added to minimise the interaction of the outlet shear layer with the plate trailing edge region.

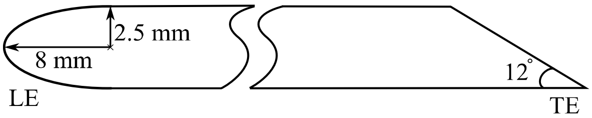


Figure 1. Schematic diagram of the flat plate.

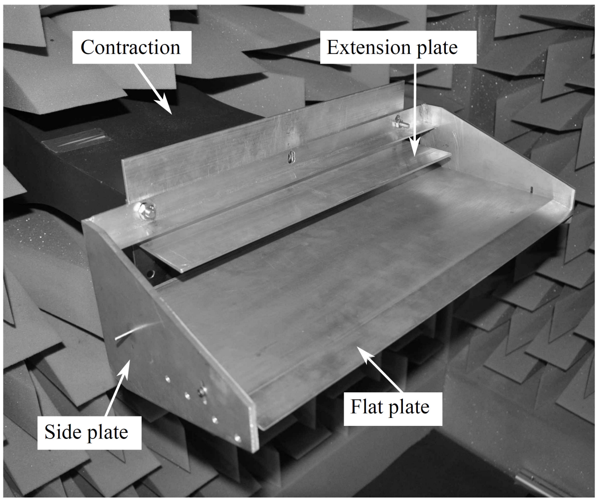


Figure 2. The flat plate attached to the contraction outlet.

The acoustic measurements were recorded using two B&K 1/2" microphones (Model No. 4190): one 585 mm directly above and one 585 mm directly below the trailing edge. The method for extracting and analysing trailing edge noise developed by Moreau et al. (2010b) was used to process the far-field noise measurements. Extraneous noise sources were removed from the far-field noise measurements using the two phase-matched microphones located above and below the trailing edge. As the two microphones measure the trailing edge noise to be equal in magnitude, highly correlated and 180° out of phase, subtracting the out-of-phase signals isolates the trailing edge noise in the far-field noise measurements. An offset value of 6 dB also needed to be removed from the resulting trailing edge noise spectra when using this method (to correct for the summation).

Hot-wire anemometry was used to measure both unsteady velocity data in the streamwise direction, and the boundary layer profile at the trailing edge. A TSI 1210-T1.5 single wire probe with a wire length of 1.27 mm and a wire diameter of 3.81 μm was used. The probe was positioned using a Dantec automatic traverse which allowed continuous movement in the streamwise (x) and vertical (y) directions. The origin of the co-ordinate system is located at the centre of the trailing edge. Both the far-field noise measurements and the velocity data were collected using a National Instruments board at a sampling frequency of 2^{15} Hz for a sample time of 8 s.

EXPERIMENTAL RESULTS AND DISCUSSION

Characteristic features of the acoustic and flow fields

According to previous research (Hersh and Hayden 1971, Paterson et al., 1973, Tam, 1974, Arbey and Bataille, 1983), airfoil tonal noise at low-to-moderate Reynolds number is characterised by the following acoustic and flow field features:

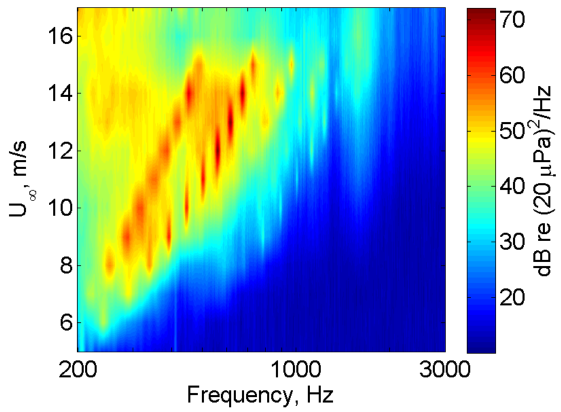
I. The frequencies of the tones increase with an increase in flow velocity and display a ladder-type structure.
II. The sound pressure level of the tones increases with an increase in flow velocity at low flow speeds before becoming saturated at moderate flow velocity. The tones then decrease in amplitude with a further increase in flow speed before becoming undetectable.
III. The boundary layer on at least one surface of the airfoil (usually the pressure surface) is laminar at the trailing edge.

