RADIATED SOUND GENERATED BY AIRFOILS IN A SINGLE STREAM SHEAR LAYER

A Thesis

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Blessed be God. Blessed be His Holy Name.
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SYMBOLS

\[ C \quad \text{Model Chord} \]
\[ \mathcal{F}(\omega) \quad \text{Gust Response Function} \]
\[ Se \quad \text{Sears Function} \]
\[ h \quad \text{Model Thickness} \]
\[ k_1 \quad \text{Streamwise Wavenumber} \]
\[ L_3 \quad \text{Model Span} \]
\[ M_L \quad \text{Approach (local) Mach Number} \]
\[ q_L \quad \text{Approach (local) Dynamic Pressure} \]
\[ r \quad \text{Distance from Model to Listening Location} \]
\[ \Phi_{PP} \quad \text{Autospectral Density of Radiated Sound Pressure} \]
\[ U_L \quad \text{Approach (local) Streamwise Velocity} \]
\[ U_0 \quad \text{Tunnel Centerline (Freestream) Velocity} \]
\[ \overline{u_2^2} \quad \text{Variance of the Lateral Component of Velocity} \]
\[ y^* \quad \text{Nondimensional Lateral Coordinate With Respect to the Center of the Shear Layer, } y/\theta \]
\[ X_b \quad \text{Streamwise Beamforming Direction} \]
\[ Y_b \quad \text{Spanwise Beamforming Direction} \]
\[ \delta \quad \text{Shear Layer Thickness} \]
\[ \theta \quad \text{Shear Layer Momentum Thickness} \]
Λ Integral Length Scale of Turbulence
Λ_\textsubscript{j}(\omega)|_i Correlation Length Scale of the \textsubscript{i}th Component of Velocity in the \textsubscript{x}_j Direction
\rho Fluid Density
Φ_{LL} Autospectral Density of Unsteady Lift
Φ_{v(y_1)v(y_2)} Two-point Cross Spectral Density of the Upwash Component of Velocity
φ_{22} Autospectral Density of Lateral Velocity Normalized by the Lateral Variance
ω Angular Frequency
CHAPTER 1

INTRODUCTION

Sound generated by the interaction of airfoil surfaces with unsteady flows is an important problem in aeroacoustics. The mechanism for sound production is the unsteady lift that is generated when the airfoil is subjected to an unsteady angle of attack. The radiated sound from an airfoil subjected to grid turbulence has been studied by several authors [1][15][12], and the basic physics are well understood. However, there remain unaddressed issues that are of practical interest in predicting radiated sound for engineering applications.

The radiated sound from an airfoil will be sensitive to the true frequency characteristics of the turbulence interacting with the airfoil. The existing model for predicting the sound production from an airfoil assumes an approach flow that is isotropic at all frequencies. Whether this model is adequate for predicting the radiated sound from an airfoil when it is subjected to an approach flow that is anisotropic over a range of frequencies remains an open question. Further, the unsteady lift of an airfoil and therefore its sound production is ultimately determined by the gust response function that is specific to the cross-sectional shape of the airfoil. It remains to be shown to what extent is a prediction of radiated sound from an airfoil is sensitive to using a geometry-specific gust response function. The limitations of not using a geometry-specific gust response function must also be investigated.
This thesis presents experimental results that address the open questions raised in the preceding discussion. Three different airfoil geometries were placed in a single stream shear layer and their acoustic production was measured. A schematic of the present problem is shown as Figure 1.1.

![Figure 1.1. Problem Schematic](image)

The single stream shear layer approach flow was selected for its significant anisotropic effects at length scales that are the order of the shear layer thickness. This facet of the experiments allows an examination of the accuracy of the isotropic model in predicting sound from an airfoil interacting with turbulence that is anisotropic over a range of frequencies. Measuring the radiated sound from three different airfoil geometries permits an examination of the impact of selecting the appropriate gust response function when making radiated sound predictions.

