Experimental Characterization and Flowfield Analysis of a Swept Shock-Wave/Boundary-Layer Interaction

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FLORIDA STATE UNIVERSITY
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EXPERIMENTAL CHARACTERIZATION AND FLOWFIELD ANALYSIS OF A SWEPT SHOCK-WAVE/BOUNDARY-LAYER INTERACTION

By

ANDREW KYLE BALDWIN

A Dissertation submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Doctor of Philosophy

2021

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LIST OF SYMBOLS

**English**

a  Speed of sound

$C_f$  Skin friction coefficient

$C_p$  Coefficient of pressure, $\frac{P - P_\infty}{0.5\gamma M_\infty^2 P_\infty}$

f  Frequency

$f_s$  Sampling frequency

$G_{xx}$  Autospectral density

h  Oil film height

I  Illumination intensity

L  Length scale

$L_i$  Intermittent separation length or Inception length

$L_s$  Separation bubble length

$L_{un}$  Upstream influence length normal to inviscid shock

M  Mach number, $\frac{u}{a}$

$M_n$  Interaction strength, $M_\infty \sin(\theta)$

n  Streamline spacing

$n_a$  Index of refraction (air)

$n_f$  Index of refraction (oil)

P  Pressure

q  Dynamic pressure

r  Radius or Recovery Factor

$R_{xx}$  Autocorrelation

$Re$  Reynolds number, $\frac{\rho U L}{\mu}$

$St$  Strouhal number, $\frac{f L^\mu}{U_\infty}$

T  Time

$T_{aw}$  Adiabatic Wall Temperature

u, U  Velocity

**Greek**

$\alpha$  Angle of attack OR angle with respect to the fin tip origin

$\alpha_F$  Fin angle

$\alpha_i$  Incipient angle

$\beta_o$  Inviscid shock angle

$\beta_{ps}$  Primary separation angle

$\beta_r$  Reattachment angle
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$\beta_{ss}$</td>
<td>Secondary separation angle</td>
</tr>
<tr>
<td>$\beta_{ui}$</td>
<td>Upstream influence angle</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Specific heat ratio</td>
</tr>
<tr>
<td>$\gamma^2$</td>
<td>Coherence</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Boundary layer height</td>
</tr>
<tr>
<td>$\delta^*$</td>
<td>Boundary layer displacement thickness</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Shock wave angle OR Momentum thickness</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>Light angle of incidence</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Mach wave angle or Dynamic viscosity</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
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<tr>
<td>$\sigma_p$</td>
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<tr>
<td>$\tau_w$</td>
<td>Wall shear stress</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Phase difference</td>
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**Subscripts**

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<tr>
<td>$\infty$</td>
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<td>$\circ$</td>
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**Other**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varnothing$</td>
<td>Hole diameter</td>
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LIST OF ABBREVIATIONS

CCD - Charged Coupled Device
CFD - Computational Fluid Dynamics
DSFV - Differential Surface Flow Vector
FCAAP - Florida Center for Advanced Aero-Propulsion
FIB - Fluoride Isopropyl Butyl
FR PSP - Fast Response Pressure Sensitive Paint
FSU - Florida State University
HVLP - High Volume Low Pressure
ISSI - Innovative Scientific Solutions Incorporated
LED - Light Emitting Diode
LES - Large Eddy Simulation
OFI - Oil Film Interferometry
PIV - Particle Image Velocimetry
PLS - Planar Laser Scattering
PSD - Power Spectral Density
PSP - Pressure Sensitive Paint
PSU - Penn State University
PSWT - Polysonic Wind Tunnel
RMS - Root Mean Square
SBLI - Shockwave Boundary Layer Interaction
SLIDE - Streakline Image Differencing Extraction
SOF - Surface Oil Flow
TSP - Temperature Sensitive Paint
VCO - Virtual Conical Origin
Shockwave boundary layer interactions (SBLI) occur on both internal and external surfaces and adversely affect both the structural and propulsive performance of high-speed flight vehicles operating in the trans/super/hypersonic flow regimes. In the absence of a comprehensive understanding of the flow physics associated with SBLI, the most common approach to mitigating the negative ramifications is structural over-design, often resulting in reduced aero-propulsion efficiencies and excessive cost. SBLI have been the subject of numerous experimental and numerical investigations focusing on simplified two-dimensional (2-D) canonical configurations derived from relatively complicated aircraft/turbomachinery components. A few recent studies have focused on addressing the knowledge gaps by examining component geometries that produce three-dimensional (3-D) SBLI and therefore a closer representation of real-world configurations.

The current experimental investigation explores the viscous/inviscid interaction of an incoming supersonic turbulent boundary layer and a single, sharp unswept fin generated shockwave. This kind of SBLI is of keen interest to the high-speed aerodynamics community as the separated flow induces a strong crossflow component, giving rise to a highly 3-D flowfield. Although previous studies on 3-D SBLI have provided a substantial knowledge base, there are still a number of consequential questions pertaining to the flowfield topology and dynamical behavior that remain unanswered. First, what is the effect of Reynolds number on SBLI flow features, in particular, the length scales associated with the shock-induced separation region and its interaction with the shock generator (sharp-fin)? Second, what is the extent of facility dependence on the 3-D SBLI? Which, if any, component(s) of the unsteadiness is inherent to the interaction and which are facility dependent and therefore limit or bias the flowfield? Are the geometric and boundary layer constraints imposed by the size of the facility necessary for numerical simulations to ensure the proper development of scaling parameters as experiments shift from the laboratory scale to flight testing. Finally, how do the spatio-temporal scales associated with SBLI vary with the interaction strength? The main objective of the present experimental study is to answer the posed questions by conducting a detailed flowfield analysis of the sharp fin induced SBLI over a range of Reynolds numbers and interaction strengths.
The research methodology involves high-fidelity experiments at the state-of-the-art wind tunnel facilities housed at the Florida Center for Advanced Aero-Propulsion at Florida State University and the data available from previously published literature. Cutting-edge global flowfield diagnostics allow for the full-field reconstruction of both skin friction (mean) and pressure (time-averaged/unsteady) underneath the single fin SBLI as the incoming Mach number ($M_\infty = 2 - 4$), fin angle of attack ($\alpha_F = 10^\circ - 20^\circ$), and unit Reynolds number ($Re/m \approx 17 \times 10^6 - 108 \times 10^6$) are parametrically varied. Reynolds number sweeps, spanning nearly an order of magnitude, illustrate that the interaction footprint is distinctly affected by the Reynolds number, with the effects being most prominent near the fin/surface junction and the outer edges of the interaction near the freestream boundary. The results indicate that the interaction flowfield becomes less receptive to Reynolds number variations as the Reynolds number continues to increase. This shrinking dependence indicates that there may be a point beyond which any further increases to the Reynolds number produce negligible differences in the flowfield i.e. Reynolds number independence. Identical surface oil flow and pressure measurements carried out in facilities of different scale/size compare favorably throughout the interaction region with Reynolds number based scaling. However, different incoming boundary layer thicknesses impose limitations on the extent of the inception region and the onset of finite fin effects. When investigating the mean skin friction between different scale facilities, the Reynolds number scaling could not be assessed due to limitations of the available data sets. An angular scaling was applied to enable proper inter-facility comparison between the conical regions of both identically matching and nominally equivalent interaction strength test cases. The results showed trends similar to those seen in the pressure measurements, with skin friction matching well between the facilities across the interaction with minor divergences in the near fin region, where viscous effects become more prominent.

