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The Flow and Noise Generated by a Sharp Trailing Edge

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Abstract

Aeroacoustic results obtained from the study of the noise generated by turbulent flow over a trailing edge are presented. The test model used was a 5 mm flat plate with a sharp trailing edge. Models with and without side walls were studied and the results show the effects of the side wall boundary layer on far-field noise. The effect of trips and wind socks on the measured noise spectra are also presented. Mean and unsteady flow data in the very near trailing edge wake were measured and provides important information on the turbulent noise sources. Such information is needed for the future development and validation of predictive models.

Introduction

Lighthill [7] originally described how free turbulence is a source of noise, such as that produced by a jet. When turbulent flow passes a sharp trailing edge (as in the case of a boundary layer on an airfoil), acoustic diffraction occurs thus increasing the efficiency of noise production [4]. This type of flow induced noise is an important source of noise for aircraft, wind turbines and submarines and needs to be understood in greater detail in order to design new, quieter technology. In particular, new aeroacoustic prediction schemes are required. Most are either too computationally demanding [10, 11] or are semi-empirical in nature [1] hence are not valid for conditions used to derive them.

A new computationally efficient predictive methodology is currently under development at the University of Adelaide [2]. This scheme combines steady CFD solutions with a boundary layer velocity space-time correlation statistical model to calculate noise. Early results are promising and since the methodology is applicable to any airfoil or hydrofoil shape, it is useful for the designers of wind turbines and submarines. However, datasets providing both boundary layer velocity data and far-field noise simultaneously are rare but are needed to validate any new predictive model. This paper presents some initial results for the baseline case of a flat plate.

The aims of this paper are as follows: (1) to present aeroacoustic test data for a flat plate test model placed in uniform flow; (2) to illustrate the influence of extraneous noise sources on the test results and (3) to present the turbulent mean and unsteady flow information near the trailing edge.

Methodology

Anechoic Wind Tunnel

Testing was performed in the University of Adelaide anechoic wind tunnel (AWT). This facility provides a 275×75 mm free jet with a low turbulence (turbulence intensity 0.3% at the exit) potential core where test models can be placed. The free jet is placed in the centre of an $8\,\mathrm{m}^3$ acoustically treated room that is anechoic down to 200 Hz. Microphones are placed in the acoustic free field (clamped to the ceiling or a stand), well away from the flow in the jet (approximately 600 mm). Further details of the AWT can be found in the literature [3, 6, 8].

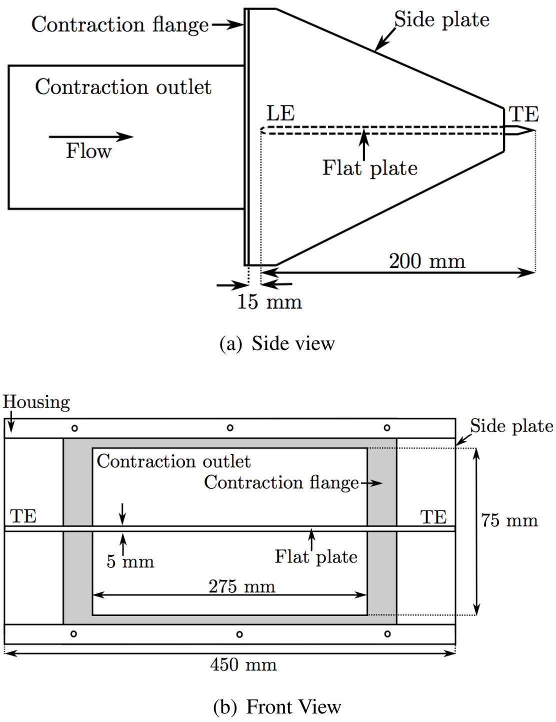


Figure 1: Test model without side walls.

Test Models

Two test models were used in this study, one with a span equal to the width of the contraction outlet ($b = 275$ mm) and another with a span $b = 450$ mm. The model with span $b = 275$ mm was held in place with two side walls that were exposed to the flow and consequently had turbulent boundary layers flowing over their surfaces. The longer span model was created to investigate the effect of the side walls on background noise by removing the side wall boundary layers. This model was held in place by a housing incorporating side plates, as illustrated in Fig. 1. Each test model has identical chord ($c = 200$ mm), thickness ($h = 5$ mm) and trailing edge geometry (apex angle approximately $12°$).