This document first provides a thorough discussion of the experimental methods used to acquire turbulence and acoustic data as well as a detailed character-
ization of the single stream shear layer. Analysis of the measured acoustic data and how those data compare to radiated sound predictions will then be presented. Finally, the thesis will conclude a discussion of the implications of the findings.
CHAPTER 2

EXPERIMENTAL METHODOLOGY

The following outlines the facility utilized in this study as well as the relevant details on the experimental techniques employed to produce the results contained in this document.

2.1 Anechoic Wind Tunnel (AWT) Facility

The measurements described in this study were acquired in an Anechoic Wind Tunnel (AWT). The AWT is composed of an open jet style wind tunnel surrounded by an anechoic room rated to absorb 99% of incident acoustic waves above 100 Hz. Air was drawn in through a turbulence management section and into an 8:1 contraction. The exit of the contraction was 0.61 m by 0.61 m in cross-section and defines the beginning of the test section. The flow in the test section was constrained on the upper and lower sides by a pair of end plates which were constructed from acoustically absorbent materials. Two shear layers were formed by the flow exiting the inlet on the sides of the test section not constrained by the end plates. This created a two sided open jet test section that allowed for the propagation sound to the surrounding anechoic room. The exit of the test section is defined by the collector plate geometry. The flow then moved through an acoustically treated diffuser section and to the primary fan. Specifics regarding
The design and construction of the AWT facility can be found in Mueller et al. [13] and Scharpf [17]. A sketch of the facility is shown in Figure 2.1. It should be noted that the shear layer collectors as described in these references have been redesigned to reduce their acoustic signature.

Figure 2.1. Sketch of the AWT Facility.

The shear layers associated with the open jet of facility (see dashed lines in Figure 2.1) provided an inherently quiet means of generating turbulence. Most other means of turbulence generation also produce unwanted noise that would have contaminated the measurement of the airfoil noise. It should be noted that the flow exiting the contraction does not separate suddenly from a sharp edge (as shown in Figure 2.1) but instead separated from a curved surface with a radius of approximately 4.8 mm.
2.2 Airfoil Models

The acoustic signature of three airfoil models were measured. Two of the models were flat plate airfoils with 5:1 elliptical leading edges and sharp trailing edges with chord \( C = 0.1016 \) m. One flat plate airfoil had a thickness of \( h = 3.2 \) mm, the other had a thickness of \( h = 6.4 \) mm. The last airfoil model was a NACA 0015 with a chord \( C = 0.127 \) m and a maximum thickness \( h = 19.1 \) mm. The span of all models was 61 cm. The leading edge of the models were located 61 cm downstream of the contraction exit. Some vibration of the flat plate airfoil models was observed during the operation of the AWT. This was mostly due to a longitudinal (spanwise) structural mode of the airfoils. Measurements of the sound levels generated by the airfoil with and without an additional structural support wire which dampened the vibrations showed no change in the acoustic signature in the frequency range of interest. Therefore, it is assumed that the flat plate airfoil models’ vibration had little to no effect on the sound generated by the interaction of the shear layer turbulence with the models’ leading edges.

2.3 Phased Microphone Array Measurements

The sound generated in the test section was measured utilizing a phased array of 40 microphones which was positioned such that the normal vector originating from the center of the microphone array was centered on the leading edge of the model. The array plane was placed parallel to airfoil chord line (shown in Figure 2.1). Specifics on the design of the array can be found in Olson [14]. Acoustic sources are spatially located by ”steering” the array in post-processing to a selected ”look” location. These post-processing methods are typically called beamforming techniques. Three beamforming methods were used in this study:
delay-sum beamforming, weighted cross-spectral matrix (WCSM) beamforming, and DAMAS. In each of these methods, only the line source related to the airfoil leading edge noise was examined. Thus, the extraneous sources caused by the operation of the AWT were ignored. A general discussion of each of these methods is provided below. Specifics regarding the array calibration, array data processing, and the accuracy of the results generated by the array used in this study are described by Shannon [19].