Simultaneously sampled high-speed pressure transducers and fast response PSP measurements allowed for a full-field investigation of the flow dynamics. The RMS pressure field highlights regions of increased unsteadiness along the interaction boundary, inviscid shock line and at/upstream of the fin tip vertex. Increased coherence levels indicate a communication mechanism is present between the inviscid shock and the interaction boundary. When compared with studies conducted in a smaller facility, findings of the current work are consistent in both the locations of increased unsteadiness and their respective magnitudes. In addition to illustrating the robustness of these
dynamical features between differing size facilities, the current work identifies the presence of elevated levels of low-frequency content. The presence of this low-frequency content has been observed in investigations associated with 2-D SBLI, but has been absent in the 3-D SBLI studies conducted in smaller facilities.

The present study has contributed significantly to a better understanding of swept 3-D SBLI, in particular, the role of Reynolds number and the size of facility on the interaction characteristics. The flowfield analysis has discovered the underlying physics associated with the fin induced SBLI. The high-fidelity experimental database generated will be very useful for the validation of numerical tools and the development of flight vehicle design guidelines.
CHAPTER 1
INTRODUCTION

1.1 Motivation

As the aerodynamics community continues its attempts to increase both the operational envelope and overall efficiency of supersonic and hypersonic flight vehicles, it has become clear that a more comprehensive knowledge of the underlying physics of shock wave/boundary-layer interactions (SBLI) is required. SBLI are omnipresent phenomena that adversely affect the performance of both high-speed flight vehicles operating in the trans/super/hypersonic regimes and rotating turbomachinery [34]. These detrimental effects are seen on both internal and external surfaces in the form of reduced control authority, highly unsteady thermo-mechanical loading, inlet instability and in some cases a complete engine unstart [26]. Additionally, the optical aberrations produced by shock wave induced density variations can negatively affect laser based communication and weapon systems. Without an approach to efficiently mitigate the adverse effects of SBLI, engineers and designers are currently forced to over-design flight vehicles and machinery systems that routinely result in excessive costs and reduced aero-efficiencies. Endeavors currently underway to produce the next generation of both commercial and military supersonic flight vehicles, succeeding precursors such as the Concorde or the SR-71 (Fig. 1.1), would greatly benefit from an overarching knowledge base.

As the name would imply, SBLI occur when a flow induced shock wave comes into contact with a boundary layer, meaning that a fundamental understanding of each individual phenomena is required when attempting to approach the resultant combination. Boundary layers form as a consequence of viscous fluid flows satisfying the no-slip condition, in which the fluid velocity at a solid surface must match the surface velocity [53]. Due to the velocity gradient that forms within the boundary layer, shear forces dominate within the region near the surface. Shock waves form due to the coalescence of multiple compression waves and cause discrete changes in almost all flow properties (pressure, temperature, density, etc.) across the shock. It is most common to see shocks modeled as discontinuities that separate an otherwise inviscid flow. In this framework, when a shock
wave interacts with a solid surface, the shock will reflect off uninhibitedly, as illustrated using an impinging shock in Fig. 1.2b. Although this gives a reasonable approximation of the mean structure of a real fluid flow, it neglects the viscous effects imposed by the boundary layer[47]. When the viscous effects imposed by the boundary layer are properly accounted for as shown in Fig. 1.2c, the abrupt increase in pressure induced by the shock causes a decrease in fluid velocity within the boundary layer [11]. If the momentum and shear forces present within the boundary are able to manage the adverse pressure gradient, the shock wave will reflect as seen in Fig. 1.2c and the flow will remain attached, although as a consequence, the boundary layer will see an increase in thickness (δ). This outcome in which no separation occurs is denoted as a “weak” SBLI. If the adverse pressure gradient generated by the shock is of significant enough magnitude that it overcomes the boundary layer viscous forces, the boundary layer will thicken to a point at which it can no longer remain attached. A free shear layer is formed at this instance and a region of reverse circulation is observed near the surface. Once the shear layer reattaches at a downstream location, a clearly defined separation bubble results in a global length scale whose size remains relatively invariant with time. The flow structure is referred to as a “strong” SBLI.

These viscous-inviscid phenomena have been a subject of interest for decades, being the focus of numerous experimental and computational studies that have been cataloged in multiple review
Figure 1.2: Diagram illustrating the underlying independent components of SBLI (viscous boundary layers and inviscid shock waves) and the potential resultant flows generated when both factors are properly considered. Adapted from [21, 58]. Not to scale.

papers [80, 65, 26, 50, 11, 21, 34] over the years. The fundamental structures that appear in 2-D SBLI (like the impinging shock seen in Fig. 1.2) have been well studied, therefore, recent studies [21, 34] have focused on and made great strides in the characterization of dynamics and inherent unsteadiness present within these interactions. However, when discussing the more complex 3-D SBLI configurations that are omnipresent in real-world application, the knowledge base derived from 2-D interactions cannot be immediately applied. A number of critical questions regarding the spatio-temporal nature of 3-D flows and the influence of parametric values, such as the Mach and Reynolds numbers, on these flows persist to the current day. The purpose of this experimental study is to broaden the general understanding of the effects of these parametric values on the mean structures of 3-D SBLI and to explore the scalability of both time averaged and unsteady flow behavior using a variety of global flowfield diagnostics. The following sections present the knowledge base necessary to investigate 3-D SBLI and a more detailed description of the objectives of current study.
1.2 Literature Review

