EXPERIMENTAL INVESTIGATION OF THE UNSTEADY TURBULENT FLOW AROUND A LEADING-EDGE SLAT CONFIGURATION

by

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Abstract

Air traffic volume is expected to triple in the U.S. and Europe by 2025, and as a result, the aerospace industry is facing stricter noise regulations. The engines and the airframe are the two principle sources of noise on an aircraft. One of the significant sources of airframe noise is the deployment of high-lift devices like a leading-edge slat which is heavily used in the vicinity of airports. The unsteady turbulent flow over a leading-edge slat is studied herein. In particular, Particle Image Velocimetry (PIV) measurements were performed on a scale-model wing equipped with a leading-edge slat in the H.J. Irving-J.C.C. Picot Wind Tunnel. Two Reynolds numbers based on wing chord were studied: $Re = 6 \times 10^5$ and $1.3 \times 10^6$. PIV measurements of the mean flow, Reynolds stresses, turbulent kinetic energy, and vorticity, revealed that a distinct shear-layer forms at the slat cusp that appears to be more curved for the lower Reynolds number case. A snapshot Proper Orthogonal Decomposition (POD) analysis indicated that differences in the time-averaged statistics between the two Reynolds numbers were tied to differences in the coherent structures formed in the slat cove shear layer. In particular, the lower Reynolds number flow seemed to be dominated by a large-scale vortex formed in the slat cove that was related to the unsteady flapping and subsequent impingement of the shear-layer onto the underside of the slat. A train of smaller, more regular vortices was detected for the larger Reynolds number case which seemed to cause the shear-layer to be less curved and impinge closer to the tail of the slat than for the lower Reynolds number case.
The impingement of the shear-layers on the slat and the main wing are expected to be significant acoustic sources.
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Nomenclature

\(< uu >\) Normal Reynolds Stress in the Streamwise Direction

\(< uv >\) Shear Reynolds Stress

\(< vv >\) Normal Reynolds Stress in the Vertical Direction

\(\alpha\) Angle of Attack

\(\delta_s\) Slat Deflection Angle

\(\omega\) Vorticity

\(c\) Wing Chord

\(Re\) Reynolds Number

\(TKE\) Turbulent Kinetic Energy

\(U\) Streamwise Velocity

\(u\) Streamwise Velocity Fluctuation

\(V\) Vertical Velocity

\(v\) Vertical Velocity Fluctuation
Chapter 1

Introduction

Aircraft noise is a longstanding problem for the aerospace industry. As urban populations expand outwards towards airports and as air travel continues to grow, it is becoming increasingly important to minimize the amount of noise produced by aircraft. Reducing engine noise has long been the subject of a significant amount of noise research but due to advances in this area, airframe noise has become the focus of growing research. For example, in his review Crighton [1], outlines various airframe noise sources and describes the landing gear and high-lift devices as two of the most prominent sources of aeroacoustic noise: High-lift devices include the trailing-edge flaps and leading-edge slats on wings. The purpose of high-lift devices is to provide increased lift to the aircraft when travelling at lower speeds, such as during takeoff and landing. The noise produced by slats is especially important during landing as the engines are throttled back.

The present investigation will focus on one particular high-lift device, the leading-edge slat. Owing to the importance of this configuration to the aerospace industry, the leading-edge slat with a tail flap configuration has received a considerable amount of research attention. In general, the flow in the slat cove depends on a variety of factors including the freestream velocity, angle of attack, slat deflection angle, slat
gap and overlap. The quantities are depicted graphically in Figure 1.1. When the slat is stowed, it is designed to blend into the main wing in order to minimize surface discontinuities as shown in Figure 1.2(a). When the slat is deployed, as in Figure 1.2(b), it exposes its sharp trailing-edge and cusp to the flow which results in a separated flow. This separation causes instabilities in the flow resulting in vorticity which interacts with the nearby surfaces of the slat thereby producing noise [3]. High-frequency slat noise has been associated with vortex-shedding from the trailing-edge of the slat while lower frequency noise has been linked to the flow in the slat cove region [4]. The low frequencies associated with the slat cove region are typically within the range of $St \sim 1-3$ ($St = f c_s / U_\infty$ where $c_s$ is the slat chord and $U_\infty$ is the freestream velocity) [4].

The goal of the present investigation is to measure the unsteady flow produced by a leading-edge slat in the cove region. This information will be used for the validation of numerical models, and to yield insight to the physics of the flow and point to likely aeroacoustic source mechanisms. In order to achieve these goals, an experimental investigation was undertaken using the H.J. Irving - J.C.C. Picot low speed wind
tunnel shown in Figure 1.3. A diagram of the particular configuration being studied is shown in Figure 1.4. Note that a leading-edge slat is normally combined with a flap on the trailing-edge, however, as the focus was only the slat cove, no tail flap was used here. Two different Reynolds numbers will be examined herein, $6 \times 10^5$ and $1.3 \times 10^6$, to determine how sensitive the flow is to Reynolds number.

Particle Image Velocimetry (PIV) was selected to measure the velocity field as these measurements yield spatial information about the statistics such as Turbulent Kinetic Energy (TKE), Reynolds stresses and vorticity, but moreover, it also yields the simultaneous spatial information required to examine the large-scale (or coherent) turbulent structures in the flow, and thus a Proper Orthogonal Decomposition (POD) analysis was also conducted on the PIV measurements in order to identify
coherent structures in the flow in the hopes of relating these structures to potential noise sources. POD is a widely used method that has been employed to observe large structures in the turbulent flow by filtering out much of the small scale turbulence. While POD has been used in many different flows [5, 6, 7, 8], it has not previously been used to identify structures in the leading-edge slat configuration.

The outline of the thesis is as follows: Chapter 2 is a review of the relevant topics to the research including aerodynamic noise, leading-edge slat noise and POD. Chapter 3 describes the experimental setup that was used, comprising details on the wind tunnel, the model wing and slat configuration as well as an overview of PIV. Chapter 3 also includes an overview of gappy POD, which was used in processing the PIV data. Chapter 4 examines the turbulent statistics, discusses their relevance to airframe noise and compares the results to previous studies. Chapter 4 also illustrates and discusses the results obtained through the POD analysis which includes instantaneous velocity reconstructions and instantaneous vorticity images. Finally, Chapter 6 presents the conclusions and provides recommendations for future work related to this study.
Chapter 2

Literature Review

The following section will give an overview of aerodynamic noise production as well as give a brief summary of the current state of research on the subject of leading-edge slat noise. It will also introduce the topic of Proper Orthogonal Decomposition (POD) and how it can be used to identify turbulent structures in the flow.

2.1 Aerodynamic Noise

2.1.1 Aeroacoustic Theory

While sound is produced through unsteadiness of a flow, it does not necessarily have to be a turbulent flow [9]. It is helpful to understanding the production of sound to begin with Lighthill’s theory of aerodynamic noise which considers the sound field produced by the unsteady motion of an unbounded fluid [10]. Lighthill’s equation [11] is:

\[
\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \frac{\partial^2 T_{ij}}{\partial y_i \partial y_j}
\]

(2.1)
where $\rho$ is the fluid density and $c_o$ is the speed of sound in the fluid. Lighthill’s stress tensor, $T_{ij}$ can expanded to:

$$T_{ij} = \bar{\rho}u_iu_j + p_{ij} - c_o^2\rho\delta_{ij}$$

where the first term on the right hand side represents the Reynolds stresses which quantify the strength of turbulence in the region. The second and third terms express the difference between the actual pressure fluctuations and the pressure fluctuations caused only by isentropic changes in the density of the ambient fluid medium. These differences are expected to be minimal in a flow where the bulk flow can be deemed incompressible and isothermal.

Lighthill shows that, assuming compact sources, for low Mach numbers and well away from surfaces that $T_{ij} \approx \bar{\rho}u_iu_j$ [11]. The solution for Lighthill’s equation is:

$$\rho(x,t) - \rho_0 = \frac{1}{4\pi c_o^4} \frac{x_ix_j}{x^3} \int \frac{\partial^2 T_{ij}}{\partial t^2} dV(y)$$

and produces a quadrupole source which is discussed in the next section.