2.3.1 Delay-sum Beamforming

According to Dougherty [7], delay-sum beamforming is likely the simplest form of time domain array processing. The appropriate time delay is added to each microphone signal such that the acoustic signal from a source at the interrogation location occurs at the same phase for each microphone in the array. The time delay for a given microphone is the acoustic travel time from the source location to the microphone. Each microphone’s time series is shifted by its respective time delay, aligning all microphone series such that the contributions from the source are in phase. All microphone signals are then averaged at each discrete time step to produce a composite array time series that is representative of the signal originating at the source. While simple, this beamforming method is not well-suited for measurement of a line source at all frequencies due to a few complications. First, any spatial aliasing effects are included in the composite array series. Also, resampling errors are induced by the phase shift of the individual microphone signals, especially at higher frequencies. Further, at higher frequencies, the spatial resolution of the array can be smaller than the source region (i.e. the leading edge span). This issue produces error because a portion of the sound originating
from the airfoil model will be rejected in the process to produce the composite array time series. Upon consideration of these limitations, delay-sum beamforming was utilized to measure sound between the frequencies of 100 Hz, the lower bound of the AWT facility’s acoustic absorption and 300 Hz, the lower bound of WCSM/DAMAS beamforming accuracy.  

2.3.2 Weighted Cross-Spectral Matrix (WCSM) Beamforming  

The weighted cross-spectral matrix beamforming method given by Dougherty [7] involves the weighting of the cross-spectral values between the array microphones via an assumed free-space Green’s function. For the results presented in this document, the autospectral components of the cross-spectral matrix have been omitted since these components do not provide any additional phase information about the sound field and can contain microphone self-noise components. The acoustic spectrum of a distributed source (i.e. leading edge noise) is computed by integrating the WCSM over an interrogation region enclosing the distributed source and dividing by the integral of the corresponding point spread functions. The effectiveness of the WCSM method is dependent on array size compared to the acoustic wavelengths being measured and the adequacy of spatial sampling. The effects of these two factors combine to define the range of frequencies for which the spatial resolution of the microphone array is reliable. The DAMAS method minimizes the error associated with these two factors.  

2.3.3 DAMAS  

The Deconvolution Approach to the Mapping of Acoustic Sources (DAMAS) given by Brooks [3] takes advantage of the fact that the weighted cross-spectral
matrix is the convolution of the true source field and the point spread function produced via the WCSM method. The DAMAS method deconvolves this relationship and outputs a map representing the true sound field. As in the WCSM method, acoustic spectra of distributed sources are produced by integrating over a defined integration region. However, in this case, a spectrum is produced only by integrating the quantity representing the true sound field. Proper definition of the integration region is important to accurately capturing the true acoustic spectrum. If the integration region is too large, the acoustic spectrum might include contributions from parasitic or uninteresting sources. If the integration region is too small, the spectrum might ignore a portion of the sound field of interest. For the present work, care was taken to define an integration region only containing the leading edge noise. A graphical example of the leading edge noise and the integration region (boxed) is shown in Figure 2.2.

![Figure 2.2. Deconvolved Beamforming Map and Integration Region](image_url)
The DAMAS algorithm utilized to produce the present work is due to Dougherty [8] and assumed uncorrelated sources. However, techniques have been developed that do not make this assumption [4].

2.4 X-wire Measurements

Velocity measurements in the shear layer were acquired using a pair of hot-wire probes, each consisting of two wires angled at 45-deg (x-wire probes) and a commercially available constant temperature anemometer (a six-channel AA-Labs AN-1003). The frequency response of the wires to a pulse were found to be greater than 50 kHz. The x-wires were calibrated over an angular range of 36 degrees in increments of 6 degrees at 11 speeds between 0 and approximately 40 m/s. Temperature drift was compensated for using methods described by Bruun [5]. Calibration curves were generated by following the method also due to Bruun [6]. The x-wire probes were calibrated before and after each data set was acquired to verify the accuracy of the calibration. Typical error between the pre- and post-calibrations was approximately 3%. All velocity measurements presented in this document were acquired in the plane 61 centimeters downstream of the AWT’s contraction exit, the location of the airfoil model’s leading edge. The hot-wire data was also processed according to the method given by Bruun [6].
CHAPTER 3
SINGLE STREAM SHEAR LAYER CHARACTERISTICS