Due to the inherent geometric complexities presented by aircraft bodies and inlets, studies were conducted on a number of canonical geometries that simplify the full-fledged structures to better grasp the fundamental physics involved. These simplified configurations, shown in Fig. 1.3, are broken into two classifications based on the nature of the flow separation experienced. Configurations such as a simple compression ramp or a shock impinging on a flat surface are what can be considered nominally 2-D interactions. These configurations exhibit a ‘closed’ separation, in which a well-defined, contained separation bubble is formed. Once the flow has been established, the distance between mean separation and attachment points forms a global length scale. Configurations like the swept compression ramp and single unswept/swept fin are classified as 3-D interactions and generate what is known as an ‘open’ separation. Like their 2-D counterparts, the 3-D interactions produce a separated region of recirculation, however, there is an additional velocity component that keeps these flows from being bounded in the same manner and allows the flows within the

![2-D SBLI Diagram](image1)

![3-D SBLI Diagram](image2)

Figure 1.3: Canonical 2-D and 3-D SBLI configurations extracted from supersonic flight vehicles. Adapted from [34]. Not to scale.
separated region to continue propagating downstream. Moving forward, the primary focus of this literature review will be on discussing the characteristics of and differences between 2-D and 3-D SBLI, though brief discussions of other characterization criteria such as the incoming boundary layer (laminar or turbulent) or the separation status (attached or separated) may appear.

1.2.1 2-D SBLI

Though the intended purpose of this study is to investigate the nature of 3-D SBLI, it is necessary to begin by discussing the general structures and dynamics that characterize 2-D SBLI, as they comprise the fundamentals required to understand their 3-D counterparts. While considered “simpler” in relation to canonical 3-D SBLI configurations, 2-D configurations merit study in their own right as they present themselves widely across the cowlings, inlets and wings of real-world supersonic flight vehicles. Numerous experimental and numerical studies have been conducted on the various canonical 2-D SBLI configurations, with summary papers of note dating back to the 1970’s [41, 44]. In addition to the previously shown impinging shock and compression ramp, 2-D configurations also include both forward and backward facing steps [23] (which could be considered a ramp with a 90° deflection angle) and normal shocks [11]. As the name would imply, SBLI are considered 2-D they exhibit no span-wise variations across the width of the flowfield. This span-wise invariance is what allows for the previously mentioned ‘closed’ separation bubble to form in the presence of a ‘strong’ SBLI. While the 2-D assumption holds nominally true, it is not uncommon for experimental works to see 3-D effects propagate inward from the interaction periphery due to sidewall influence and other facility restraints [12].

To highlight the pertinent length scales and physical behavior commonly seen in 2-D SBLI, the compression ramp (also known as a compression corner) is presented below in more detail. Like the impinging shock interaction, when a ‘weak’ SBLI forms in response to the sudden change in flow direction brought about by a compression ramp the boundary layer will thicken but flow will remain attached. Illustrated in Babinsky and Harvey[11], the ‘weak’ interaction can modeled almost identically to an inviscid flow except in the immediate vicinity of the flow surface. In moving to the ‘strong’ compression ramp SBLI, a brief moment should be taken to mention what delineates the strength of an interaction. The general strength of an SBLI is governed by two basic factors, the incoming Mach number and the deflection angle that causes a shock wave to form (with the exception of normal shock SBLI). The Mach number and deflection angle are the independent
variables necessary to determine the shock wave angle ($\theta$), which in turn is used to calculate the inviscid pressure ratio across the shock wave, thus dictating the resultant adverse pressure gradient that opposes the boundary layer shear forces. An increase in either the incoming Mach number or the deflection angle will increase the likelihood of inducing separation. As an example, Settles et al [86, 84], examined the compression ramp SBLI using a wide range of deflection angles for a relatively constant Mach number ($M_\infty = 2.9$). From the study, it was found that a ramp angle of $15^\circ$-$18^\circ$ would induce incipient separation (non-uniform alternating periods of attached/separated flow), with lower ramp angles keeping the flow attached and higher ramp angles inducing full separation.

Returning to the compression ramp flow features, assuming the requirements to induce full separation have been met a strong SBLI will form as shown in Fig. 1.4. The separation point of the boundary layer can be seen to lie upstream of the ramp corner and reattaches at a point downstream of the corner. Size of the separation bubble, i.e. the reach up/downstream of the corner, is dictated by the strength of the interaction. Using surface oil flow, Settles et al. [87]
showed that the stream-wise extent of the separation bubble \( L_s \) increased with increasing ramp angle (constant \( \text{M}_\infty \)). The presence of the separation bubble generates compression waves that coalesce to form the separation shock. As shock waves are inherently unsteady, the position of the separation shock foot is constantly moving, the span of this motion is denoted by the intermittent separation length scale \( L_i \). These separation length scales are routinely used in the Strouhal number when discussing flowfield dynamics and will be discussed further in the following section. A reattachment shock forms behind the separation bubble, which joins together with the separation and inviscid shocks to form a lambda shock. Based on the velocity disparity downstream of the inviscid and reattachment shocks, a slipline can be seen to emanate from the triple point of the lambda shock. Shown below the compression ramp diagram in Fig. 1.4 are the typical trends that would be seen for the surface skin friction and pressure. For both flow properties, the locations of separation and reattachment are the primary drivers of change. The surface pressure is seen to rise from the freestream value significantly as the flow crosses through the regions where the separation and reattachment shock feet exert their respective influence, before reaching a semi-equilibrium downstream of the lambda shock. The skin friction exhibits a more interesting behavior as the flow direction at the surface changes on multiple occasions, resulting in the sign changes seen on the plot. The first instance comes when the incoming flow meets the reversed flow induced by the separation bubble, producing a skin friction node \( \left( \frac{C_f}{C_{f\infty}} = 0 \right) \) of convergence at the separation point. A second node of divergence occurs at the reattachment point when the flow returns to its original direction.