The models were tested with and without boundary layer trips. Two trips were used. The first was 0.12 mm thick and constructed of single sided tape. The second was much larger at 1.64 mm thick and was made by placing an additional layer of double sided tape on top of the first trip. Both trips were located 20 mm downstream of the leading edge.

Velocity Measurements

Unsteady velocity data were obtained 0.7 mm downstream of the trailing edge using hot-wire anemometry. A TSI 1210-T1.5 single wire probe was used in all tests. The probe has a $L = 1.27$ mm long sensor wire and a wire diameter of $d = 3.81\,\mu$m

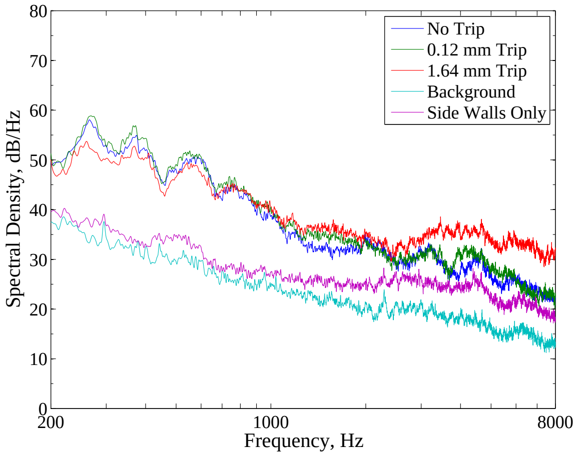


Figure 2: Single microphone noise measurement at $U_\infty = 38$ m/s using side walls and two boundary layer trips. No wind sock was used on the microphone. The microphone was located 565 mm directly above the mid-span of the trailing edge.

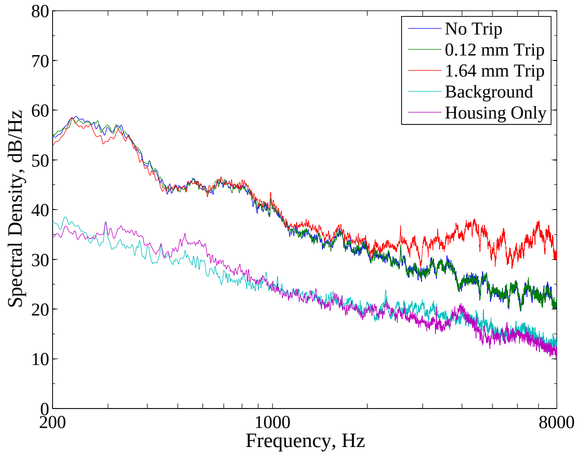


Figure 3: Single microphone noise measurements at $U_\infty =$ 38 m/s using no side walls and two boundary layer trips. No wind sock was used. The microphone was located 565 mm directly below the mid-span of the trailing edge.

corresponding to a length-to-diameter ratio of $L/d = 333$. The sensor was connected to a TSI IFA300 constant temperature anemometer system. The probe was positioned using a Dantec automatic traverse with 6.25 μm positional accuracy. Data were acquired over a vertical line spanning $y = \pm 30$ mm either side of the trailing edge.

Velocity data were sampled at a frequency of 2^{14} Hz over 12 s of sampling time. When converted to an autospectrum, the data record was divided into 96 data windows of 2048 samples each before the FFT procedure was applied with a resulting frequency resolution of 8 Hz.

Noise Measurements

Noise generated by the model with side walls was measured using a single microphone mounted 565 mm directly above the mid-span of the trailing edge. A 1/2 inch B&K Model 4190 microphone used for these measurements.

Two 1/2 inch microphones manufactured by BSWA Technology (Model MP 205) were used for the model without side walls: one above and one below the mid-span of the trailing edge. The top and bottom trailing edge microphones were located at the same radial distance from the trailing edge, perpendicular to the direction of the flow. Two radial distances were used, 565 and 558 mm from the trailing edge, as indicted in Figs. 3 and 4.