A 2D surface plot of the far-field acoustic spectra for the flat plate at free-stream velocities between U_∞ = 5 and 17 m/s ($0.7 \times 10^5 \leq Re_c \leq 2.3 \times 10^5$) is shown in Fig. 3 (a). This figure shows that the flat plate radiates high amplitude tones at speeds between U_∞ = 5 and 15 m/s. The frequencies of the tones are observed to increase with an increase in flow velocity and display a clear ladder-type frequency structure consistent with feature (I).

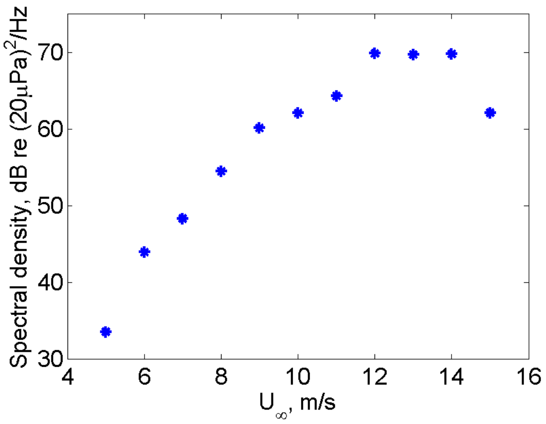
Figure 3 (b) shows the amplitude of the peak tonal component as a function of free-stream velocity. At very low flow speeds, the amplitude of the peak tone increases with an increase in flow velocity. The intensity of the peak tone reaches a maximum at U_∞ = 12 m/s, before decreasing with a further increase in flow speed and becoming undetectable at U_∞ = 16 m/s. The peak tone therefore displays amplitude saturation consistent with feature (II).

The mean velocity profile (U/U_∞) measured in the very near wake (0.7 mm downstream of the trailing edge) at U_∞ = 15 m/s is given in Fig. 3 (c). In this figure, the mean velocity profile is compared with the theoretical Blasius profile for laminar flow on a flat plate. The mean velocity profile is asymmetric about the trailing edge and shows that the flow is much more developed on the top beveled surface than on the lower flat surface. The profile below the trailing edge has a Blasius velocity profile indicating that the flow is laminar through the boundary layer on the lower flat surface of the plate consistent with feature (III). While the mean velocity profile is shown here for U_∞ = 15 m/s only, the plate was found to have a laminar boundary layer on the lower flat surface and a more developed boundary layer on the top beveled surface at all flow speeds between 5 and 17 m/s. It is worth noting that flow separation is expected to occur on the top bevelled surface of the plate in which case a small portion of the mean velocity profile in the separated region above the trailing edge may not be valid.

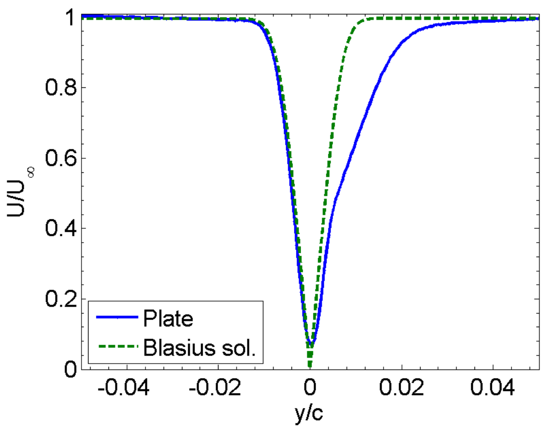
The fact that the flat plate acoustic and flow fields display the characteristic features associated with the production of tonal noise identified in previous literature indicates that the tonal noise mechanism studied here is the same as that investigated by others (Hersh and Hayden 1971; Paterson et al., 1973; Tam, 1974; Arbey and Bataille, 1983).



(a) 2D surface plot of the far-field acoustic spectra at U_∞ = 5 - 17 m/s.



(b) Amplitude of the peak tonal component.

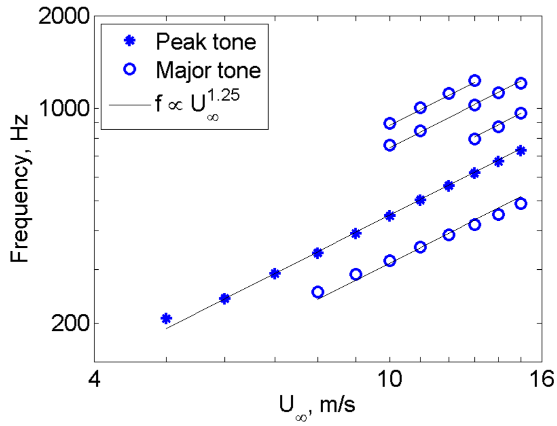


(c) Mean velocity profile compared to the Blasius solution at U_∞ = 15 m/s. Positive and negative y values indicate a position above and below the trailing edge respectively.