Lighthill’s equation applies only when there are no boundaries or surfaces in the acoustic field. When there is a boundary present, it alters the sound field physically in two ways; first, the sound generated by the quadrupoles in Lighthill’s solution can be reflected and diffracted by the solid boundaries. Secondly, the quadrupoles will only be distributed in the region away from the solid boundary which may cause a resultant dipole at the boundary. Lighthill’s equation (2.1), was modified by Curle [11] to include solid boundary effects:

$$\frac{\partial^2 \rho}{\partial t^2} - c_o^2\nabla^2\rho = \frac{\partial F_i}{\partial x_i} - \frac{\partial^2 T_{ij}}{\partial y_i \partial y_j} - \frac{\partial Q}{\partial t}.$$  

There are several noticeable differences between Lighthill’s and Curle’s theories. The
rate of mass injection per unit volume, the third term on the right hand side, is represented by the $Q$ term in (2.4) and is linked to the change in velocity over a surface. This term is important in cavitation or when a moving surface is present. The solution, assuming a compact source, an incompressible bulk fluid and that the boundary is a solid stationary surface, is [10]:

$$\rho(x, t) - \rho_0 = \frac{1}{4\pi c_0^4} \frac{x_i x_j}{x^3} \int \frac{\partial^2 T_{ij}}{\partial t^2} dV(y) - \frac{1}{4\pi c_0^3} \frac{x_i}{x^2} \frac{dF_i}{dt} - \frac{1}{4\pi c_0^2} \frac{\rho_0}{x} \int \frac{\partial u_i}{\partial t} dS_i(y)$$  (2.5)

in which $F_i = - \int p_{ij} dS_j$ which represents the fluid force acting on the surface.

In (2.5), there are two new terms in addition to the quadrupole term that was obtained in (2.3). The second term in (2.5) is a result of the solid boundaries and indicates that unsteady forces acting on a solid surface cause acoustic dipoles. The third term is associated with monopole sources and is usually associated with cavitation in liquids.

Alternative theories to Lighthill’s acoustic analogy do exist, such as vorticity based aeroacoustic models like Powell [12] and Howe’s [13]. However, these have been shown to be equivalent to Lighthill’s acoustic analogy for quadrupole sources and won’t be discussed here as dipoles are the dominant acoustic sources for $M<1$.

2.1.2 Acoustic Sources

The three types of noise sources relevant to aerodynamic sound are monopoles, dipoles and quadrupoles which differ from each other in terms of their directivity. A 2D graphical depiction of each noise source is shown in Figure 2.1. The directivity of a source can be thought of as the way sound pressure changes angularly at a set distance away from the source. A monopole source can be thought of as a bubble that is continually expanding and contracting, radiating noise equally in all directions. As stated, these sources are associated with unsteady velocity changes of a surface
like found in cavitation. When two monopoles are separated by a small distance, are equal in strength but are in opposite phase, a dipole is said to be present. The net force on the fluid from the oppositely phased dipoles emits the sound waves [14]. The directivity of this source differs from the monopole in that the noise is not radiated equally in all directions. Dipoles are linked to surface pressure fluctuations which are caused by time-varying surface forces. Quadrupoles are simply two identical dipoles which are also oppositely phased and separated by a small distance [14] and are related to the gradients of turbulent stresses in the flow. If there is no cavitation present and for $M<<1$, the dipole sources are the dominant source.

### 2.2 Leading-Edge Slat Noise

Several studies have been done, both computational and experimental, on various leading-edge slat and wing configurations. The slat is the leading contributor of noise in the high-lift device noise spectrum. Potential noise source mechanisms
associated with the leading-edge slat include the free shear-layer vortex reattachment, the unsteadiness of the vortex core and vortices shed from the trailing-edge [15], which has been studied extensively [16, 17, 18].

2.2.1 Experimental Investigations

There have been a number of studies on the subject of leading-edge slat noise that have made use of PIV, surface pressure measurements using microphones, and also some which use Laser Doppler Anemometry (LDA). These are discussed below. Issues that are encountered with leading-edge slat noise experiments are the lack of large anechoic facilities and this forces mostly small scale wind tunnel tests. This introduces Reynolds number effects on results as components can not always be constructed to scale i.e. trailing-edge and slat cusp thickness. It is also very difficult to obtain 3D measurements in a leading-edge slat flow due to the obstructive nature of the slat and main wing geometry [15].

A substantial experimental investigation by Choudhari et al. [20] in the Langley Low-Turbulence Pressure Tunnel using a three-element airfoil configuration was performed over the course of three separate testing periods spanning three years. The wing chord was \( c = 55 \) cm at a Reynolds number of \( Re = 7.2 \times 10^6 \). Five unsteady pressure transducers were placed near the trailing-edge of the slat. The far-field slat noise spectra was dominated by a high-amplitude, high-frequency peak which was likely due to vortex shedding at the slat trailing-edge. Other noise mechanisms were found in the slat cove but could not be clearly understood with the measurements acquired in the study. This noise was attributed to vortex shedding from the trailing-edge and was partially attributed to a more blunt trialing-edge persisting on the model.

An experimental PIV investigation by Jenkins, Khorrami and Choudhari [3] on a model wing with a chord length of \( c = 45.7 \) cm was done at the NASA-Langley Basic
Figure 2.2: Vorticity Images From An Experimental Study at $\alpha = 6^\circ$ (a) Mean Vorticity (b) Instantaneous Vorticity [3].

Aerodynamics Research Tunnel at a Reynolds number of $Re = 3.64 \times 10^6$ at angles of attack of $\alpha = 4^\circ, 6^\circ$ and $8^\circ$. The model used in the investigation included a leading-edge slat as well as a tail flap. The mean velocity plots show regions of high negative velocity near the lower slat surface along with slow moving fluid in other areas of the slat cove. A large recirculation region was found in the cove region for all three angles of attack with the largest region found in the $\alpha = 4^\circ$ case. An example of the mean and instantaneous vorticity results is provided in Figure 2.2. Distinct vortices can be seen emanating from the slat cusp and reattaching to the lower surface of the slat in both the instantaneous and mean vorticity images. They also showed that as the angle of attack decreases, the turbulent region at the reattachment point is spatially larger and that the highest levels of turbulent kinetic energy are at the reattachment point. It was also found that the reattachment produces large velocity fluctuations and initiates the interaction of vorticity with the surface which can then be entrained back into the recirculation region.

A study by Takeda et al. [19] was done using PIV measurements as well as LDA on a three-element high-lift airfoil configuration with a model chord length of $c = 0.764$ m at a Reynolds number of approximately $Re = 1.5 \times 10^6$. The experiments were performed at two different angles of attack, $\alpha = 5^\circ$ and $10^\circ$. In agreement
with Jenkins, Khorrami and Choudhari [3], a shear-layer formed from the slat cusp and proceeded to impinge at a reattachment point on the slat with a slow recirculation zone inside the slat cove. The turbulent kinetic energy was also found to be at its maximum where the shear-layer impinges on underside of the slat which is suspected as the main noise generation mechanism within the cove [19]. From the LDA measurements the Reynolds stresses in the streamwise direction, $< uu > / U_\infty$, were also shown. The Reynolds stresses were shown to have a strong presence in the shear-layer, in agreement to Jenkins et al. [3]. Both the Reynolds stresses and TKE were found to decrease in the lower angle of attack case. Similar to Jenkins et al. [3], the cove flow was found to become less turbulent as the angle of attack was increased and vortices could be observed exiting through the slat gap.

### 2.2.2 Computational Models and Simulations

A companion computational study to the experiments of [3] was performed by Khorrami et al. [21] at a Reynolds number of $Re = 7.2 \times 10^6$ using the same three-element high-lift airfoil configuration. The results using RANS simulations indicated the formation of a free shear-layer and subsequent impingement on the underside of the slat. They showed that vortices are formed at the slat cusp and proceed to roll up the shear-layer and eventually impinge upon the underside of the slat at the reattachment point. As the vortices in the shear-layer approach the underside of the slat, they undergo severe stretching and distortion, which is likely a low frequency acoustic source. It was also discovered that although clear vortex shedding from the slat cusp was present, the shedding was intermittent and no distinct pattern could be found.

In another computational simulation by Lockhard and Choudhari [4], done by solving the RANS equations using the CFL3D flow solver, developed by NASA at a Reynolds number of $Re = 1.7 \times 10^6$ based on the stowed chord of $c = 45.7$ cm.
Although the Reynolds number is considerably lower than for full-scale applications, they argued that the simulations are still suitable for validating predictions of slat cove noise sources [4]. As illustrated in Figure 2.3, spanwise rollers form off of the slat cusp and break up into more random structures as they propagate along the shear-layer. It was believed that the noise is caused by the stretching and destruction of vortices and structures at the reattachment point on the slat as well as the propagation past the trailing-edge of the slat [4]. It was determined that the unsteadiness in the slat region is predominantly caused by the shear-layer between the much slower moving fluid in the recirculation zone in the cove and the high velocity fluid that exits through the gap. Velocity fluctuation and TKE profiles are shown in Figure 2.4 and were shown to agree very well with experiments performed by Jenkins, Choudhari and Khorrami [3]. It was found that the fluctuations in the streamwise direction, $u$, were originally dominant, but the vertical fluctuations, $v$, quickly become the strongest. The fluctuations in the vertical direction increase until near the reattachment point at which point they decrease significantly and the spanwise fluctuations, $w$, increase and is shown in Figure 2.4, where $S$ is the shear-layer trajectory. The TKE levels were highest at the reattachment point, but also had a maximum approximately where the spanwise rollers, which formed at the cusp, began to break down which is well-illustrated in Figure 2.3. One of the main findings of this investigation was that the directivity pattern is consistent with that of a dipole source in the streamwise, vertical and spanwise directions.