All microphones were calibrated before commencing the acoustic tests. The microphone data were collected using a National Instruments board at a sampling frequency of 50 kHz for a sample time of 16 s. The time domain data were bandpass filtered between 100 and 20 000 Hz. The noise data are presented in narrow band format with a frequency resolution of 1 Hz.

Results

Far-field Acoustic Data

Noise spectra generated by flow over the model with side walls are presented in Fig. 2. In this experiment, the free stream velocity was $U_\infty = 38$ m/s. No wind sock was used on the microphone. The background noise spectrum represents the noise generated by the free jet only. Significant additional noise was created by the side wall boundary layers, as seen in the noise spectrum (without test model) shown in Fig. 2. When the flat plate model was inserted into the test jet, higher noise levels were recorded, however amplitudes are barely above the side wall level at higher frequencies, thus contaminating the noise signal.

Noise data are also presented in Fig. 2 for the cases where boundary layer trips were placed on the model. The effect of the trips was to increase the amplitude of the noise generated at higher frequencies.

Figure 3 presents noise spectra for the model with no side walls at identical flow conditions to the case presented in Fig. 2. No wind sock was used in this test. The background noise level (free jet) and the noise of the housing (with side plates out of the flow) are very nearly identical, indicating the new housing has no influence on noise measurements.

Noise measurements for the model with and without trips show that the results for no trip and for the smaller trip have nearly identical spectra and it is not until the larger trip is used that additional higher frequency noise is introduced into the spectrum.

Comparing Figs. 2 and 3, the sidewalls introduce considerable background noise. The source of the noise is most likely due the additional acoustic diffraction at the trailing edges of the side walls along with the interaction of side wall boundary layer turbulence with the leading edge [1]. By removing the side walls, two sources of noise that can potentially corrupt trailing edge noise measurements are eliminated.

During operation of the AWT, air inside the anechoic room is disturbed and creates low velocity flow over the microphone positions. This small velocity creates some microphone self noise that can be eliminated by using microphone wind socks. Figure 4 presents acoustic results for the case of no side walls using microphones fitted with wind socks. In comparison with Fig. 3, no large differences were recorded, hence wind noise is not a significant issue in the AWT at these microphone measurement locations.

Figure 4 shows noise results for two microphones, each located directly above and below the mid-span of the trailing edge. Each microphone measures a nearly identical spectrum. Other measurements [8] show that the phase is 180° apart, which is predicted from trailing edge noise theory [5]. Further checks using cross correlation measurements with additional microphones [8] showed that the contribution from the leading edge

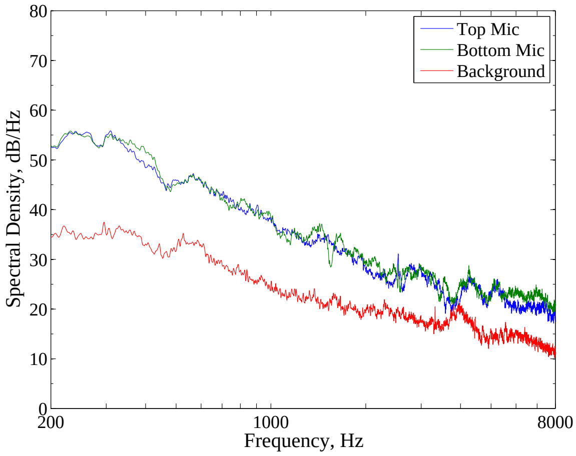


Figure 4: Noise measurements at $U_\infty = 38$ m/s using no side walls and no boundary layer trips. The microphones were located 558 mm directly above and below the mid-span of the trailing edge. Wind socks were used on each microphone. Background measurements were taken using the top microphone.

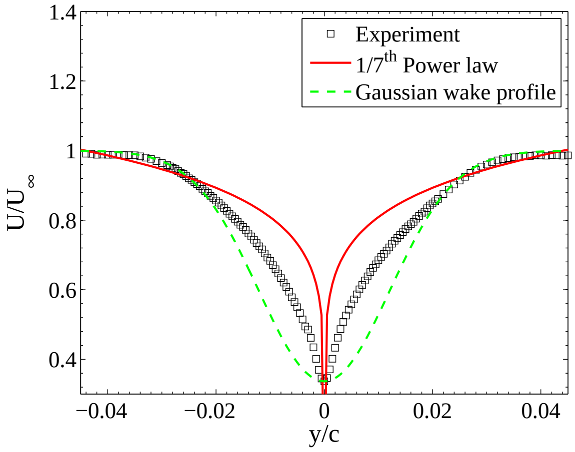


Figure 5: Mean velocity at the trailing edge.

was also negligible, confirming that trailing edge noise is the dominant acoustic source being measured.