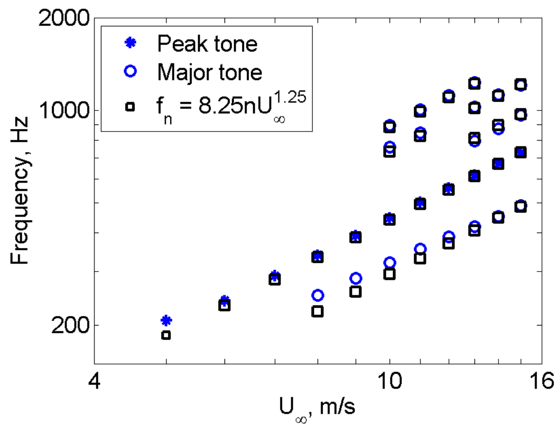
Figure 3. Characteristic features of the flat plate acoustic and flow fields associated with the production of tonal noise.

Tonal frequency scaling laws

Figure 4 (a) shows the frequencies of the dominant tones radiated by the flat plate as a function of free-stream velocity. In this figure, a major tone refers to a peak that is at least 10 dB above the surrounding broadband noise level but is lower in amplitude than the peak tone. Paterson et al. (1973) observed that the frequencies of the tones radiated by NACA 0012 and NACA 0018 airfoils increased according to $U_\infty^{0.8}$ for small increases in flow speed and that the power law of $U_\infty^{1.5}$ described the average frequency behaviour of the tones. These scaling laws derived by Paterson et al. (1973) for an airfoil do not describe the ladder structure of the flat plate tonal noise frequencies. Instead, the frequencies of the flat plate tones were found to scale with free-stream velocity according to $U_\infty^{1.25}$, as shown in Fig. 4 (a). The discrepancy in the frequency scaling laws is attributed to significant differences in the geometry of the airfoils used by Paterson et al. (1973) and the flat plate studied here.



(a) Tonal frequencies scaled with free-stream velocity according to $U_\infty^{1.25}$.



(b) Tonal frequency relationship compared to predictions with the empirical model in Eq. (1).

Figure 4. Flat plate tonal noise frequency scaling and empirical prediction.

An empirical model is now proposed to approximate the frequencies of the discrete tones produced by the flat plate. The tonal frequencies, f_n, can be be calculated from free-stream velocity according to

$$f_n = 8.25 n U_\infty^{1.25}, \quad (1)$$

where n is an integer. This empirical formula describes the ladder like structure of the tonal noise frequencies in Fig. 4 (a), with each rung of the ladder given by various integer values of n from 2 to 6. The peak tonal frequency can be calculated from Eq. (1) by setting $n = 3$.

Estimates of the tonal noise frequencies calculated using Eq. (1) are plotted against the actual tonal frequencies of the flat plate in Fig. 4 (b). While there is a slight difference between the predicted and actual frequencies on the lowest rung of the frequency ladder at low flow speeds, this formula can be used to predict the flat plate tonal noise frequencies.

Application of a feedback model to flat plate tonal noise

Tam (1974) has derived equations that describe the total phase change around the aeroacoustic feedback loop. Analysis similar to that of Tam (1974) can now be used to determine whether an aeroacoustic feedback loop is responsible for the flat plate tonal noise.

Let L be the distance between the origin of aerodynamic disturbances in the laminar boundary layer, referred to as point A, and the location of the acoustic source, referred to as point B. The total phase change in going from point A to point B and back along the feedback loop must be equal to an integral multiple of 2π according to

$$2\pi n = \theta_s + \theta_v, \quad (2)$$

where n =1, 2, 3… and θ_s and θ_v are the phase contributions due to the acoustic and flow disturbances, respectively. These phase contributions are defined as

$$\theta_s = \frac{2\pi f L}{c_0} \text{ and} \quad (3)$$

$$\theta_v = \frac{2\pi f L}{c_v}, \quad (4)$$

where c_0 is the speed of sound, c_v is the convective velocity of the aerodynamic disturbance and f is the associated frequency. Using Eqns. (2) – (4) the aeroacoustic feedback loop length, L, from point A to point B, is given by