Lockhard and Choudhari believed that the noise is caused by the stretching and destruction of vortices and structures at the reattachment point on the slat as well as the propagation past the trailing-edge of the slat. It was determined that the unsteadiness in the slat region is predominantly caused by the shear-layer between the much slower moving fluid in the recirculation zone in the cove and the high velocity fluid that exits through the gap. Velocity fluctuation and TKE profiles are
Figure 2.3: 3D Instantaneous Vorticity Using RANS [4].

Figure 2.4: Velocity Fluctuation and TKE Profiles From A Computational Study [4].
shown in Figure 2.4 and were shown to agree very well with experiments performed by Jenkins, Choudhari and Khorrami [3]. It was found that the fluctuations in the streamwise direction, \( u \), were originally dominant, but the vertical fluctuations, \( v \), quickly become the strongest. The fluctuations in the vertical direction increase until near the reattachment point at which point they decrease significantly and the spanwise fluctuations, \( w \), increase and is shown in Figure 2.4, where \( S \) is the shear-layer trajectory. The TKE levels were highest at the reattachment point, but also had a maximum approximately where the spanwise rollers, which formed at the cusp, began to break down which is well-illustrated in Figure 2.3. One of the main findings of this investigation was that the acoustic directivity pattern is consistent with that of a dipole source in the streamwise, vertical and spanwise directions.

In a separate study done by Choudhari and Khorrami [22], the CFL3D flow solver was again used on a three-element model with the same specifications as the experimental study done by Jenkins et al. mentioned above [3]. The Reynolds number examined in this investigation was \( Re = 1.7 \times 10^6 \). Again, the shear-layer rolls up into discrete spanwise vortices immediately after the slat cusp. They found that the vorticity structures approaching the reattachment area are partially ejected through the slat gap and are also partially trapped in the recirculation zone and convected back to the slat cusp. This trapped vorticity is believed to induce eruptions of secondary vorticity in the slat cove which contribute to the unsteadiness of the shear-layer. The turbulent kinetic energy distribution was found to be similar to the PIV experiments done by Jenkins et al. [3], with the highest levels of TKE were found in the reattachment region despite the PIV only capturing 2D TKE. The maximum level of TKE in these numerical simulations is approximately 0.04. The velocity fluctuations in the streamwise and vertical direction were found to be the strongest immediately following the slat cusp and also near the trailing-edge, near the reattachment point.
2.3 Proper Orthogonal Decomposition (POD)

Proper Orthogonal Decomposition (POD) is an unbiased method employed to identify and characterize the large-scale or coherent structures in a turbulent flow. The large-scale structures are often hidden by the small turbulent motions of the flow and can be difficult to identify. POD consists of projecting the random turbulent velocity field on to orthonormal basis functions by which the dominant components of an infinite-dimensional process with only a finite number of modes can be captured. Lumley [23] was the first to introduce POD to the turbulence community in order to identify coherent structures in the flow and to remark that a POD mode represents a structure only if it contains a dominant percentage of energy.

The snapshot POD method, first developed by Sirovich [24], is used in the present analysis. It is now widely used on the dense vector fields acquired using PIV. Each instantaneous PIV measurement is taken as a snapshot of the flow with $N$ being the total number of snapshots. The snapshot POD method is much less computationally intensive as it reduces the dimension of the problem to $N$, as opposed to $n_c \times N_{grid}$, where $n_c$ is the number of components of velocity and $N_{grid}$ is the number of spatial grid points of the measurement area. For snapshot POD, the fluctuating velocity components $(u_j^n, v_j^n)$ from the number of snapshots, $N$ are arranged into a matrix $U$ [5].

\[
U = \begin{bmatrix}
  u_1 & u_2 & \cdots & u_N \\
  \vdots & \vdots & \ddots & \vdots \\
  v_1 & v_2 & \cdots & v_N
\end{bmatrix}
\]

In which $j$ runs through each velocity position to $M$, for each snapshot. The auto-
covariance matrix can then be created as

$$\tilde{C} = U^T U \quad (2.7)$$

from which the following eigenvalue problem can be solved,

$$\tilde{C} A^i = \lambda^i A^i \quad (2.8)$$

where $A^i$ are the eigenvectors and $\lambda^i$ are the eigenvalues. The eigenvalues are then ordered in regards to eigenvalue size.

$$\lambda^1 > \lambda^2 > ... > \lambda^N = 0 \quad (2.9)$$

The basis for calculating the POD modes, $\phi^i$, is constructed from the eigenvectors of (2.8) shown below:

$$\phi^i = \frac{\sum_{i=1}^{N} A^i_n u^n}{\| \sum_{i=1}^{N} A^i_n u^n \|} \quad (2.10)$$

In which $i = 1, 2, ..., N$ and $A^i_n$ is the $n^{th}$ eigenvector component which corresponds to $\lambda^i$ from (2.8). By projecting the fluctuating part of the velocity on to the POD modes, the value of each POD coefficient, $a_i$, can be found. Each snapshot can then be expanded using the POD modes and POD coefficients. To find the POD coefficients, (2.11) is used, where $\Psi = [\phi^1, \phi^2, ..., \phi^N]$:

$$a^n = \Psi^T u^n \quad (2.11)$$

Therefore, for each snapshot, $n$, the fluctuating part can be reconstructed per:

$$u^n = \sum_{i=1}^{N} a^n_i \phi^i = \Psi a^n \quad (2.12)$$
By ordering the eigenvalues and eigenvectors as has been done in (2.9), it makes certain that the modes with the most energy are the first modes. This allows for an accurate reconstruction of the snapshot by only using the first few modes in a flow with dominant structures [5].

### 2.4 Motivation

This study is part of a large ongoing project undertaken by Bombardier Aerospace to improve the prediction and modeling of airframe noise and use the findings to reduce airframe noise. The wing models used in the existing literature have a tail flap but it is unclear to what effect the absence of a tail flap will have on the flow in the slat cove region. Much of the existing literature directed towards leading-edge slat noise has been performed at one Reynolds number and angle of attack was varied. No study has examined changes in the turbulent flow in a leading-edge slat configuration at different Reynolds numbers. By comparing two different Reynolds numbers, differences and similarities in the flow for the exact same configuration of the leading-edge slat can be studied. Finally, there has been little previous effort to study the structures that are present in the slat cove region. By applying the snapshot POD process to the slat cove region, the small scale turbulence can be filtered out and the large scale structures can be examined. This process has never been employed in a leading-edge slat configuration and can yield valuable insight into differences between the two Reynolds numbers and noise sources within the slat cove.
Chapter 3

Experimental Setup and Image Processing

3.1 Experimental Setup

The experiments were performed in the H.J. Irving-J.C.C. Picot Wind Tunnel located in Noonan, New Brunswick, previously shown in Figure 1.3. The wind tunnel is normally an open jet wind tunnel and has a one meter diameter with a maximum velocity of $U_\infty = 83$ m/s and a turbulence intensity of less than 1%. An image of the model wing and slat is shown in Figure 3.1(a). The model wing has a chord of $c = 31.5$ cm, is made from aluminum, and was designed to span the wind tunnel using 40 separate sections. The leading-edge slat, also constructed from aluminum, was machined as one piece and has a chord of 25% of the wing chord. The wing and slat installed in the wind tunnel is shown in Figure 3.1(b). The wing was set at an angle of attack of $\alpha = 13^\circ$ with the slat deflection angle, $\delta_s$, set at an angle of $20^\circ$ from the nose of the leading edge of the main element. The slat trailing-edge was positioned at 0.02$c$ ahead of the nose of the wing and a gap, defined by the circle from the slat trailing-edge to the wing leading-edge of 0.024$c$. The wing and slat
geometry and configuration were given by Bombardier Aerospace and did not include a tail flap. As a consequence, a large angle of attack is necessary to avoid separation from occurring on the lower surface of the slat. In order to position the slat in the correct alignment as well as to keep the view of the PIV camera unobstructed, special “J”-shape brackets were machined to connect the slat to the main element. The Reynolds numbers that are studied in this study were $Re = 6 \times 10^5$ and $1.3 \times 10^6$ based on the wing chord.

PIV experiments are an effective measurement tool in the field of fluid dynamics as it allows for a non-intrusive method to measure the flow and because it provides information at an instant in a plane. PIV experiments are done by introducing particles into the flow upstream of the area being studied and should be small enough in order to accurately follow the motion of the fluid without changing the properties of the fluid. As these particles are carried downstream, they are illuminated by a light sheet generated by a pulsed laser. Two rapid consecutive images of the light scattered by the small particles are then taken by a digital camera. The images can
then be processed on a computer and a velocity field can be obtained by special software designed to track the particles between the two images.