**Unsteadiness in 2-D SBLI.** As shock waves are inherently unsteady by nature, investigating the fundamental dynamics exhibited by SBLI becomes a crucial task in properly characterizing both 2-D and 3-D interactions. As the separation bubble pulsates and shock feet position shift up/downstream, the regions that these features move across are continuously exposed to a repetitive increase and decrease in both surface pressure and temperature. This irregular thermo-mechanical loading and unloading of the underlying surface is one of the most significant negative effects produced by SBLI and can lead to premature material fatigue. While there are discrete changes in both the pressure and temperature induced by shock motion, when considering SBLI generated in the supersonic flow regime (as is the purpose of this work) the temperature effects are relatively less of a concern and as such will not be discussed in this review. However, it should be noted
that when operating in the hypersonic regime, thermal effects caused by SBLI must be thoroughly understood to achieve the desired performance. Review papers by Dolling [26], and more recently Gaitonde [34], have discussed the critical nature of fully understanding the heat transfer present in these interactions and the difficulty in accurately measuring or modeling high heat transfer rates.

The unsteadiness that is observed in 2-D SBLI occurs over a wide band of frequencies and is most commonly conveyed in terms of non-dimensional frequency, the Strouhal number (St = fL/U∞). The characteristic length scales most often used in the Strouhal number are the separation bubble length (Ls) and the incoming boundary layer thickness (δ). The highest frequencies are associated with the turbulence present within the incoming boundary layer, having a Strouhal number on the order of approximately 1 (Stδ ∼ 1) [75]. The frequency band of StLs ∼ 0.5 is linked to the shedding that occurs along the separation induced shear layer, corresponding to Kelvin-Helmholtz shedding [1]. The motion seen in the separation bubble produces unsteadiness in the frequency band around StLs ∼ 0.1. Finally, the lowest frequencies of interest (StLs ∼ 0.03) appear to coincide with large scale bubble breathing and the motion of the shock foot. This low frequency phenomena has been the subject of intense study in recent years [21] as researchers work to discern the physical mechanisms that govern this behavior, focusing on two distinct driving forces. One viewpoint being that the unsteadiness is driven by large structures present in the upstream boundary layer [36, 35], while the other poses that the separation characteristics (bubble dynamics and shear layer) drive the unsteadiness[27]. Both positions are examined below.

Beginning with the upstream mechanism, initial mathematical theories by Plotkin [69] proposed a model that described how the broad range of velocity fluctuations present in the upstream boundary layer resulted in low frequency unsteadiness exhibited by the shock motion. In early experiments involving the study of a Mach 3 compression ramp [8], it was found that the burst frequency present in the upstream boundary layer was of a similar order of magnitude as the unsteadiness seen in the shock wave motion. Experiments utilizing both time resolved flow visualizations and surface pressure measurements on a rear facing step [70] illustrated that reattachment of the shear layer was significantly influenced by structures found in the incoming boundary layer. The same study, and additional works by the same researchers [72], also gave experimental credence to the model proposed by Plotkin using previously collected blunt fin data. High-speed, near-wall, PIV and pressure measurements conducted by Beresh et al. [16] showed a clear correlation be-
tween the instantaneous ‘fullness’ of the boundary layer and the shock motion. Positive velocity fluctuations in the lower portion of the boundary layer corresponded to downstream motion of the shock structure, while the negative fluctuations were due to the reverse shock motion. This makes physical sense as the increased momentum of a fuller boundary layer profile results in the ability of flows to be more resistant to separation, thereby shifting the location of the instance of separation. Conducting PIV and PLS in both the stream-wise and span-wise planes on a Mach 2 compression ramp, Ganapathisubramani et al. [36, 35] discovered the presence of large ‘superstructures’ in the upstream boundary layer measuring $8\delta - 40\delta$ in length. These long structures presented regions of low and high velocity influenced the oscillation dynamics seen in the separation line (surrogate), being denoted as ‘local’ influences. It was also determined that non-superstructure oscillations in the upstream boundary layer and in the downstream separation bubble, cumulatively denoted as ‘global’ influences, could contribute to the low-frequency unsteadiness. Ganapathisubramani et al. [36, 35] noted that while both local and global influences affected the separation/shock motion, the local influences contributed more than the global influences.

Having examined the work of researchers who posited the presence of an upstream mechanism that governs the low-frequency motion seen in SBH, the following looks at a number of works who found evidence of influence coming from the region of the separation bubble (i.e. downstream). In a similar vein as Andreopoulos and Muck [8], Thomas et al. [92] examined how the dynamics of a relatively weak set of compression ramp interactions was impacted by the burst sweep mechanism present in the upstream boundary layer. The work found that the separation and reattachment points of the bubble moved in opposite directions, resulting in bubble expansion and contraction. Additionally, high levels of coherence were observed between in the reattachment and intermittent regions pointing towards the presence of a downstream mechanism. Large eddy simulations (LES) conducted by Touber and Sandham [93] were run for the impinging shock configuration, modeled after experiments conducted in other works [27, 28]. The study did not exhibit any of the ‘superstructures’ found in Ganapathisubramani et al., through the low-frequency behavior was still present leading to the thought that their impact was less significant than previously expected. This along with the similarity of convective velocities of disturbances and the motion insinuate that global instabilities in the vicinity of the separation bubble drive the unsteadiness mechanism. Two similar models proposed by Wu and Martin [100] and Piponniau et al. [68] respectively,
considered the entrainment effects induced by the separation shear layer. Mass from within the separation bubble would regularly be entrained and shed from the separation induced shear layer, then recharged in the region of the reattachment point producing a feedback loop.

Although investigations typically focused on whether the low-frequency motion of the shock and separation bubble were driven by upstream or downstream mechanisms, it was not uncommon for works to see the effects of both [29, 18, 94, 74]. In the last decade, different authors have come to acknowledge the omnipresence of both upstream and downstream influences on flow unsteadiness [20, 88, 21] and have attempted to discern when the respective effects play a dominant or secondary role. Based on the overall findings, it appears that the strength of the interaction plays a pivotal role in the determination of the dominant factors, which is often characterized by the inviscid shock strength and the Reynolds number. For weaker interactions fluctuations found upstream of the separation appear to correlate well with observed bubble dynamics. For stronger interactions, the separation bubble pulsates in a manner consistent with instabilities found downstream, most notably at the reattachment.