3.1 Point Statistics

Detailed multi-point velocity measurements were made in order to document the mean flow and turbulent characteristics of the shear layer. The mean of the streamwise component of velocity is shown in Figure 3.1. The mean profile is typical of a single stream shear flow. The nondimensional streamwise velocity is 1 in the freestream of the open jet and decreases through the shear layer to a value that is reflective of fluid entrainment on the low side of the shear layer. The momentum thickness of the shear layer was calculated to be $\theta = 0.025$ meters and the shear layer thickness was calculated to be $\delta = 0.1422$ meters.

The RMS profiles of both the streamwise and cross stream velocity components are shown in Figure 3.2. The RMS profiles also exhibit typical values obtained in shear layers [16]. The peak streamwise RMS velocity is approximately 18% of the high-side velocity and the peak lateral RMS velocity is approximately 12% of the high-side velocity. When the lateral displacement coordinate is nondimensionalized by momentum thickness, the maximum of the lateral nondimensional RMS velocity was found to be approximately $0.5\theta$ to the high-side of the maximum of streamwise RMS velocity.

In both Figure 3.1 and Figure 3.2, $y/\theta = 0$, the center of the shear layer, is taken to be the lateral location where the streamwise velocity is 50% of the
high-side streamwise velocity. The three vertical lines appearing in both Figure 3.1 and Figure 3.2 indicate the lateral test locations where the airfoil models were later placed for acoustic measurements. These locations are $y/\theta = -3$, $y/\theta = -1$, and $y/\theta = 0.5$. The lateral RMS velocity is a near a maximum at $y/\theta = -1$ and will produce the greatest unsteady lift, thus the greatest sound production, from the airfoil models. The test locations at $y/\theta = -3$ and $y/\theta = 0.5$ were selected for their large difference in mean streamwise velocity but comparable unsteadiness in lateral velocity. The nondimensional autospectral densities (ASD) of streamwise and lateral velocity at the three test locations are shown in Figure 3.3. The characteristics of the nondimensional ASDs are typical for moderate Reynolds number flows with a $-5/3$ slope apparent over about one decade of frequency values.

It is observed that the nondimensional ASDs of streamwise velocity collapse
Figure 3.2. SSSL RMS Velocity Profiles.

Figure 3.3. Normalized Autospectra of Velocity at Test Locations.
over a larger frequency range than the nondimensional ASDs of lateral velocity. The nondimensional ASDs of streamwise velocity only deviate significantly from each other at higher frequencies. Panel (b) of Figure 3.3 shows that there is a clear shift of energy from lower frequencies to higher frequencies when moving from the high-speed side of the shear layer to the low-speed side of the shear layer.

3.2 Correlation Length Scale of Turbulence, $\Lambda_j(\omega)|_i$

3.2.1 Isotropic Model

Since the turbulent statistics in the approach flow can be assumed homogeneous in the direction parallel to the airfoil span, the frequency dependent correlation length scale can be defined as [11]:

$$\Lambda_j(\omega)|_i = \frac{1}{2} \int_{-\infty}^{\infty} \phi_{ii}(x_j; \omega) dx,$$

(3.1)

where $\Lambda_j(\omega)|_i$ is the correlation length scale of the $i$th component of velocity in the $x_j$ direction. The integrand is the normalized cross-spectral density of the velocity at points separated in the spanwise direction. This quantity is identically the square root of coherence of velocity between two measurement locations. It will be demonstrated in the following chapter that the turbulence characteristics of direct interest for predicting radiated sound from an airfoil are the normalized autspectrum density of the lateral component of velocity as well as the correlation length scale of the upwash velocity along the direction parallel with the airfoil, $\Lambda_3(\omega)|_2$. Although these functions can, in principle, be obtained for a given flow field with difficulty, they can be replaced by easily determined quantities if the flow is assumed to be isotropic. This is often a necessary assumption simply due to a lack of
detailed information regarding the true nature of turbulent flow fields in complex geometries. Lynch et al.[11] provided a simplified expression for the correlation scale:

\[
\frac{\Lambda_3(\omega)}{\Lambda} = \frac{3\pi}{2} \frac{(k_1\Lambda)^2}{\left[1 + (k_1\Lambda)^2\right]^\frac{1}{2} \left[1 + 3(k_1\Lambda)^2\right]},
\]