For this experimental investigation, the velocity field was obtained using a LaVision PIV system. The flow was illuminated using a 120 mJ Solo 120XT Nd-Yag laser and images were captured using an ImagerIntense digital camera with a 50 mm Nikon lens. The timing between subsequent images of an image pair must be long enough to adequately capture the physics of the flow but short enough so as to avoid a particle leaving the field of view and is therefore highly dependent on the flow velocity. A total of 540 quality image pairs were acquired for a Reynolds number of $Re = 6 \times 10^5$ while a total of 851 quality image pairs were acquired for $Re = 1.3 \times 10^6$. The data was processed using an interrogation window size of 32 x 32 pixels and an overlap of 50%. A 86 x 65 vector field was produced, for a total of 5590 individual vectors.

The flow was seeded with particles which were generated by a Rosco Model 1900 theatrical fog machine which produced approximately 5 µm particles. The Stokes number, a dimensionless number that relates the time scale of the particle to the time scale of the flow, was calculated to be $S<<1$ which returns an acceptable flow tracing accuracy for high Reynolds numbers [25]. An ongoing issue was the distribution of fog particles in the wind tunnel for the experiment. Because the wind tunnel is a suction tunnel, the fan is upstream of the model and could not aid in mixing the particles evenly throughout the flow. As a consequence, not enough fog particles were being captured by the PIV system to regularly obtain quality images of the entire field of view. To overcome this problem, a device was constructed using PVC pipe to distribute the seeding more evenly at the inlet of the tunnel.

A common problem of PIV experiments is the glare from the model when the laser is fired, resulting in poor quality images. The solution that was employed to reduce the glare was to coat the bottom of the model wing and slat with rhodamine dye. Rhodamine dye absorbs green wavelength light, which is the laser color, and
fluoresces red wavelength light. The camera is equipped with a band pass filter to only allow green light to pass which significantly reduced the amount of glare from the model.

For 2D PIV experiments it is preferable if the laser sheet and camera are perpendicular and that they do not look through angled windows. For this reason a 16-sided test section with a span of approximately one meter to match the diameter of the wind tunnel was designed and constructed and is shown installed in the wind tunnel in Figure 3.2. Circular flanges on each end allowed the test section to match up to the existing wind tunnel. A small window made with Lexan on one side of the test section allowed for the camera to view the leading-edge slat while the laser sheet was shot from the bottom through a larger window.

The difficulty of these experiments should not be understated, as many issues were encountered including glare and seeding as previously mentioned. There were also mechanical issues with the wind tunnel which were eventually resolved and did not affect the quality of the results. At certain wind tunnel speeds, a loud resonating
sound could be heard coming from the wind tunnel however this noise was not present at the speeds studied in this investigation. In addition, it is difficult to obtain data in the slow-moving slat cove region simultaneously with the fast moving fluid in the freestream. This requires the timing of the laser pulses to be just right, in order to capture both the movement of particles in the slow recirculation zone as well as the fast-moving particles in the freestream. Condensation was also a constant hindrance, as the wing, slat and windows of the test section had to be occasionally cleaned due to the warm air from outside the wind tunnel condensing in the colder wind tunnel flow. It is believed that condensation caused a small area of erroneously measured data throughout the experiments and for this reason a process called gappy POD had to be applied to this area and is discussed in more detail below.

The uncertainty of the mean streamwise and mean vertical velocity at the 95% confidence interval is shown in Figure 3.3 and Figure 3.4 for both Reynolds numbers. The uncertainty was calculated using

$$p = \frac{2\sigma_x}{\sqrt{N}}$$

[27], where $$\sigma_x$$ is the standard deviation and $$N$$ is the number of repeated statistically-independent measurements, in this case being the number of snapshots. The highest levels of uncertainty are near the slat cusp for $$U$$ and near the slat gap for $$V$$ for both Reynolds numbers. This was expected because of the larger velocity fluctuations occur in these regions. The uncertainty in the higher Reynolds number case was slightly greater with a maximum of approximately 0.9 m/s compared to approximately 0.6 m/s for the lower Reynolds number case. The highest level of uncertainty is less than 2% of the freestream velocity. An estimation of the uncertainty in $$< u^2 >$$ and $$< v^2 >$$ are shown in Figure 3.5 and Figure 3.6 for each Reynolds number. This was calculated using

$$p = \frac{\sqrt{< u^4 >}}{\sqrt{N}}$$

or the fourth moment of $$u$$ and $$v$$ [28].

There is also systematic uncertainty associated with PIV experiments which includes the “peak-locking” effect as one of the larger sources of systematic error [26]. A histogram of the raw velocity vectors for both the streamwise velocity is shown in
Figure 3.7 in order to locate any bias towards integer velocity values. These show peaks at expected values, such as the freestream velocity and near zero because of the flow inside the slat cove, but no other peaks seem to be present and peak-locking does not appear to be a cause of concern. As peak-locking can be one of the larger sources of systematic uncertainty, no further analysis was done as other sources of systematic error are small, often below 1 mm/s. The statistical uncertainty has a much greater effect than the systematic in regards to total error.

3.2 Gappy POD

Unfortunately when performing PIV experiments, small regions of the flow may be erroneously measured. This can be caused by factors such as glare or seeding issues. Gappy POD is a process used to reconstruct missing or "gappy" data. This technique was first developed by Everson and Sirovich [29] to reconstruct human face images from missing data sets and has become a standard method for reconstructing missing data. It has also previously been applied to aerodynamic data reconstruction [6, 30].

For the velocity field $U^k$, a corresponding mask vector, $n^k$, is defined as $n_i^k = 0$ if $U_{ik}$ is missing and $n_i^k = 1$ if $U_{ik}$ is known, where $U_{ik}$ denotes the $i$th element of $U^k$. The POD basis for the snapshot set $\{U^i\}_{i=1}^m$ is set as $\{\phi^i\}_{i=1}^m$, where all the snapshots are completely known. Another solution vector, $g$, is assumed to have missing elements with the corresponding mask $n$ and represents a solution whose behavior can be characterized with the existing snapshot set [6]. An expansion, similar to that in (2.12), can be used to represent the intermediate repaired vector $\tilde{g}$ in terms of POD basis functions in which $b_i$ are the POD coefficients.

$$\tilde{g} \approx \sum_{i=1}^m b_i \phi^i \quad (3.1)$$

The error between the original and repaired vectors must be minimized and is defined
Figure 3.3: Uncertainty At The 95% Confidence Level in m/s for Re = 6x10^5 In (a) U (b) V.
Figure 3.4: Uncertainty At The 95% Confidence Level in \( m/s \) for \( Re = 1.3 \times 10^6 \) In (a) \( U \) (b) \( V \).
Figure 3.5: Uncertainty in $m^2/s^2$ for $Re = 6 \times 10^5$ for (a) $<u^2>$ (b) $<v^2>$. 
Figure 3.6: Uncertainty in $m^2/s^2$ for $Re = 1.3 \times 10^6$ for (a) $\langle u^2 \rangle$ (b) $\langle v^2 \rangle$. 
Figure 3.7: Histogram Of The Raw Streamwise Velocity Vector Distribution for (a) \( Re = 6 \times 10^5 \) (b) \( Re = 1.3 \times 10^6 \).
By differentiating (3.2) with respect to each of the POD coefficients, \( b_i \), in turn, the coefficients that minimize the error, \( E \), can be found and leads to a system of linear equations as seen in (3.3).

\[
Mb = f
\]  

(3.3)

Where \( M_{ij} = (\phi^i, \phi^j)_n \) and \( f_i = (g, \phi^i)_n \) in which the brackets signify pointwise multiplication. Solving for (3.3) for \( b \), the intermediate repaired vector, \( \tilde{g} \) can be found using (3.1). The incomplete vector, \( g \), can then be completed by replacing the missing elements by the corresponding repaired elements in \( \tilde{g} \) [6].

The gappy POD procedure can be extended to cases where the snapshots are not completely known and the POD basis can be constructed using an iterative procedure. The set of incomplete data is represented by \( \{g^k\}_{k=1}^m \) and an associated set of masks \( \{n^k\}_{k=1}^m \). The mask describes where data are available and where it is missing. The missing elements of the snapshots are filled in using average values found from the following [6].

\[
h^k_i(0) = \begin{cases} 
g_i^k & \text{if } n_i^k = 1 \\
\bar{g}_i & \text{if } n_i^k = 0
\end{cases}
\]

(3.4)

In which

\[
\bar{g}_i = \frac{1}{P_i} \sum_{k=1}^{m} g_i^k, \quad P_i = \sum_{k=1}^{m} n_i^k
\]

and \( h^k(l) \) denotes the \( l \)th iterative guess for the vector \( h^k \). A set of POD basis vectors can then be calculated for this set of snapshots then used to iteratively refine the guess for the incomplete data.

The following steps summarize the process.
1) The basic POD procedure described in Section 2.3 is used on the set of snapshots, \( \{ h_k^{(l)m} \}_{k=1}^m \), beginning with \( l = 0 \), to obtain the POD basis vectors for the current iteration, \( \{ \Phi_k^{(l)m} \}_{k=1}^m \).