Mean and RMS Velocity Data

The source of trailing edge noise is the turbulent flow field about the trailing edge. In order to understand these sources in better detail, a limited investigation of the turbulent flow was performed. Velocity measurements were performed using the model without side walls at a free stream velocity of $U_\infty = 34.8$ m/s. No trips were used on the model during these tests.

Figure 5 presents the mean velocity profile (U/U_∞) in the very near wake measured $x = 0.7$ mm downstream of the trailing edge. The velocity profile shows a minimum at $y/c = 0$. This minimum location was actually measured to be 0.8 mm below the edge location; however the data has been offset by this amount so that the minimum mean velocity is plotted at $y/c = 0$. The reason for this small offset is likely due to manufacturing errors resulting in unequal taper angles on each side of trailing edge as well as slightly different transition locations on each side of the plate.

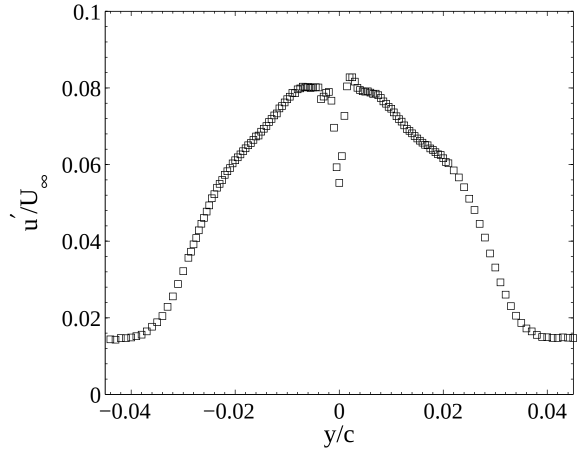


Figure 6: RMS velocity at the trailing edge.

Figure 5 also compares $1/7^{\text{th}}$ power law (representative of a turbulent boundary layer) and Gaussian (turbulent wake) profiles [9] with the experimental data. Despite the closeness of the measurement position to the trailing edge, the velocity profile is seen to be in a state somewhere between a boundary layer and a wake.

Figure 6 plots normalised rms velocity fluctuations (u'/U_∞) against normalised vertical distance (y/c). Turbulent energy is concentrated towards the centre before falling towards a minimum at $y/c = 0$. This is consistent with the mean flow data if the flow consists of a boundary layer re-organising itself into a turbulent wake. Some features of the boundary layer are still observed, such as a small inner maximum in u'/U_∞ that is known to occur in the inner layers of a boundary layer.