Some of the most recent numerical and experimental studies attempting to discern the governing forces in 2-D SBLI unsteadiness have made great strides, continuing to find sources both up and downstream. As with previous studies, Candola et al. [19] and Estruch-Samper and Chandola [30] have found the shear layer to be a key contributor in the observed unsteadiness using axisymmetric steps. Both studies showed that eddies responsible for the entrainment and expulsion of mass from the recirculation region grow and evolve when moving downstream. While the upstream conditions (boundary layer thickness and edge velocity) have little impact on the flow once well into the separated region, these factors have an impact on the initial instabilities at the formation of the shear layer, thereby playing a role in the evolutionary process of the shear layer eddies. Porter and Poggie [73] and Poggie [71] looked into how induced forcing effects the unsteadiness, finding that the system in receptive to forcing as observed by the shock and separation bubble location becoming “synchronized” to said forcing. This is said to support a model of separation unsteadiness in which the boundary layer turbulence is able to influence a weakly damped global mode of the separation bubble. This however, gives rise to some debate as it lies in contrast to statements by Adler and Gaitonde [1]. Their work found that the absolute instabilities present in interactions
are maintained by the feedback produced by the perturbations present in the recirculation region, causing a self-sustainability and general insensitivity to external forcing.

1.2.2 3-D SBLI

Having conducted a review of the primary structures and key dynamics of 2-D SBLI, an inspection of the comparable and dissimilar attributes of 3-D SBLI can begin in earnest. As mentioned previously, an additional velocity component is present in 3-D SBLI that causes the flowfield topology to exhibit non-homogeneous span-wise behavior. The recirculation zone (in some cases zones) that forms as a result of the shock induced separation continues to grow in size as it propagates downstream, prohibiting the delineation of a global length scale \((L_s)\) related to the separation bubble. This non-uniform bounding of the region of separated flow is known as an ‘open’ separation. Additional classifications, detailed in Settles and Dolling [80], can be used to further differentiate the wide range of geometries that generate 3-D interactions. The first classification refers to whether a given test geometry has any inherent length scales aside from the incoming boundary layer. Geometries such as the blunt fin and cylinder can be characterized by their diameter and are therefore ‘dimensional’, while interactions such as the unswept single sharp fin and swept compression ramp have no such associated length scale and are termed ‘dimensionless’. The second classification is related to the size of the incoming boundary layer \((\delta)\). For most geometries that generate 3-D SBLI there is a point at which further increasing the geometry height (as compared to the incoming boundary layer thickness) no longer produces any change to the resultant interaction. Geometries that fall under this classification are termed ‘semi-infinite’, while those that do not are known as ‘non-semi-infinite’.

As this work utilizes experimental results from the unswept single sharp fin to investigate the influence of various factors on 3-D SBLI, its flowfield will be explained in detail. The single fin interactions forms when an incoming supersonic boundary layer interacts with a fin placed at an angle of attack with respect to the incoming flow. The resultant oblique inviscid shock wave causes a discrete pressure change that the incoming viscous boundary layer is unable to overcome, causing a region of separated flow to form. This separation vortex propagates outward, as shown in Fig. 1.5, producing an ‘open’ separation described previously. The interaction is known to be both ‘semi-infinite’ and ‘dimensionless’.
Initial studies of the single sharp fin configuration relied heavily on surface oil flow visualizations. These studies revealed separation and reattachment lines, showing the boundaries of the open separation zone, as well as the upstream influence line which denotes the point at which the incoming flow begins to be affected by the interaction. The section normal to the inviscid shock in Fig. 1.5 shows that within this slice, the 3-D interaction appears quite similar to the previously discussed 2-D compression ramp, having a region of “reverse” flow with nodes at the separation and attachment lines. When observing higher interaction strength ($M_n > 1.5$) cases, as determined by the incoming freestream Mach number ($M_\infty$) and the shock wave angle ($M_n = M_\infty \sin \theta$), a secondary separation region was also observed. While the secondary separation has been seen over a wide range of interaction strengths, the secondary reattachment line has only been observed for very strong interactions [85, 78, 32] and often lies extremely close to the secondary separation line making it hard to discern.

When following these flow features and the inviscid shock line downstream from the fin tip, it was seen that the features’ curvatures eventually became constant and appear as straight lines. When each feature was extrapolated upstream (using the straight line section of the flow features), they were found to intersect at a point upstream of the fin tip [81, 82]. A new spherical coordinate system was constructed about the upstream junction, dubbed the virtual conical origin (VCO), to take advantage of the conical assumption and simplify the study of interaction [46]. The conical assumption, which states that flow exhibits invariant behavior with relation to radial distance, has
been successfully applied to the interaction in a number of studies. The assumption is only seen to gradually break down in two locations, along the fin/floor junction and in the region immediately adjacent to the fin tip, highlighted in Fig. 1.5, known as the inception region. For this reason, the unswept single sharp fin SBLI is termed to be quasi-conical [37].

Efforts to visualize the interaction above the floor surface have shed significant light on the flow structures present. Studies utilizing techniques such as conical shadowgraphy and PLS [5, 6] conducted in a plane normal to the inviscid shock captured the lambda-shock structure and visualized the separation bubble. Shown in the section view of Fig. 1.5, the inviscid shock bifurcates into the two legs (separation and rear) of the lambda-shock and sits above a vortex. Above, emanating from the triple point of the lambda-shock, a slip-line forms between the flow passing through a single inviscid shock and the higher-velocity flow that passes through the bifurcated shocks close to the boundary layer. Recent experimental studies [10] have used PIV to quantify the velocity above the surface and high-speed conical shadowgraphy to investigate the dynamical nature of the lambda shock motion.

**Flowfield Scaling Efforts.** Efforts to provide simple predictive scaling methods regarding a single unswept fin in supersonic flow date back to the 1970’s, where the Mach number and deflection angle were used to produce thresholds for when incipient primary [51, 52] and secondary separation [102] would occur.

\[ M_{\infty} \alpha_i = 0.3 \quad \text{and} \quad M_{\infty} \alpha_{i2} = 0.6 \]  