2) The first of these POD basis vectors is then used to repair each member of the snapshot set, as described above. The intermediate repaired data for the current iteration, \( l \), is given by (3.5) below where \( p \) is the number of modes used to reconstruct the data.

\[
\tilde{h}_k^l = \sum_{i=1}^{p} b_i^l \phi_i^l
\]  

(3.5)

3) The values from the intermediate repaired data are used to reconstruct the data for the succeeding iteration using the following

\[
h_i^l(l+1) = \begin{cases} 
    h_i^k(l) & \text{if } n_i^k = 1 \\
    \tilde{h}_i^k(l) & \text{if } n_i^k = 0 
\end{cases}
\]

4) Set \( l = l + 1 \) and repeat the procedure until the maximum number of iterations is reached or until the solution has converged.

The importance of the gappy POD process is illustrated in Figure 3.8 which represents the time-averaged Turbulent Kinetic Energy for \( Re = 1.3 \times 10^6 \) as an example. In Figure 3.8(a), gappy POD is not used and a large spot of very high TKE is visible in the shear-layer and causes issues in the subsequent full POD analysis. This spot was likely caused by condensation on the window of the test section or on the model, but could have been related to glare from the model or a seeding issue. After using gappy POD to reconstruct the area where the data is flawed, the data behaves as expected, as shown in Figure 3.8(b).
Figure 3.8: Turbulent Kinetic Energy \( \frac{\langle uu \rangle + \langle vv \rangle}{2} \) Normalized By \( U'_\infty^2 \) At \( Re = 1.3 \times 10^6 \) With (a) No Gappy POD And (b) Gappy POD.
Chapter 4

Experimental Results and Discussion

In this Chapter, the statistics obtained from the PIV data and the results obtained from the POD analysis are examined and discussed. Section 4.1 shows the turbulent statistics results and draws comparisons to previous experimental and computational studies. Section 4.2 presents the POD results which include the energy distribution of the POD modes, a comparison of low-dimensional reconstructions using different numbers of modes to examine the large scale structures in the slat cove region. A comparison of the structures and flow behaviour between the lower Reynolds number and the higher Reynolds number case is discussed.

4.1 Turbulent Statistics Results and Discussion

Turbulent statistics obtained from analyzing the PIV data are presented in this section. These statistics were obtained after applying the gappy POD process discussed in the previous chapter.

A comparison of the mean streamwise velocity for an angle of attack of $\alpha = 13^\circ$ at freestream velocities of 30 m/s and 65 m/s, is shown below in Figure 4.1. These
velocities correspond to Reynolds numbers of $Re = 6\times10^5$ and $1.3\times10^6$ respectively. Mean velocity vectors are also overlayed on to the scalar plot. The colour plot here corresponds to the mean streamwise velocity, $U$. In the following figures, as well as those in Section 4.2, the slat is overlayed on to the image in order to show its relative position during the experiments. The main wing is positioned just outside of the field of view and can not actually be seen, however by examining the mean velocity plots and referring to Figure 1.4, the location of the nose can be determined.

As seen in the surface plot, the flow in the slat cove is much slower due to the presence of the slat and the slat causes the flow to be directed upward and through the slat gap. This is better illustrated in a similar colour plot, this time showing the $V$ component of velocity, in Figure 4.2. Here, large $V$ values are present where the flow begins to accelerate around the nose of the wing. When the Reynolds number is increased from $6\times10^5$ to $1.3\times10^6$, the mean flow does not change dramatically however the recirculation zone in the slat cove appears to be smaller and the region of high shear which forms after the slat cusp becomes straighter. This suggests that there is some flow dependence on Reynolds number (at least in the range examined here). For both cases, the vector plots indicate the presence of a mean recirculation zone under the slat, consistent with others [3, 19].

The Reynolds stresses $< uu >$, $< vv >$ and $< uv >$, normalized by $U_\infty^2$, are shown in Figure 4.3, Figure 4.4, and Figure 4.5, respectively. It should be noted that these are all of the components of the Reynolds stress tensor that could be measured using the current experimental setup. In these figures, the overlayed vectors correspond to both components of the mean velocity field.

In Figure 4.3(a), it can be observed that the highest levels of the $< uu >/U_\infty^2$ term are present immediately downstream of the slat cusp and become smaller towards the rear of the slat for $Re = 6\times10^5$. These turbulent stresses are no doubt indicative of both the turbulence and unsteadiness generated in a shear-layer. Similar
Figure 4.1: Mean Streamwise Velocity Component, $U$, at (a) $Re = 6 \times 10^5$ and (b) $Re = 1.3 \times 10^6$. Vectors denote both $U$ and $V$ components of the mean velocity field while the colormap denotes the mean streamwise component in m/s.
Figure 4.2: Mean Vertical Velocity Component, $V$, at (a) $Re = 6 \times 10^5$ and (b) $Re = 1.3 \times 10^6$. Vectors denote both $U$ and $V$ components of the mean velocity field while the colormap denotes the vertical streamwise component in m/s.
behaviour is noted for the larger Reynolds number case, with the strongest fluctuations just downstream of the slat cusp, but the normalized strength of the Reynolds stresses are approximately half as large as for the lower Reynolds number flow. A higher level of the Reynolds stresses in the streamwise direction is also present in the slat cove and near the underside of the slat in the lower Reynolds number case. The local maxima in $< uu >/U_\infty^2$ at the slat cusp agrees qualitatively with the numerical simulations done by Lockhard and Choudhari [4], despite the fact that there was a flap on their wing and the angle of attack was smaller.

The normalized Reynolds stresses, $< vv >/U_\infty^2$, are also shown in Figure 4.4, for both Reynolds numbers examined. The color plots indicate that the highest levels of the turbulent normal stresses are present where the flow is accelerating through the slat gap for both Reynolds numbers, which is consistent with the findings of Lockhard and Choudhari [4]. The normalized results are again slightly lower for the larger Reynolds number case.

Similar plots of the normalized Reynolds shear stress, $< uv >/U_\infty^2$, for $Re = 6 \times 10^5$, shown in Figure 4.5(a), indicate that the normalized shear stress is greatest in the shear-layer towards the middle of the slat and downstream, where the flow is just beginning to accelerate upwards towards the slat gap. Similar behaviour occurs and is better shown in the $Re = 1.3 \times 10^6$ case where the normalized strength of the fluctuations is lower.

The Turbulent Kinetic Energy (TKE) is a useful term for numerical validation and allows for a better visualization of the shear-layer as it is not dependent on the angle of slat deployment\(^1\). An approximation of the TKE is shown in Figure 4.6 which was created by summing the two measured normal components of the Reynolds stresses, $< uu >/U_\infty^2 + < vv >/U_\infty^2$. For $Re = 6 \times 10^5$, shown in Figure 4.6(a), the highest levels of normalized TKE are located in the shear-layer and also near the

\(^1\)which Cartesian components of Reynolds stresses are.
Figure 4.3: $<uu>$ Normalized By $U_\infty^2$ At (a) $Re = 6 \times 10^5$ And (b) $Re = 1.3 \times 10^6$. 
Figure 4.4: $<vv>$ Normalized By $U_\infty^2$ At (a) $Re = 6\times10^5$ And (b) $Re = 1.3\times10^6$. 
Figure 4.5: \( \langle u v \rangle \) Normalized By \( U_\infty^2 \) At (a) \( Re = 6 \times 10^5 \) And (b) \( Re = 1.3 \times 10^6 \).
reattachment point on the underside of the slat. In Figure 4.6(b), the highest levels of normalized TKE are also in the shear-layer but are located mainly at the reattachment point. Consistent with the Reynolds stresses, the normalized TKE levels are significantly smaller for the higher Reynolds number case. A higher level of TKE is also present in the slat cove in the lower Reynolds number case. The qualitative behaviour of the TKE levels in the shear-layer, the increase and subsequent decrease, then increase towards the nose of the wing are quite similar to those shown in Figure 2.6 by Choudhari and Lockhard. The TKE levels computed by Choudhari and Lockhard using all three components of the normal stresses are about 0.04 in the first maxima and increase up to 0.06 at the nose of the wing; the levels in the shear-layer are comparable to those measured here, but given the fact that only two components of TKE are used here, this suggests that the TKE is larger than what was computed by Choudhari for the lower Reynolds number case. This could be due to Reynolds number effects, as the Reynolds number in Choudhari's work was $Re = 1.7 \times 10^6$ as opposed to $Re = 6 \times 10^5$ here. These results also agree well with the TKE profiles obtained by Jenkins et al. [3] as well as 3D TKE profiles by Choudhari and Khorrami [22], who found that the highest levels of TKE are present at the slat cusp and at the reattachment point for three different angles of attack. The magnitudes of the normalized 2D TKE at these two points is approximately 0.04 which compares well to the higher Reynolds number case in the present study, at approximately 0.04. The maximum TKE for the lower Reynolds number case is closer to 0.05 at the slat cusp and reattachment point. However, it should be noted that the Reynolds number was $Re = 3.64 \times 10^6$ in the experiments done by Jenkins et al., which is much higher than the present study.