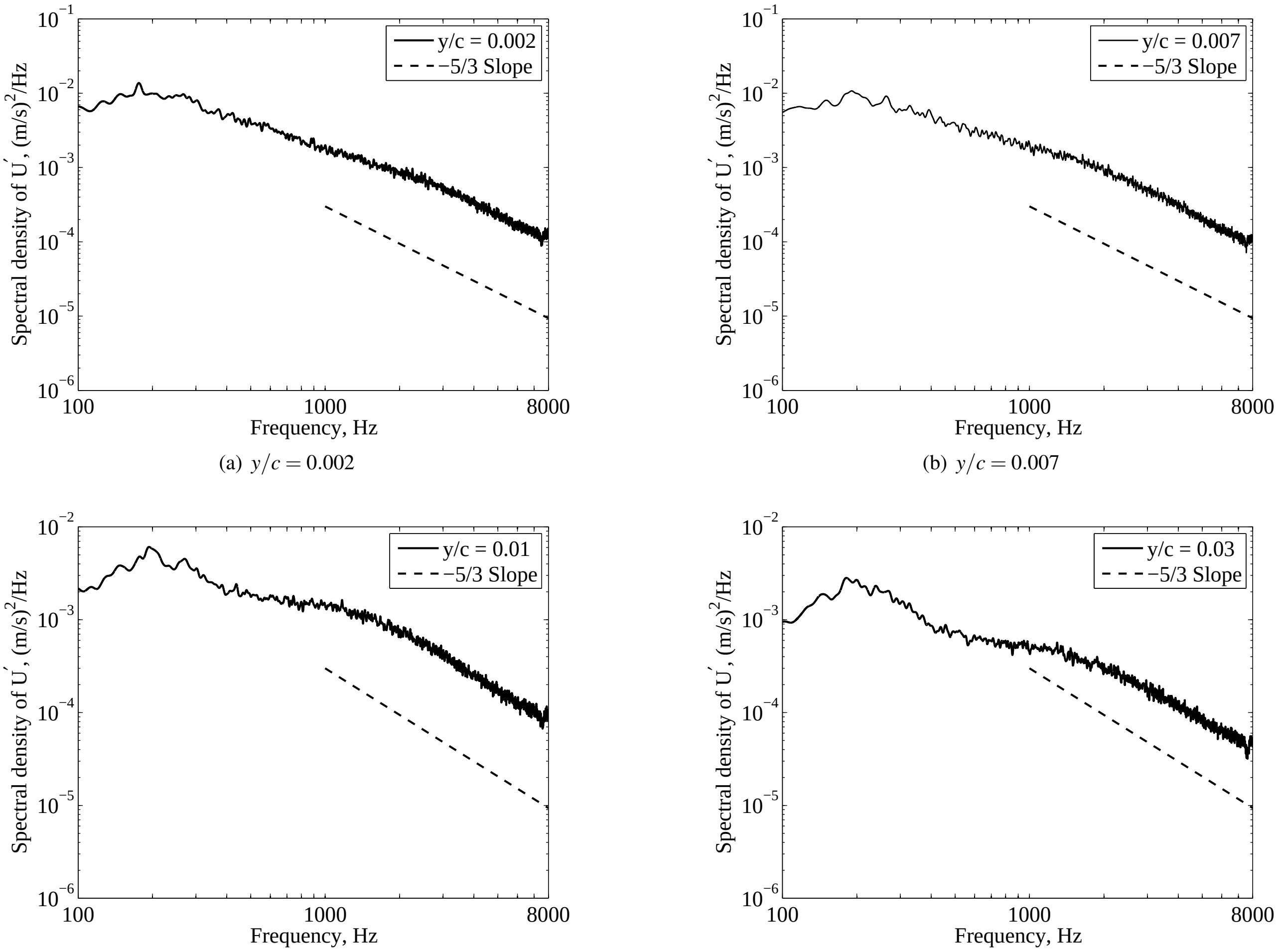
Velocity Spectra

Figure 7 shows measured velocity spectra at various y/c locations in the near wake. Each spectra has a well defined inertial sub-range at the higher frequencies, as shown by the -5/3 slope above 2000 Hz. Close to the trailing edge, the spectra are more energetic. As the measuring location moves away from the trailing edge, the form of the spectrum changes, with significant energy retained at the lower frequencies. While an estimate of the trailing edge noise created by turbulence with these spectra is impossible without two point measurements and an indication of the correlation length scale, the high energy at low frequencies must be a significant contributor to the noise source measured at low frequencies (Fig. 4).

Conclusions

The results of an investigation of the flow and noise generated by a sharp edged flat plate have been presented. The results include both mean and unsteady turbulence information near the trailing edge as well as far-field noise spectra. Thus elements of the complete chain of physical processes, from unsteady fluid dynamics to sound received at an observer, are available for the validation of new predictive models. Additional results are necessary, such as the measurement of two-point space-time correlation functions, and this is the subject of on-going work.

Also summarised are some of the issues involved in the measurement of far-field noise in an anechoic wind tunnel. Some extraneous noise sources were identified and suppressed. The effects of both small and large boundary layer trips on noise were also presented. It is hoped that this information will be useful for other researchers in the field.



(a) $y/c = 0.002$ (b) $y/c = 0.007$

(c) $y/c = 0.01$ (d) $y/c = 0.03$

Figure 7: Velocity spectra at various y/c locations.

Acknowledgements

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