During the 1980’s, a significant amount of experimental effort was invested in producing scaling laws for the 3-D configurations shown in Fig. 1.3. Work conducted by Settles and Teng [83] focused on studying the conical and/or cylindrical nature present in high-speed swept compression ramp flows. It was found that cylindrical symmetry was present when dealing with an attached inviscid shock, while conical symmetry appeared when the inviscid shock was detached. With the establishment of the conical reference frame, Zheltovodov et al. [103] introduced a set of empirical relations that described the angular location of the upstream influence (\( \beta_{ui} \)), primary separation (\( \beta_{ps} \)) and reattachment lines (\( \beta_r \)) with respect to the VCO. The relations were also found to reasonably apply to semi-cones as well [11]. A study by Settles and Kimmel [81] looked at a large number of shock generators (swept/unswept fins, cones and compression corners/ramps) using parameters such as
the interaction strength \((M_n)\), peak pressure ratio across the interaction \((\frac{P_2}{P_1})\) and Reynolds number \((Re)\). It was found that characteristics that would appear with each respective interaction were largely governed by the inviscid shock wave strength and orientation. The same parameters also played a role in allowing for inter-configuration comparisons. Reynolds number studies of the same period [25, 82] correlated the Reynolds number \((Re_\delta)\), incoming boundary layer thickness \((\delta)\) and inceptive length \((L_i)\); measured from the VCO to the furthest extent of the inception region along the inviscid shock trace; to describe the behavior of SBLI. These studies were limited in their scope due to restrictions on the available testing parameters and the size of the facility. The correlations, developed using data over a Mach number range of 2.5 - 4, would later be expressed in the simplified expression [79] shown in Eqn 1.2.

\[
\frac{L_i}{\delta} \propto \frac{M_n}{Re_\delta^{1/3}}
\]  

(1.2)

A renewed interest in the study of SBLI has brought about recent works that have been able to find correlations by which the mean interactions of various configurations may be scaled. First used in Arora et al. [9], the inviscid shock angle and Mach wave angle, \(\beta_o\) and \(\mu\) respectively, were incorporated to produce a modified angular reference that provided a comparable scaling for the single fin interaction when comparing nominally identical shock strengths using mean surface pressure distributions [14, 24]. This preliminary scaling was able to facilitate a basic study of the effects of facility size spanning an order of magnitude with respect to tunnel cross-sectional area [14]. To account for the magnitude differences present when these comparisons were made, Deshpande [24] used the freestream and maximum interaction pressures to effectively normalize various data sets, \((P_w-P_\infty)/(P_{max}-P_\infty)\). Vanstone et al. [96] explored the quasi-conical/cylindrical nature of the swept compression ramp using surface oil flow and PIV, determining that while the various components of velocity achieve invariant conical behavior, it is not at the same point in the flow. Mears et al. [59] made spatially resolved pressure measurements, both steady and unsteady, on the surface underneath the single unswept fin using pressure sensitive paint (PSP). The study provided precursory illustrations that wind tunnel facilities with differing size boundary layers could be scaled to align and highlighted some limitations of the previously established semi-empirical scaling laws, finding scaling the Reynolds number with an exponent of 0.7 (as opposed to 1/3) resulted in a better match at Mach 2. Computationally, the work of Adler and Gaitonde [3]
discussed the inceptive properties/effects of the single fin interaction and the two mechanisms most broadly associated with this behavior, the bow shock curvature and the incoming boundary layer. Additionally, they proposed a secondary inceptive origin, and its potential ability to improve the reproducibility between various experimental and/or computational techniques. This secondary origin was confirmed experimentally by Mears [58]. In terms of Reynolds number, Baldwin et al [14] showed that normalized pressure data extracted from the conical region of flow was nearly invariant to Reynolds number variation almost one order in magnitude. Studies conducted on the 2-D compression ramp showed that as the Reynolds number increased the flow had an increased resistance to separation, as shown by shifts in the upstream influence/primary separation locations [45, 84]. Little work has been done in understanding the Reynolds number effect (for a single geometry and boundary layer thickness) for 3-D SBLI, but the current work looks to remedy this issue by examining surface oil flow and global pressure measurements over a range of test conditions and geometry orientations.

**Unsteadiness in 3-D SBLI.** While significant work has been done to thoroughly characterize the time averaged flowfield structures in 3-D SBLI, an understanding of the flowfield dynamics present in these interactions markedly lags behind. Ideally, researchers would be able to leverage the vast knowledge base that has been accumulated regarding 2-D SBLI unsteadiness, but due to the intrinsic differences between 2-D and 3-D SBLI this is not immediately possible. As has already been discussed, the non-spanwise homogeneous ‘open’ separation exhibited by 3-D SBLI does not produce a true bounded recirculation region, but rather a crossflow velocity induced vortical structure that continues to grow in size as it propagates downstream. This lack of a bounded recirculation bubble immediately causes issues when attempting to apply some of the proposed feedback mechanisms from 2-D interactions that are reliant on the structure. Additionally, the continual variation in the size of the vortical region prevents the establishment of a global mean separation length scale, even with the successful application of either cylindrical or conical symmetry applied to the flowfield to simplify their study. As a majority of 3-D SBLI are dimensionless, the length scales most commonly associated with the interactions (for non-dimensionalization purposes) are the incoming boundary layer thickness and the inception length.

Early experimental studies on the unsteadiness found in 3-D interactions focused on the measurement of pressure fluctuations on the surface beneath the generated shock structures. Schmisseur
and Dolling [77] examined the flowfield produced by a single un-swept fin (at multiple angles of attack) for a Mach 5 flow. Using high-frequency pressure transducers, they showed that the RMS pressure ($\sigma_p$) exhibited a similar quasi-conical behavior to that seen in mean pressure measurements. It was also found that the frequencies associated with the separation shock were approximately an order of magnitude higher than those seen at the same flow conditions when examining 2-D SBLI. Single fin studies conducted at Mach 3 and 4 by Garg and Settles [38] first noticed peaks in the RMS pressure near the reattachment line and close to the fin/surface junction (possibly induced by slipline fluctuations). Also noted was that local peaks in the RMS data appeared in approximately the same location (angular position in the conical reference frame) as the inflection points present in the mean pressure curves. A more recent work by Arora et al [10] examined both surface pressure fluctuations and the overlying lambda structure dynamics using high speed conical shadowgraphy. The experimental work showed that the low-frequency dynamics that dominate 2-D interactions were absent, dynamics that were also absent in matching LES simulations conducted by Adler and Gaitonde [2, 4]. In both experimental and computational studies the unsteadiness was dominated by mid ($0.01 < St_\delta < 0.2$) and high ($St_\delta > 0.2$) frequency unsteadiness. Elevated coherence levels seen between the intermittent separation region and the region underneath the separation bubble, along with correlations of the rear and separation shocks seen in the high speed shadowgraphy, assert the existence of correlated motion between the two shock legs. While most all previous experimental studies had been primarily restrained to the conically developed region of the flowfield, for various reasons, Mears at el [59] was able to probe the entire surface underneath the single fin SBLI using PSP. Spatially resolved global unsteady pressure measurements highlighted quasi-2-D behavior near/immediately upstream of the fin tip due to the presence of ‘bow-like’ structures. Additionally, relatively increased RMS pressure levels emanating from the fin tip and stretching downstream along the upstream influence and separation regions were observed, most likely caused by the shock foot motion.