Figure 4.7 shows the normalized time-averaged spanwise vorticity component, $\langle \omega_z \rangle / U_\infty$. It is obvious from Figure 4.7 that the normalized vorticity is the greatest immediately following the slat cusp. This is quite similar to behaviour noted
Figure 4.6: Turbulent Kinetic Energy \( \frac{\langle uu \rangle + \langle vv \rangle}{2} \) Normalized By \( U_\infty^2 \) At (a) \( Re = 6 \times 10^5 \) And (b) \( Re = 1.3 \times 10^6 \).
in both computational and experimental studies [3, 21]. This plot clearly shows the shear-layer behaviour, and in both cases the mean development of the shear-layer bends upwards towards the trailing-edge of the slat. However, the shear-layer for the lower Reynolds number case appears more curved, whereas the shear-layer for the higher Reynolds number, whilst still curved, tends toward a straighter path as it propagates from the slat cusp to the reattachment point.

The results based on the statistics obtained from the data are qualitatively similar to those in previous experimental and computational studies [3, 4, 19]. For both Reynolds numbers, a well-defined shear-layer clearly forms immediately following the slat cusp and eventually impinges on the underside of the slat. For both cases, trends associated with the development of the Reynolds stresses are also in agreement with the numerical study done by Lockhard and Choudhari [4], as the regions with the highest levels of $< uu >$ and $< vv >$ correspond to the same regions in that study. This is significant, as the slat configuration employed here behaves in a similar manner in comparison to the other investigations despite the lack of a tail flap. Some differences do persist for the two Reynolds numbers. In particular, the magnitude of the normalized Reynolds stresses and normalized TKE contours indicate that these quantities are lower for the higher Reynolds number case. The mean vorticity plots indicate that the shear-layer is straighter for the larger Reynolds number.

In order to explain the difference between these statistics for the two Reynolds numbers and to better understand the acoustic sources in the flow, the coherent structures in the slat cove are now examined using instantaneous plots of spanwise vorticity, $\omega_zc/U_\infty$, as is often done in slat literature [3, 4]. The instantaneous vorticity plots shown in Figure 4.8 and Figure 4.9 illustrate the shear-layer at various instances in time during the experiment. As PIV measurements are not time resolved, it should be noted that the four plots in Figure 4.8 and Figure 4.9 are taken at statistically independent instants and should not be considered to be a sequence.
Figure 4.7: Time-Averaged Spanwise Vorticity Normalized By $c/U_\infty$ At (a) $Re = 6 \times 10^5$ And (b) $Re = 1.3 \times 10^6$. 
As can be observed for both Reynolds numbers, the shear-layer exhibits similar behaviour in each instance in time however each image differs slightly from the others indicating that the shear-layer is unsteady. Vorticity is also present in the slat cove near the impingement point, and this may be associated with small scale turbulence getting enveloped into the recirculation zone. This process will certainly cause pressure fluctuations on the underside of the slat which will act as acoustic dipole sources.

4.2 POD Results and Discussion

In this section, the results from the POD analysis conducted on the PIV data are presented and discussed. Results include the energy spectrum, mode-shapes, and
Figure 4.9: Instantaneous Spanwise Vorticity Normalized By $c/U_\infty$ At Four Different Instances At $Re = 1.3 \times 10^6$. 


low-dimensional instantaneous velocity reconstructions. Using the snapshot POD process used by Meyer [5] combined with the gappy POD described in Section 3.2, it was possible to determine an optimal set of eigenfunctions (in an energy sense) from the PIV data set. The first mode contains the largest amount of energy, the second mode contains the second most and so on.

For the present study, 540 snapshots were used for $Re = 6 \times 10^5$ and 851 snapshots were used for $Re = 1.3 \times 10^6$, meaning the flow is resolved into the corresponding number of modes. The number of snapshots corresponds to the number of quality images that were obtained for each Reynolds number. The POD mode shapes and energy content were found to be insensitive to the number of snapshots chosen for $N>200$.

The relative energy recovered for each of the first 30 modes is presented in Figure 4.10. A table showing the relative amount of energy captured in the first ten modes as well as the total of those ten modes is included for comparison (Table 4.1). It is evident that the energy distribution for the first 10 modes for the two cases is very similar, i.e. the first ten modes capture 20.58% of the energy at $Re = 6 \times 10^5$ while at $Re = 1.3 \times 10^6$, 20.45% of the energy is captured. In Figure 4.10, the cumulative energy contained in the first 30 modes is also shown, represented by the dashed line. Through the first 30 modes, the total energy also appears to be similar. For $Re = 6 \times 10^5$, 31.0% of the energy is captured and for $Re = 1.3 \times 10^6$, 32.7% of the energy is captured. The amount of TKE captured in the first 30 modes is significant as it represents nearly a third of the total energy in only a small portion of the total number of snapshots. Moreover, the fact that similar amounts of energy are contained in the first few modes suggests that both flows possess similar levels of organization; for example, one would expect that a more organized flow would contain a greater portion of energy in a given number of POD modes [31].

It is usually ill-advised to attempt to interpret individual POD mode shapes as
Figure 4.10: Energy Distribution And Cumulative Energy For 30 Modes (a) $Re = 6 \times 10^5$ And (b) $Re = 1.3 \times 10^6$. 
Table 4.1: Relative and Cumulative Energy Captured In The First 10 POD Modes (%)

<table>
<thead>
<tr>
<th>Re</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>9th</th>
<th>10th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>6x10^5</td>
<td>6.42</td>
<td>2.84</td>
<td>2.7</td>
<td>1.87</td>
<td>1.51</td>
<td>1.28</td>
<td>1.14</td>
<td>1.06</td>
<td>0.93</td>
<td>0.84</td>
<td>20.58</td>
</tr>
<tr>
<td>1.3x10^6</td>
<td>6.15</td>
<td>2.94</td>
<td>2.67</td>
<td>1.76</td>
<td>1.42</td>
<td>1.24</td>
<td>1.19</td>
<td>1.16</td>
<td>1.00</td>
<td>0.92</td>
<td>20.45</td>
</tr>
</tbody>
</table>

independent structures, although some insight into the organization in the flow can be gained here by examining the first few modes. In Figure 4.11, the streamwise component of the first eight POD modes are shown for $Re = 6x10^5$. The first mode shape shown in Figure 4.11(a), is clearly associated with the shear-layer, and looks quite similar to the plots of mean vorticity. Incidentally, this first mode also captures 6.42% of the TKE which is more than twice the amount captured in any other mode. Thus, it can be concluded that the shear-layer is the dominant flow feature, at least from an energy perspective, in the leading-edge slat configuration.

The second POD mode appears to be associated with the flow in the slat cove region and with the shear-layer just downstream of the slat cusp. This mode may act in combination with mode 1 to cause a flapping shear-layer. Examining Figure 4.11(b) and beyond, it is much more difficult to interpret the POD modes, as the structures are not as obvious. However, in certain modes, such as the 3rd, 6th and 8th modes, an alternating pattern is present which may indicate the presence of vortices propagating along the shear-layer. The vertical component of the first eight POD modes are shown in Figure 4.13. This shows results similar results to Figure 4.11, with the first mode being associated with the shear-layer and alternating color patterns shown in later modes. The alternating vertical velocity patterns are likely associated with the up and down wash created by the passage of coherent vortices.

Figure 4.12 and Figure 4.14 show a similar plot of the first eight streamwise and vertical POD modes respectively for $Re = 1.3x10^6$ and demonstrate a similar situation to the lower Reynolds number case. In Figure 4.12(a), the shear-layer
Figure 4.11: Streamwise Component Of First 8 POD Eigenmodes, $\Phi_i$, For $Re = 6 \times 10^5$ (a) 1$^{st}$ Mode, (b) 2$^{nd}$ Mode, (c) 3$^{rd}$ Mode, (d) 4$^{th}$ Mode, (e) 5$^{th}$ Mode, (f) 6$^{th}$ Mode, (g) 7$^{th}$ Mode and (h) 8$^{th}$ Mode.
is once again present in the first mode, which captures 6.15% of the TKE. This percentage of TKE captured is nearly identical to the amount of TKE captured in the first mode for the $Re = 6 \times 10^6$ case and is again more than twice the amount of energy captured in any other mode. There are noticeable differences between the first POD modes of each case. Comparing Figure 4.11(a) and Figure 4.12(a), it appears as though the first mode for $Re = 1.3 \times 10^6$ is still associated with the shear-layer, although not as smooth or as well-defined as for the lower Reynolds number case. As previously stated, it is difficult to interpret the POD modes, however, in certain modes an alternating pattern can be observed. Also, the first eight modes are not identical for the two Reynolds numbers examined; certain modes, shapes such as the third mode in Figure 4.11(c), and the second mode in Figure 4.12(b), do appear to be quite similar despite being out of phase. Due to the very small difference in captured energy between these two modes, 2.7% and 2.94% it is possible that there has been a slight reordering of the modes due to small changes in modal energy content with Reynolds number. This has previously been noted previously in the 3D wall jet [31, 32]. Differences between the mode shapes and the ordering of the modes, indicate that there are corresponding differences in the coherent structures formed in the slat cove for the two Reynolds numbers. This is consistent with the subtle differences in turbulent statistics with Reynolds number shown earlier.