$$L = \frac{n}{f\left(\frac{1}{c_0} + \frac{1}{c_v}\right)}. \quad (5)$$

This aeroacoustic feedback model was applied to simultaneous measurements of the far-field noise and flow about the plate trailing edge at the selected free-stream velocity of U_∞ = 15 m/s. The far-field acoustic spectrum for the flat plate at U_∞ = 15 m/s is shown in Fig. 5 along with the background noise spectrum measured with the top trailing edge microphone. In this figure, the difference between two consecutive tonal frequencies is $\Delta f \approx$ 244Hz. The tones observed in the far-field noise spectra are the 2nd - 5th harmonics: f_2 = 480 Hz; f_3 = 729 Hz; f_4 =960 Hz and f_5 = 1212 Hz, of the fundamental with frequency f_1 = 244 Hz. While the fundamental tone, f_1, is not observed in the far-field noise spectra, it is detected in the wake velocity spectra as discussed later in the paper.

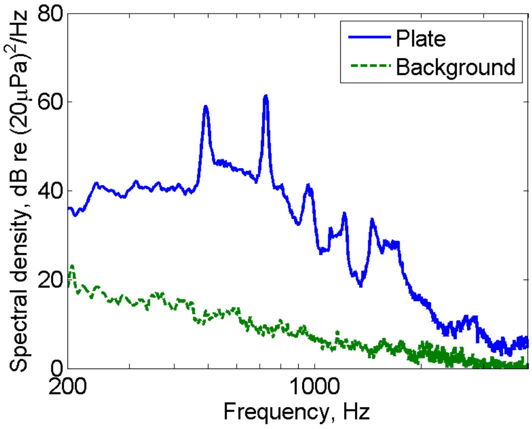
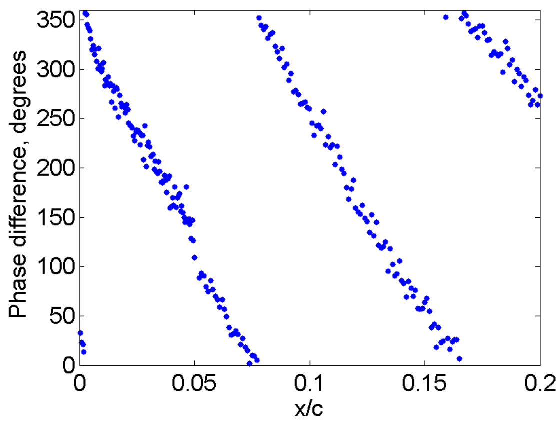
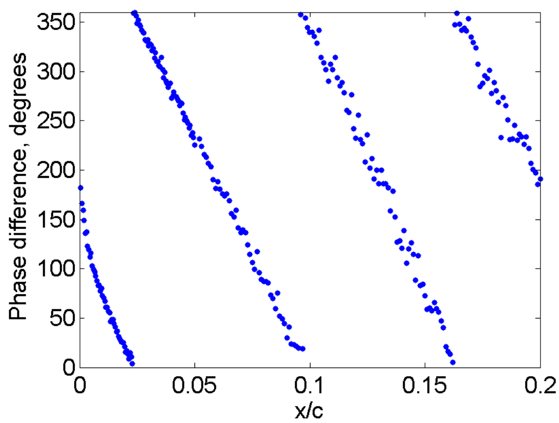


Figure 5. Far-field acoustic spectra at U_∞ = 15 m/s compared to background noise spectra.



(a) f_2 = 480 Hz.



(b) f_3 = 729 Hz.

Figure 6. Phase difference between the fluctuating velocity measured in the streamwise direction at y/c = -0.0035 downstream of the trailing edge and the far-field acoustic pressure signal for U_∞ = 15 m/s.

Figure 6 shows the phase difference between the fluctuating velocity measured in the streamwise direction in the wake of the flat plate and the far-field acoustic noise at f_2 and f_3 when U_∞ = 15 m/s. The phase measurements at tonal frequencies f_4

and f_5 follow the same trend as those for f_2 and f_3 in Fig. 6 but are not shown for brevity. The phase difference between the fluctuating velocity and far-field acoustic signals at f_2 and f_3 in Fig. 6 varies linearly indicating the development of strong aerodynamic fluctuations in the wake. The convective velocity, c_v, of aerodynamic disturbances at tonal noise frequencies f_2 and f_3 can be calculated from the phase information in Fig. 6 according to

$$c_v = \frac{1}{m} 2\pi f, \qquad (6)$$

where m is the gradient of the data shown in Fig. 6, given by $m = \Delta\theta_d / \Delta x$ where θ_d is the phase difference in radians and x is the probe position. Using Eq. (6) and the gradient of the data in Fig. 6 close to the trailing edge, flow disturbances at f_2 have a convective velocity of c_v = 6.6 m/s while at f_3, flow disturbances have a convective velocity of c_v = 7.1 m/s.