Investigations of the stream/spanwise velocity fields at/above the underlying surface have also proven fruitful at expanding the understanding of 3-D unsteadiness. Multiple studies on the swept compression ramp at Mach 2 conducted by Vanstone et al [97, 98] have used both high speed PIV and PLS to look at fluctuations in the velocity field. The PLS revealed the presence of superstructures ([35]) that effected the local position of the instantaneous separation line, with high
momentum structures reducing the size of separation and vice versa. As with the studies conducted by single fin studies, the swept compression ramp showed that mid and high-frequency bands had significant contributions to the unsteadiness when compared to the low-frequency band, though upon further examination it was found that the low-frequency band had the highest correlation with the upstream fluctuations. Time scales based on the mid-frequency band correspond to those found in the incoming superstructures, suggesting that there is a connection to the convection speed of said structures.

### 1.3 Objectives of the Current Study

The present work focuses on expanding the understanding of 3-D SBLI in three areas: the effects of Reynolds number, the interaction strength, and the test facility dependence, that have not been thoroughly investigated and are necessary to further the aerospace community’s comprehension of these fundamental interactions.

As mentioned in the previous section, the effects of Reynolds number on the single fin interaction has been studied through a limited scope. Parametric variation of the Reynolds number has traditionally been limited as previously used wind tunnels have only been able to modify the Reynolds number via the boundary layer thickness (the only relevant length scale). This was achieved by switching from test section floors to raised flat plates, requiring multiple varying size fins. The established scaling laws, while proven effective so far, may not convey a robustness to completely describe the effects of Reynolds number variation while having a nominally invariant boundary layer thickness. The state-of-the-art primary wind tunnel facility used in the present study has the capability to operate at a single freestream Mach number over a wide Reynolds number envelope; in some cases almost an order of magnitude variation is possible. This manner of parameter variation (constant $M_{\infty}$, variable Re/m) is analogous to a supersonic vehicle flying at different altitude conditions, as the constant geometry of the body is exposed to a wide range of flow conditions induced by changing air pressure and density. Conducting tests in this manner should allow for the isolation of how Reynolds number variation affects 3-D SBLI. Preliminary studies using discrete, mean pressure sensors [14] on a small ($\delta \approx 3\text{mm}$) boundary layer have shown that the (minor) effects are predominantly seen near the periphery of the interaction. These results are further expanded upon using global pressure flow diagnostics (PSP) to gain a better perspective
of the Reynolds number effect on the flowfield topology with a relatively larger boundary layer ($\delta \approx 15\text{mm}$). The Reynolds number dependency has the potential to provide future guidance for both experimental and numerical studies, as some facilities and computational methods are Reynolds number restricted due to size, resource allocation, and processing times, respectively.

Second, it is well known that the interaction strength plays a significant role in determining the shape and feature characteristics present in SBLI. Basic efforts have shown that nominally matching the interaction strength can be used as a bridge when comparing work conducted at different Mach numbers and angles of attack when comparing mean surface pressures, though these scalings have not been able to be successfully applied to other common flow measures, such as skin friction, RMS and unsteady pressures. The current study attempts to expand upon the understanding of how the spatio-temporal scales of 3-D SBLI change with varying fin angle and interaction strength and what physical mechanisms are effected by said variations. The use of highly spatially-resolved quantitative experimental techniques provide a significantly increased capability when compared to previously conducted studies.

Finally, this investigation hopes to define if/how the SBLI flowfield and fluid structures observed are wind tunnel facility dependent. Do the experimental restrictions imposed by the physical size of various wind tunnels used to study the single fin interaction affect findings? The obvious implications of this information pertain to the up/down-scaling of laboratory research and eventual jump to full-size application. Small-scale facilities have limitations not only in terms of the geometric restrictions of their test sections, but also by the significant impact that sidewalls have when investigating in a confined space. While moving to a larger facility reduces the role of sidewall effects, the increase in tunnel size generally causes the incoming boundary layer to thicken, which may hinder the ability of aerodynamicists to achieve a ‘semi-infinite’ interaction or cause the inception region to significantly grow [79]. It is critical to understand whether interaction characteristics, especially the unsteady dynamics, observed empirically are solely a product of the flow physics or if they have become biased by the test facility. By having a profound grasp of these effects, it becomes much easier to methodically design and implement future endeavors. To achieve this, data sets gathered in the present study and from previously published literature (from facilities with varying test section and boundary layer sizes) are investigated.
CHAPTER 2
EXPERIMENTAL METHODS

2.1 Florida State University Polysonic Wind Tunnel

Primary experiments were carried out in the Polysonic Wind Tunnel at the Florida Center for Advanced-Aero Propulsion at Florida State University. The Polysonic Wind Tunnel (PSWT), shown in Fig. 2.1, is a blow-down type facility equipped with a 0.3m x 0.3m square cross-section [31]. Through the use of fixed ratio nozzle blocks, the PSWT is capable of operating in the subsonic ($M_\infty = 0.22 - 0.6$), transonic ($M_\infty = 0.6 - 1.2$) and supersonic flow regimes ($M_\infty = 1.6, 2.0, 3.0, 4.0$ and 5.0). The facility air supply is provided by a $110m^3$ dry air reservoir that can be pressurized up to 3,450kPa, which can allow for wind tunnel test of up to 90 seconds. The state of the art tunnel boasts an excellent flow quality, achieved through the implementation of an acoustically treated stagnation chamber, five fine mesh conditioning screens, a flow straightener and a 10:1 inlet contraction ratio. The stagnation pressure and temperature are monitored using an MKS 120A Baratron pressure transducer and RDF Corporation 29384-B-21 Fast Response RTD, respectively. A wide range of Reynolds numbers can be achieved for a given Mach number through the variation of the stagnation pressure. The PSWT is equipped with two interchangeable tests sections, a 0.3m

Figure 2.1: The Polysonic Wind Tunnel at the Florida Center for Advanced-Aero Propulsion at Florida State University.
x 0.3m x 1.2m slotted wall transonic test section and a 0.3m x 0.3m x 0.6m solid wall sub/supersonic test section. Optical access can be provided on multiple sides of both test sections, allowing for the use of many advanced flow diagnostic techniques. Test models can be mounted on the wind tunnel floor, ceiling or side walls as well as on an arc sector-mounted sting. The arc sector can be actuated during testing, pitching from $-10^\circ$ to $12^\circ$ and rolling from $-180^\circ$ to $180^\circ$.