(3.2)

which now allows radiated sound to be predicted based on the autospectrum of upwash velocity and an estimate of the integral length scale of the turbulence, \(\Lambda\). Figure 3.4 is a nondimensionalized plot of the isotropic model.

Figure 3.4. \(\frac{\Lambda_3(\omega)}{\Lambda}\): Isotropic Model

The assumption of isotropic turbulence is generally valid only at high wavenumbers. This will effectively restrict the range of validity of Equation 3.2 to high frequencies.
3.2.2 Direct Calculation via Two Point Hot Wire Measurement

The single stream shear layer can be assumed to be homogeneous in the z-(spanwise) direction. A necessary but not sufficient condition for isotropy at a given frequency is that the coherence of lateral and streamwise velocity be zero at that frequency. As shown in Figure 3.5, u-v coherence is nonzero for nondimensional frequencies $f\theta/U_L < 0.2$ for all three test points. This suggests that a sound radiation prediction using of the correlation length scale from the isotropic model will not accurately predict sound at these frequencies.

![Figure 3.5. Coherence of u- and v- Components at a Point](image)

Therefore, $\Lambda_3(\omega)|_2$ was determined via direct measurement. Figure 3.6 shows for each test location the square root of coherence of lateral velocity for several separation distances.

A polynomial fit was applied to each curve in Figure 3.6 to remove the noise.
present at higher frequencies. The polynomial curves were forced to decay exponentially with frequency when they intercepted a coherence value that corresponded to the statistical zero based on number of data samples acquired and ensemble size used to find coherence (shown as a dotted line in the figure). The resulting curve fits are shown as Figure 3.7. It can be seen in this figure that the range of frequencies as well as the magnitude of the square root of coherence decreases when moving from the high-side of the shear layer to the low-side of the shear layer.

The square root of coherence was integrated according to Equation 3.1 to produce the true correlation length scale of lateral velocity in the spanwise direction at each of the test locations. Figure 3.8 is a nondimensionalized plot of this information.
Unlike the correlation length scale found by the isotropic model, the true correlation length scale has large length scales at low frequencies. These large length scales are due to the shear layer instability present at these low frequencies.
This is best seen by a comparison to the isotropic model shown as Figure 3.9.

![Figure 3.9. \( \Lambda^3(\omega)^2 \): Model vs. Direct Measurement at \( y^* = -1 \)](image)

The true correlation length scale clearly deviates from the isotropic model at \( f\Lambda/U_L = 0.17 \) which corresponds to approximately \( f\theta/U_L = 0.135 \). Thus, as expected, the correlation length scale from the isotropic model does not agree the true correlation length scale at frequencies where the shear layer is anisotropic.
CHAPTER 4

AIRFOIL ACOUSTICS

4.1 Theory

If an airfoil is assumed to be acoustically compact, the spectral density of its radiated sound can be modeled as a compact dipole. Therefore,

$$
\Phi_{PP}(\omega) = \frac{k^2 \sin^2 \beta}{16\pi^2 r^2} \Phi_{LL}(\omega).
$$

(4.1)