According to Eq. (5), the aeroacoustic feedback loop length, L, for tonal frequency f_2, where n = 2, is 27 mm (L/c = 0.135). At tonal frequency f_3, where n = 3, the aeroacoustic feedback loop length, L, is 28.6 mm (L/c = 0.143).

Figure 7 shows a 2D map of the power spectral density of the fluctuating velocity u' ($(\mathrm{m/s})^2$/Hz) measured in the streamwise direction in the laminar boundary layer below the plate surface and in the wake at y/c = -0.0035 when U_∞ = 15 m/s. High intensity velocity fluctuations are visible at the far-field tonal noise frequencies, f_2 - f_5, both upstream and downstream of the trailing edge. In the wake, an additional high energy peak is observed at the fundamental frequency of f_1 = 244 Hz (see Fig. 7 (b)). This fundamental tone is not observed in either the flow field upstream of the trailing edge or in the far-field noise spectra.

In Fig. 7, high amplitude fluctuations at tonal noise frequencies f_2 and f_3 are observed to exist much further upstream and downstream of the trailing edge than a distance of L from it. There is no sudden increase in the amplitude of the fluctuations at f_2 or f_3 at a distance L upstream of the trailing edge as would be expected if acoustic waves produced at the trailing edge were coupling with aerodynamic fluctuations at this point. There is also no measured change to the fluctuations at f_2 or f_3 at a point L from the trailing edge in the wake. In addition, very low coherence (of approximately 0.3) was measured between the acoustic and velocity signals at f_2 and f_3 at a distance L both upstream and downstream of the trailing edge. This is compared to high coherence (of approximately 0.95) being measured between the acoustic and velocity signals at f_2 and f_3 close to the trailing edge. The experimental measurements therefore do not support a feedback loop between aerodynamic fluctuations in the laminar boundary layer and the acoustic waves produced at the trailing edge or at a point in the wake.

Flat plate tonal noise mechanism

The tonal noise production process of the flat plate is attributed to vortex shedding from the trailing edge. The steep angled geometry of the beveled trailing edge creates a sudden adverse pressure gradient, separation and vortex shedding in the wake. The high intensity aerodynamic fluctuations observed in the wake at the fundamental frequency, f_1, and at harmonics of the fundamental, f_2 - f_5, in Fig. 7 (b) are due to vortex shedding from the trailing edge. Aerodynamic fluctuations at vortex shedding harmonics are then diffracted by the sharp trailing edge producing strong tonal noise at frequencies f_2 - f_5 as shown in Fig. 5. The high amplitude fluctuations at f_2 - f_5 observed upstream of the trailing edge in Fig. 7 (a) are acoustic disturbances. This is evidenced by Fig. 8 which shows the change in phase between the fluctuating velocity measured in the streamwise direction upstream of the trailing edge and the far-field acoustic noise at frequencies f_2 and f_3 when U_∞ = 15 m/s. Again, the phase measurements at tonal frequencies f_4 and f_5 follow the same trend as those for f_2 and f_3 in Fig. 8 but are not shown for brevity. Upstream of the trailing edge, the phase difference between the fluctuating velocity and far-field acoustic signals in Fig. 8 is nearly constant indicating that the acoustic component of velocity is dominant there.

Further experimental evidence supporting this suggested flat plate tonal noise mechanism is given in a recent study by the authors (Moreau et al., 2011). It is important to note that the flat plate tonal noise mechanism is the subject of an ongoing study. At this stage, it is still unclear as to why tonal noise is produced at only harmonics of the vortex shedding frequency, f_2 - f_5, and not at the fundamental, f_1. This may be due to the fact that vortex shedding at the fundamental is not of sufficient strength to generate high amplitude tonal noise when aerodynamic fluctuations at this frequency are diffracted by the trailing edge. To determine exactly why the fundamental, f_1, is not observed in acoustic measurements, more detailed flow and noise data will be measured and numerical flow simulations to model the flow over the flat plate will be performed.