As previously mentioned, one of the strengths of POD is that it can be used to filter out the small scale turbulence which obscures the larger scale structures using a low-order reconstruction of the unsteady velocity field. However, in order to do this, a suitable number of modes must be selected to reconstruct the flow. This was done by comparing reconstructions of instantaneous streamwise and vertical fluctuating velocities using a different number of modes for both Reynolds numbers. In Figure 4.15(a), a single instant of the actual streamwise instantaneous fluctuating velocity is shown in the scalar field and is accompanied by the corresponding vector
Figure 4.12: Streamwise Component Of First 8 POD Eigenmodes, $\Phi_i$, For $Re = 1.3 \times 10^6$ (a) $1^{st}$ Mode, (b) $2^{nd}$ Mode, (c) $3^{rd}$ Mode, (d) $4^{th}$ Mode, (e) $5^{th}$ Mode, (f) $6^{th}$ Mode, (g) $7^{th}$ Mode and (h) $8^{th}$ Mode.
Figure 4.13: Vertical Component Of First 8 POD Eigenmodes, $\Phi_i$, For $Re = 6 \times 10^5$
(a) 1$^{\text{st}}$ Mode, (b) 2$^{\text{nd}}$ Mode, (c) 3$^{\text{rd}}$ Mode, (d) 4$^{\text{th}}$ Mode, (e) 5$^{\text{th}}$ Mode, (f) 6$^{\text{th}}$ Mode,
(g) 7$^{\text{th}}$ Mode and (h) 8$^{\text{th}}$ Mode.
Figure 4.14: Vertical Component Of First 8 POD Eigenmodes, \( \Phi_i \), For \( Re = 1.3 \times 10^6 \)
(a) 1\(^{st}\) Mode, (b) 2\(^{nd}\) Mode, (c) 3\(^{rd}\) Mode, (d) 4\(^{th}\) Mode, (e) 5\(^{th}\) Mode, (f) 6\(^{th}\) Mode,
(g) 7\(^{th}\) Mode and (h) 8\(^{th}\) Mode.
field in the second column representing both the u and v components of the actual fluctuating velocity for $Re = 6 \times 10^5$. This is accompanied by similar plots showing the reconstructions using the first 5 POD modes, first 10 modes and the first 20 modes in Figure 4.15(b)-(d). Figure 4.17 displays similar results with the vertical component of velocity. Figure 4.16 and Figure 4.18 display similar plots for one instance of streamwise and vertical fluctuating velocity for $Re = 1.3 \times 10^6$, respectively.

For both Reynolds numbers, the unfiltered results are irregular and noisy but the POD low-dimensional reconstruction using 5 POD modes successfully filters out these small scale disturbances and the underlying shear-layer and recirculation in the slat becomes observable. When more modes are included, more details of the flow are evident but the flow becomes noisier.

By examining the reconstructions that are displayed in Figure 4.15-4.18, an optimal number of modes can be chosen to reconstruct the flow. When choosing the number of modes, a compromise has to be made; with a high number of modes, more energy can be captured but comes at the expense of a noisier velocity field. From Figures 4.15-4.18, it can be seen that the 10 mode reconstructions yield slightly more information in regards to flow features than the 5 mode reconstruction. The 20 mode reconstructions appear to be much noisier than the 5 and 10 mode reconstructions, and is especially evident from the vector plots for the higher Reynolds number case shown in Figure 4.17(d) and Figure 4.18(d). The 10 mode reconstructions contained more information than the 5 mode reconstructions while still capturing similar features in the flow to the 20 mode reconstructions. For these reasons, low-dimensional reconstructions using the first 10 modes were selected for study. As mentioned earlier, 10 modes captures essentially the same amount of energy for both Reynolds numbers, i.e. 20.58% of the energy for the $Re = 6 \times 10^5$ case and 20.45% of the energy for $Re = 1.3 \times 10^6$.

Low-dimensional reconstructions using the first 10 POD modes which were taken
Figure 4.15: Instantaneous Streamwise Fluctuating Velocity Reconstructions For $Re = 6 \times 10^5$ (a) Actual (b) 5 POD Modes (c) 10 POD Modes (d) 20 POD Modes.
Figure 4.16: Instantaneous Vertical Fluctuating Velocity Reconstructions For $Re = 6 \times 10^5$ (a) Actual (b) 5 POD Modes (c) 10 POD Modes (d) 20 POD Modes.
Figure 4.17: Instantaneous Streamwise Fluctuating Velocity Reconstructions For $Re = 1.3 \times 10^6$ (a) Actual (b) 5 POD Modes (c) 10 POD Modes (d) 20 POD Modes.
Figure 4.18: Instantaneous Vertical Fluctuating Velocity Reconstructions For \( Re = 1.3 \times 10^6 \) (a) Actual (b) 5 POD Modes (c) 10 POD Modes (d) 20 POD Modes.
at random instants are shown in Figure 4.19. Each row displays a statistically-independent streamwise fluctuating velocity reconstruction in the left column with the corresponding vertical fluctuating velocity reconstruction on the right column. In these figures, the colormap shows the instantaneous streamwise fluctuating component of velocity while the vector field denotes both $u$ and $v$ components of fluctuating velocity. It is important to take note that the scalar and vector fields denote only the fluctuating component of velocity. Scalar plots of streamwise and vertical instantaneous velocity reconstructions overlayed with the vector field with the mean added back on are shown in Appendix A. These plots were useful for observing the mean flow but were not very helpful in regards to observing the large scale structures in the flow. It is difficult to observe the behaviour in the cove region as the vectors are small compared to the vectors in the shear-layer and freestream.

In the left column of Figure 4.19(a) through (d), streamwise velocity fluctuations associated with the shear-layer are apparent; this is not unexpected as it is similar to the first POD mode. The magnitudes of the fluctuations are often quite large, at times exceeding 25% of the mean flow velocity. Most of the instantaneous streamwise velocity reconstructions display clear evidence of an unsteady flapping shear-layer, and evidence of backflow above. While the images appear loosely similar, there are often subtle differences between each of them. For example, in both Figure 4.19(c) and (d), there are large downward fluctuating velocities present near the leading-edge of the main wing; inspection of the overlayed vector field at these locations show that this causes two regions of counter-rotating flow. In these images, the shear-layer appears to impinge, or at least is in close proximity to, the underside of the slat instead of hitting the main wing or exiting through the slat gap as it does in other instances. This process will certainly cause large pressure fluctuations on the underside of the slat and thus act as a dipole acoustic source.

At other instances, such as in Figure 4.19(e) through (h), the shear-layer can be
observed to flap much more strongly. In these images the high speed streamwise fluctuations associated with the unsteady shear-layer are directed upwards into the slat cove about midway along the slat. This is accompanied by strong flow reversals in the slat cove and below the shear-layer. Not surprisingly, this behaviour is accompanied by large positive and negative vertical velocity fluctuations and this seems to be related to a large vortex-like structure, as indicated in the vector field. This process will certainly cause large pressure fluctuations on the underside of the slat and thus act as a dipole acoustic source.

At later instants like those shown in Figure 4.19(k) and (l), the shear layer appears to be oscillating so strongly that the positive streamwise velocity fluctuations seem to impinge onto the slat cove very early, even before the midspan. This is certainly related to the large vortex illustrated by the vectors, although it appears to have moved slightly upstream from instants (e) and (h).

In Figure 4.20, a similar figure of 16 instantaneous streamwise velocity reconstructions is shown for $Re = 1.3 \times 10^6$. Once again, evidence of the unsteady shear-layer appears in a significant number of the streamwise reconstructions as shown in the left column of Figure 4.20(a) and (b). In Figure 4.20(c), a region of negative vertical fluctuating velocity is once again present near the trailing-edge. However, in contrast to the lower Reynolds number case where large recirculating vortices were present in the slat cove, it appears as though the shear-layer is much more wavy and appears to be comprised of trains of smaller vortices formed off the slat cusp that propagate along the shear-layer. These small vortices can be seen in Figure 4.20(d)-(l), in both the streamwise and vertical velocity reconstructions and in the vector plots. These vortices can be observed by the alternating color of the streamwise and vertical fluctuating velocity plots, from positive to negative velocities.