Equation 4.1 demonstrates that the spectral density of the airfoil’s unsteady lift must be known to predict the radiated sound. It can be shown that the variation in the frequency dependent unsteady lift variation with span is described by

$$
\frac{dL}{dr}(\omega) = \pi \rho u_2(\omega, r) U_\infty F(\omega)
$$

(4.2)

where $F(\omega)$ is the airfoil’s gust response function. If the airfoil can be considered thin ($\frac{t}{C} \ll 1$), and if the approach flow is locally two-dimensional, inviscid, incompressible, and lateral velocity disturbances are small compared to the mean streamwise approach flow, the appropriate gust response function to use with Equation 4.2 is the Sears function [18], $Se\left(\frac{\omega C}{2U_\infty}\right)$. The total lift as a function of frequency is computed by taking the integral of Equation 4.2 over the span of the body. The result is combined with the definition of spectral density to produce
the spectral density of unsteady lift as given by Blake [2]:

\[ \Phi_{LL}(\omega) = [\pi \rho C U_{\infty} F(\omega)]^2 \int \int \Phi_{v(y_1)v(y_2)} dy_1 dy_2, \]  

(4.3)

where the integrand is the two-point cross spectral density function of the upwash component of velocity. As noted in Section 3.2.2, the expression for the radiated sound can be simplified significantly if the turbulent statistics in the approach flow can be assumed homogeneous in the direction parallel to the airfoil span. This allows the double integral of the cross spectral density shown in Equation 4.3 to be simplified to the frequency dependent correlation length scale first shown in Section 3.2.2:

\[ \Lambda_j(\omega)|_{i} = \frac{1}{2} \int_{-\infty}^{\infty} \phi_{ii}(x_j; \omega)dx, \]  

(4.4)

Equations 4.3,4.1, and 3.1 combine to express the spectrum of radiated sound in the direction normal to the airfoil chord:

\[ \frac{\Phi_{PP}(\omega)}{q_i^2 M_L^2} = 2 \frac{u_2^2}{U_L^2} \left( \frac{L_3}{r} \right)^2 \left( \frac{\omega C}{2U_L^2} \right)^2 \phi_{22}(\omega) \left( \frac{\Lambda_3(\omega)|_{2}}{L_3} \right) F^2(\omega). \]  

(4.5)

Equation 4.5 demonstrates that in order to accurately predict the sound generated by the airfoil, the correct gust response function must be selected in addition to correctly modeling the spanwise correlation length scale of turbulence. A gust response function correction factor to account for the finite leading edge thickness of airfoils was given by Howe[10]:

\[ exp \left[ \frac{-kh}{4} - \frac{(kh)^2}{20.25} \right]. \]  

(4.6)
This result was derived from a conformal map of a rounded edge and verified with experimental data by Gershfeld[9]. The result gives an unsteady lift that decreases exponentially as the length scale of the turbulence approaches that of the airfoil thickness. For example, if the gust response correction factor is included in lifting function in Equation 4.3, at \( f = \frac{U}{h} \) the unsteady lift spectrum is predicted to be approximately 4% of the value given by Equation 4.3 if the gust response correction factor is not included.

4.2 Comparison

Radiated sound predictions using the spanwise correlation length scale from isotropic method and radiated sound predictions using the measured spanwise correlation length scale were compared with the measured sound production from the airfoil models. These comparisons can be grouped into two categories. In the first category, the airfoil model location in the shear layer was fixed at \( y/\theta = -1 \), the location of maximum lateral velocity fluctuation, and model geometry was varied. In the second category, the airfoil model geometry was fixed and the location of the model in the shear layer was varied. Acoustic measurements were acquired at eight tunnel centerline velocities for each test configuration (a model and shear layer location). Tunnel centerline velocities ranged from 15 m/s to 30 m/s in 2.5 m/s increments. This information is summarized in Figure 4.1.
Figure 4.1. Experiment test matrix.