CONCLUSION

This paper has presented results of an experimental investigation on the tonal noise generation mechanism of a sharp-edged flat plate at low-to-moderate Reynolds number. An empirical formula has been derived to estimate the tonal frequencies produced by flow past the flat plate. A feedback model based on that developed by Tam (1974) has been applied to the experimental data to demonstrate that the characteristics of the flat plate tonal noise and flow fields do not support an aeroacoustic feedback mechanism between aerodynamic fluctuations in the laminar boundary layer and the acoustic waves produced at the trailing edge or at a point in the wake. In this case, the tonal noise produced by the flat plate is considered to be governed by vortex shedding at the sharp trailing edge. Velocity fluctuations at selected vortex shedding harmonics are diffracted by the trailing edge producing strong tonal noise.

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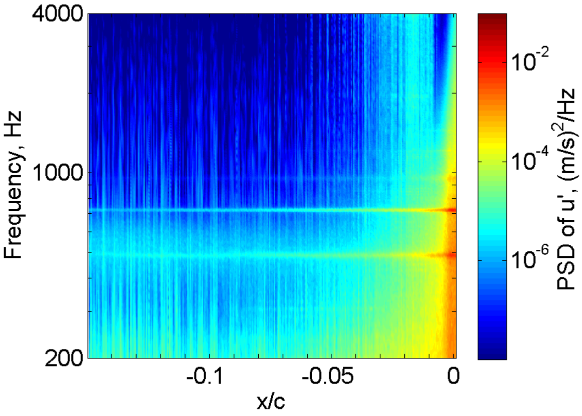
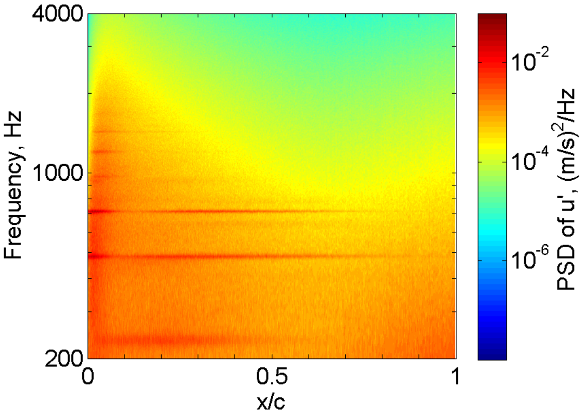
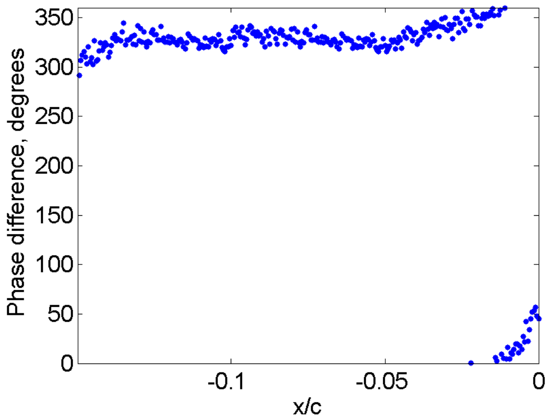


(a) Upstream of the trailing edge.

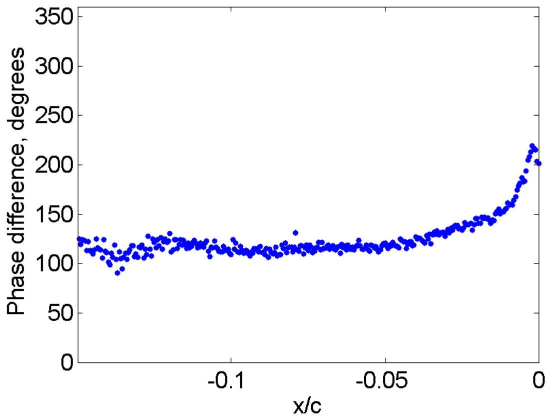


(b) Downstream of the trailing edge.

Figure 7. Color plot of the fluctuating velocity measured in the streamwise direction at y/c = -0.0035 for U_∞ = 15 m/s.



(a) f_2 = 480 Hz.



(b) f_3 = 729 Hz.

Figure 8. Phase difference between the fluctuating velocity measured in the streamwise direction at y/c = -0.0035 upstream of the trailing edge and the far-field acoustic pressure signal for U_∞ = 15 m/s.

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