In the $Re = 6 \times 10^5$ case, a large vortex was often present in the shear-layer, however not with the frequency of which the smaller vortices appear in the $Re = 1.3 \times 10^6$
Figure 4.19: Random Instantaneous Velocity Reconstructions Using 10 POD Modes For \( Re = 6 \times 10^5 \). Vectors denote \( u \) and \( v \) components of fluctuating velocity.
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<td>$Y$ (mm)</td>
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<td>-60 -40 -20 0 20</td>
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</table>

Figure 4.19: Continued.
Figure 4.19: Continued.
Figure 4.19: Continued.
case. This implies that the structures observed at the higher Reynolds number, although energetic, are physically smaller than those observed at the lower Reynolds number flow. It is also noteworthy that the vortices are not in the same position in each image, suggesting that although the instants are statistically-independent, the vortices are propagating along the shear-layer and either hit the underside of the slat or near the nose of the main wing, similar to what was concluded in other studies (i.e. [3, 4]); though the impingement seems to be more confined to the rear of the slat than for the lower Reynolds case. The presence of negative streamwise fluctuating velocity in the slat cove in these images is also worth noting as this suggests that some of the flow could be both entering the recirculation zone by way of the small vortices and also near the trailing-edge of the slat. The images shown in Figure 4.20(m) through (p) show instants where it is possible that the shear-layer vortices are weakening.

4.3 Summary

Turbulent statistics indicated that, in general, the mean flow for the two Reynolds number cases behaves quite similar. The Reynolds stresses and TKE plots, however, indicated that the normalized fluctuations were larger for the lower Reynolds number case. These and the mean vorticity plots also indicated that the shear-layer was more curved and more diffuse for the lower Reynolds number case.

A POD analysis indicated that the energy was distributed reasonably uniformly for both flow. In both cases, the first mode seemed to be associated with an unsteady shear-layer and contained roughly 6% of the flow energy, more than twice that contained in any other mode. It was determined that a low-dimensional reconstruction using the first 10 POD modes allowed the small-scale structures to be filtered out and the coherent structures to be observed.
The POD reconstructions of the instantaneous velocity field indicated that there are significant differences in the coherent structures for each Reynolds number. The most noteworthy difference is the presence of the more regular smaller vortices propagating along the shear-layer in the \( Re = 1.3 \times 10^6 \) case as opposed to the presence of a larger vortex for the \( Re = 6 \times 10^5 \) case. This larger vortex seemed to cause the shear-layer to impinge all along the slat cove and thus causes the mean shear-layer to be more curved for the lower Reynolds number case.

Figure 4.21 provides a cartoon of the main differences in the structures and the shear-layer for both Reynolds number flows. The lower Reynolds number reconstructions show many images with the shear-layer but also show a large vortex present with the shear-layer actually striking the underside of the slat near its’ midspan. Other images showed a strong backflow in the slat cove, also causing a large vortex. The higher Reynolds number reconstructions also show the shear-layer but also show a number of images with small vortices propagating along the shear-layer. The unsteadiness of the shear-layer, while impinging on the underside of the slat and on the nose of the main wing and the proximity of vortex-structures to the wall, would be a strong source of noise in the slat cove region.
Figure 4.20: Random Instantaneous Velocity Reconstructions Using 10 POD Modes For $Re = 1.3 \times 10^6$. Vectors denote $u$ and $v$ components of fluctuating velocity.
Figure 4.20: Continued.
Figure 4.20: Continued.
Figure 4.20: Continued.
Approximate points of shear layer impingement.

Large vortex related to large pressure fluctuations on the underside of the slat.

Figure 4.21: Basic Diagram Showing Structures And shear-layer For (a) $Re = 6 \times 10^5$ and (b) $Re = 1.3 \times 10^6$. 
Chapter 5

Conclusions and Recommendations

5.1 Conclusions

An experimental study was undertaken to investigate the flow over a leading edge slat for two Reynolds numbers, \( Re = 6 \times 10^5 \) and \( Re = 1.3 \times 10^6 \). Unlike earlier studies, this leading edge slat was not equipped with a tail flap and this required the use of higher angle of attacks than used in previous studies. PIV measurements on the slat cove region were performed to yield flow statistics and to examine the coherent structures in the flow.

The mean flow and turbulent statistics measured here were similar to previous experimental and computational investigations, [3, 4, 19] that used a tail flap. In particular, it was found that the highest levels of streamwise velocity fluctuations, \( < uu > \), were present immediately following the slat cusp while the highest levels of vertical velocity fluctuations, \( < vv > \), were present near the slat gap and reattachment point. The highest levels of TKE were present in the region of the reattachment point and in the shear-layer. The variation of TKE in the shear-layer...
also provided good quantitative results with Jenkins et al. \cite{3}, especially for the higher Reynolds number. These findings are significant as they were qualitatively similar to the results obtained in previous studies, despite the lack of a tail flap in the present experiments. This indicates that the flow is behaving in a similar manner to the 3-element configurations used in other investigations.

The PIV measurements indicated that the mean flow field for the two Reynolds numbers examined here was quite similar. The TKE and Reynolds stresses, however, indicated that the normalized turbulent fluctuations were larger for the lower Reynolds number case. The distributions of TKE and the mean vorticity also indicated that the shear-layer was more curved for the lower Reynolds number case.

The snapshot POD was applied to both components of the turbulent velocity field. The results indicated that the energy was distributed reasonably uniformly for both Reynolds numbers examined; the cumulative energy contained in the first 10 modes differs only by 0.13% in the two cases. The velocity fluctuations associated with the first mode shape seemed to be associated with the shear-layer and contained roughly 6% of the flow energy, more than twice that contained in any other mode.

A low-dimensional reconstruction using the first 10 POD modes was used to examine the coherent structures in the slat cove. For $Re = 6 \times 10^5$, an unsteady shear-layer was present in the reconstructions. This shear-layer was observed to flap and impinge on the underside of the slat from the middle of the slat on towards the trailing-edge of the slat and onto the main wing element. This was often accompanied by the presence of a large vortex in the slat cove.

For the higher Reynolds number flow, similar instantaneous velocity reconstructions, showed a shear-layer was once again present. Unlike the $Re = 6 \times 10^5$ case, many of the reconstructions for the higher Reynolds number case showed evidence of numerous smaller vortices in the shear-layer. This caused the shear-layer to impinge on the underside of the slat closer to the trailing-edge of the slat than for the lower
Reynolds number flow. This, in turn, causes the straighter and less curved mean shear-layer position observed in the turbulent statistics. The lower normalized TKE and Reynolds stresses are also likely a result of differences in these two processes.

From the information that has been gathered from the statistics and POD analysis, it is possible to speculate on the production of noise producing mechanisms in the cove region of the leading-edge slat. It was found that the shear-layer is quite unsteady and impinges on either the underside of the slat or on the nose of the main element. It was also evident from the instantaneous fluctuating velocity reconstructions that vortices were present in the shear-layer and the destruction or degradation of these vortices upon impingement would certainly be a major source of noise. Additionally, the proximity of these convecting vortices to the slat or main wing and the accompanying unsteady pressure fluctuations would also create a strong acoustic source. Noise mitigation strategies should likely focus on modifying or reducing the unsteadiness of the shear-layer and the accompanying vortices.

5.2 Recommendations

It would be beneficial to observe the behavior of the turbulent flow around the leading-edge slat configuration at various angles of attack. Many of the existing studies of the flow in the leading-edge slat cove have done experiments at multiple angles of attack and it would be useful to perform and compare with the present results. Performing a POD analysis at different angles of attack and with the Reynolds numbers used here would also be worthwhile to see how the large-scale structures change with increasing and decreasing angles of attack. Examining the results of a POD analysis at other Reynolds numbers is also recommended to observe the differences in the structures at Reynolds numbers higher, lower and in between the two Reynolds numbers that are studied here to see if the observed differences change
gradually or there is some type of regime change.

It would also be useful to do unsteady pressure measurements in the slat cove. Pressure measurements taken on the underside of the slat can be used to estimate the time-resolved velocity field using Linear Stochastic Estimation (LSE) and POD. This would help validate the findings in the present study by putting the instantaneous reconstructions in sequence, allowing the cause of noise sources in the leading-edge slat configuration to be studied more in-depth.
Bibliography


Appendix A: Additional Low-Dimensional POD Reconstructions
Figure 5.1: Random Instantaneous Velocity Reconstructions Using 10 POD Modes Normalized By $U_\infty$ For $Re = 6 \times 10^5$. Vectors denote $u$ and $v$ components of velocity.
Figure 5.1: Continued.
Figure 5.1: Continued.
Figure 5.1: Continued.
Figure 5.2: Random Instantaneous Velocity Reconstructions Using 10 POD Modes Normalized By $U_\infty$ For $Re = 1.3 \times 10^6$. Vectors denote $u$ and $v$ components of velocity.
Figure 5.2: Continued.
Figure 5.2: Continued.
Figure 5.2: Continued.
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Stephen J. Wilkins, Patrick R. G. Richard, and Joseph W. Hall,

Stephen J. Wilkins, Patrick R. G. Richard, and Joseph W. Hall,