Figure 4.2 compares measured acoustic data to three predictions of sound radiation: implementing the isotropic correlation length scale, implementing the isotropic correlation length scale and Howe’s correction for Sears’ gust response function, and implementing the measured correlation length scale and Howe’s correction for Sears’ function. This figure is for the flat plate airfoil with $t = 0.003$ m at $y/\theta = -1$ and tunnel centerline velocity at 30 m/s. However, the results in this figure are typical of results from the rest of the test configurations.
Figure 4.2. Comparison of Radiated Sound Predictions with Acoustic Data

It is clear that the prediction using solely the isotropic correlation length scale is inadequate for predicting the sound for most of the frequency domain. However, when Howe’s correction to Sears’ function is applied, the sound prediction using the isotropic correlation length scale has good agreement with the measured acoustic data as well as the sound prediction using the measured correlation length scale with Howe’s correction applied. For nondimensional frequencies less than 5, neither sound prediction agrees with the measured acoustics. This could be due in part to error in the delay-sum beamforming method used to preduce spectral densities in this frequency range. However, the sound prediction using the measured correlation length scale and Howe’s correction more closely matches the trend with decreasing frequency suggested by the measured acoustic data.
4.2.1 Dependence Airfoil Geometry

The data presented in this section is for a fixed shear layer location and varying airfoil geometry. Acoustic measurements are compared with radiated sound predictions using the measured correlation length scale and Howe’s correction are presented. The acoustic noise floor of the empty AWT facility at the same tunnel centerline velocity is also presented in these results as well as following results as a reference. Figure 4.3 compares the measured sound from the thinner flat plate airfoil, \( t = 0.003 \) meters, with the predicted sound.

![Figures](image)

(a) \( U_0 = 22.5 \) to 30 m/sec, increasing vertically  
(b) Maximum test velocity

Figure 4.3. Autospectral Density of Sound Pressure Radiation, \( t = 0.003 \) m, \( y^* = -1 \)

The first panel of Figure 4.3 shows comparisons for the four fastest tunnel centerline velocities (for clarity) and the second panel shows the results from the maximum tunnel centerline test velocity, 30 m/s. The approach velocity at this location in the shear layer is approximately 68% of the centerline velocity. Here we see excellent agreement between the prediction and the measured data for most
frequencies with some deviation at the lowest frequencies, possibly due to error in measurement.

Figure 4.4 compares the measured sound from the thicker flat plate airfoil, \( t = 0.006 \) meters, with the predicted sound.

![Figure 4.4. Autospectral Density of Sound Pressure Radiation, \( t = 0.006 \) m, \( y^* = -1 \)](image)

It is noted that the nondimensional sound production from this model is lesser than the thinner airfoil model. This is consistent with the assertion that as airfoil thickness increases compared to the turbulent structures in the approach flow, unsteady lift and therefore sound production decreases. Again, there is good agreement between the measured and predicted sound over most frequencies with deviations at the lowest measured frequencies.

In the case of the NACA airfoil model, the thickness parameter of Howe’s correction to Sears’ function was tuned so that the predicted sound radiation matched the measured acoustic data. The optimum value of thickness corresponded to 11%
of the chord length. This is the airfoil thickness at a chordwise location approximately one third of the way to the location of maximum thickness from the leading edge of the airfoil. As in the previous results, Figure 4.5 shows the predicted sound using the measured correlation length scale and the appropriate correction to the gust response function.

![Figure 4.5](image_url)

(a) $U_0 = 22.5$ to 30 m/sec, increasing vertically  
(b) Maximum test velocity

Figure 4.5. Autospectral Density of Sound Pressure Radiation,  
$t_{\text{max}} = 0.019$ m, $y^* = -1$

The increased effective leading edge thickness of the NACA airfoil results in much less sound production as illustrated in the intersection of the measured acoustic data with the noise floor of the AWT.

4.2.2 Dependence on Location in Shear Layer

The data presented in this section is for a fixed airfoil geometry (the thinner of the two flat plate airfoils) and varying shear layer location. Again, acoustic measurements are compared with radiated sound predictions using the measured
correlation length scale and Howe’s correction are presented. Figure 4.6 presents a comparison of the acoustic data measured with the airfoil model at $y/\theta = -3$ with the predicted sound production.

Figure 4.6. Autospectral Density of Sound Pressure Radiation, $t = 0.003 \text{ m, } y^* = -3$

The prediction has good agreement with the measured sound in trend. However, when this result is compared with the results shown in Figure 4.7 (a reproduction of Figure 4.3 for easy comparison), it is observed that deviation from the prediction’s trend is greater at this shear layer location than at $y/\theta = -1$. 
Finally, Figure 4.8 compares the measured acoustic data from the airfoil model
when placed at $y/\theta = 0.5$ with the predicted sound production. The predicted sound roughly matches the trend of the acoustic data for the middle frequencies but misses the trend at high frequencies. At all frequencies and all centerline test velocities, the predicted sound production is less than the measured sound production. Caution must be when interpreting these results. The low local velocity (approximately 35% of tunnel centerline velocity) reduces the signal-to-noise ratio of the microphone array. Thus, the measurements may be biased high. However, intermittency effects could be significant at this location in the shear layer. The present sound radiation prediction method does not take intermittency effects into consideration. Thus, radiated sound predictions shown for this shear layer location may fail to capture the true sound production from the airfoil.
CHAPTER 5

CONCLUSIONS

The conclusions that can be drawn from the results presented in the previous chapters follow. It will be demonstrated that the experimental results provide a firm resolution to the open questions posed in the introduction of this document.

First, the spanwise correlation length scale of lateral velocity of a single stream shear layer found using the isotropic model has excellent agreement with the true correlation length scale for nondimensional frequencies \( f \Lambda/U_L > 0.17 \). This nondimensional frequency corresponds to the nondimensional frequency \( f\theta/U_L = 0.135 \). It was shown that at the nondimensional frequency of \( f\theta/U_L = 0.135 \), the u-v coherence at a point is nonzero (\( \sim 0.2 \)). Since u-v coherence is a necessary condition for local isotropy, the shear flow is anisotropic at this frequency. This result indicates that the isotropic model for the correlation length scale is an adequate model for the correlation length scale in a single stream shear layer down to frequencies where the flow field is weakly isotropic. These nondimensional frequencies roughly correspond to a dimensional frequency of about 85 Hz and reduced frequency \( \omega C/2U_L \) of about 0.2. Given this information, it is not surprising that the predicted sound using the true correlation length scale as well as the predicted sound using the correlation length scale given by the isotropic model both match the measured acoustic data so well for most test cases. No acoustic measurements were taken below a dimensional frequency of 100 Hz due
to test facility limitations. The data are above the frequency at which one would see an appreciable difference in sound prediction due to the difference between the true and the modeled correlation length scales.

Second, for most of the frequencies for which airfoil acoustics were measured, neither the sound prediction using the correlation length scale from the isotropic model nor the prediction using the true correlation length scale accurately captured the true acoustics unless the appropriate gust response function was included in the prediction. It was shown that Howe’s correction to Sears’ function must be applied in order to accurately predict leading edge sound production from thick, flat, elliptical leading edge airfoils. These data also show that when Howe’s gust response correction is used for the airfoil geometries for which it was designed, the true gust response function of the flat plate airfoils is captured almost exactly.

Third, it was also shown that Howe’s correction to Sears’ function is also applicable to a NACA 0015 airfoil if the thickness parameter of the correction is tuned to the correct effective thickness. For the present work, the appropriate thickness was at a chordwise location about one-third of the way from the leading edge of the airfoil to the chordwise location of the maximum airfoil thickness. If the thickness parameter of Howe’s correction was taken to be two times the radius of the leading edge, the sound production from the airfoil overpredicted the measured acoustic data. If the thickness parameter was taken to be the maximum thickness of the airfoil, the sound production from the airfoil underpredicted the measured acoustic data. This result suggests that the rule for determining the effective thickness of non-elliptic leading edge airfoil could be determined by repeating Howe’s methodology for this geometry. That is, an appropriate correction to the Sears function could be derived using a conformal map of the airfoil.
The preceding research does produce a new question for further investigation. The results from fixing airfoil geometry and varying placement in the shear layer suggest that intermittency effects might be impacting the prediction of radiated sound from the airfoil. Future work should determine how turbulence intermittency can be accounted for in a radiated sound prediction for an airfoil in a shear flow.
REFERENCES