![Boundary layer profiles measured for multiple unit Reynolds numbers at Mach 2, along with the boundary layer power law.](image)

Figure 2.2: Boundary layer profiles measured for multiple unit Reynolds numbers at Mach 2, along with the boundary layer power law.

The current study utilized freestream Mach numbers of 2, 3, and 4 to produce a wide range of test conditions to compare with both internal and external data sources. Based on the freestream Mach numbers and fin angle of attack (listed in the next section), the interaction strengths tested spanned from 1.26 - 2.14. Through variation of the wind tunnel stagnation pressure a range of unit Reynolds numbers (1/m) from $17.1 \times 10^6$ to $108 \times 10^6$ was achieved. In order to characterize incoming flow, boundary layer measurements were carried out on the floor of the Polysonic Wind Tunnel and at a raised offset (8 mm) to obtain better resolution. Measurements were made approximately 25.4mm upstream of the model leading edge, using a 16 probe total pressure rake connected to a $\pm 207kPa$ differential electronic pressure scanner. Example boundary layer profiles, taken at Mach 2, can be seen in Fig. 2.2. When compared with the equilibrium boundary layer power law \[ \frac{u}{U_\infty} = \left( \frac{y}{\delta} \right)^{1/7} \] [76], the generated boundary layer profiles indicate a minor momentum deficit.
near the wall. The boundary layer thickness ($\delta$) was determined as the location at which the boundary layer velocity equaled 99% of the freestream velocity, having an uncertainty of ± 0.5 mm based on the pitot rake resolution. All of the boundary layer conditions and characteristics for the PSWT floor used in these experiments are listed in Table 2.1.

Table 2.1: Wind tunnel conditions and boundary layer characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$M_\infty = 2$</th>
<th>$M_\infty = 3$</th>
<th>$M_\infty = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_o$ (kPa)</td>
<td>138</td>
<td>483</td>
<td>1517</td>
</tr>
<tr>
<td></td>
<td>345</td>
<td>965</td>
<td></td>
</tr>
<tr>
<td></td>
<td>552</td>
<td>1379</td>
<td></td>
</tr>
<tr>
<td>$T_o$ (K)</td>
<td>292</td>
<td>292</td>
<td>292</td>
</tr>
<tr>
<td>$Re_\infty$ (m$^{-1}$)</td>
<td>$17.6 \times 10^6$</td>
<td>$37.3 \times 10^6$</td>
<td>$71.3 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td>$43.9 \times 10^6$</td>
<td>$74.7 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$70.2 \times 10^6$</td>
<td>$107 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>$\delta$ (mm)</td>
<td>13.4</td>
<td>17.0</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td>12.9</td>
<td>16.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.1</td>
<td>16.4</td>
<td></td>
</tr>
<tr>
<td>$\delta^*$ (mm)</td>
<td>1.8</td>
<td>3.7</td>
<td>5.4</td>
</tr>
<tr>
<td>$\theta$ (mm)</td>
<td>0.64</td>
<td>0.76</td>
<td>0.69</td>
</tr>
</tbody>
</table>

### 2.2 Test Models

The single sharp unswept fin used in the PSWT was 101.6mm tall and 127mm long (Fig. 2.3). The fin had the capability to be mounted at discrete angles of attack ($\alpha_F$) of 10°, 15°, 20° and 25°, with respect to the incoming freestream flow (as shown in Fig. 2.3b). An L-bracket bracer was attached to the back side of the fin for mounting purposes. The bracket/fin were mounted to a 278.6mm diameter modular surface plug using a combination of bolts and precision pins to ensure stability and proper angular alignment. The surface plug was then installed into the floor of the wind tunnel and high quality optical glass windows were installed into the ceiling and both sidewalls of the test section.

Due to the variety of flow diagnostic techniques implemented in the current study, minor modifications were made to the surface plug in order to better facilitate each technique. For surface oil flow visualization (Section 2.3) a surface plug without any instrumentation was used to avoid any adverse effects caused by surface imperfections. While conducting steady pressure sensitive paint
Figure 2.3: Single fin model used in the Polysonic Wind Tunnel marked with the installed pressure port (black P1-P16) and unsteady pressure transducer (red K1-K8) locations. The model had the ability to be adjusted to different angles ($\alpha_F$) with respect to the incoming flow (left to right).

experiments (Section 2.5), sixteen pressure taps were drilled ($\varnothing$ 0.508mm) into the surface and connected to an electronic pressure scanner as shown in Fig. 2.3b, denoted by the black P1-P16 labels. To study the dynamics present within the single fin interaction, eight additional ports ($\varnothing$ 1.702mm) were added to allow for the installation of traditional unsteady pressure transducers, shown by the red K1-K8 labels in Fig. 2.3b.

2.3 Surface Oil Flow Visualization

Surface oil flow visualizations were carried out to acquire a qualitative sense of the inherent complexities of the three dimensional flow over the range of Reynolds numbers and interaction strengths tested. The visualization technique illustrated the location and extent of various flow features, e.g. upstream influence line, primary/secondary separation and reattachment, and served to guide the placement of discrete pressure sensors. A mixture of mineral oil and a dry fluorescent pigment, which varied in ratio depending on the stagnation pressure (Reynolds number), was speckled onto the surface plug using a stiff bristled brush. An additional line was often painted onto the surface in front of the interaction so that extra mixture would coalesce along the primary separation line, to provide better definition. A second method of producing surface oil flow
visualizations was implemented to allow for the automatic quantification of streamline direction throughout the flowfield using a cross-correlation based methodology; a more detailed description follows in Section 2.4.2. These surface oil flow visualizations consisted of spreading a thin layer of mineral oil onto the surface plug before using a sifter to sprinkle the dry fluorescent pigment on top of the mineral oil.

![Image](a) Before wind tunnel test.  ![Image](b) After wind tunnel test.

Figure 2.4: Speckle method application surface oil flow visualization before and after the wind tunnel test. Flow is from left to right.

Once the oil was spread (using either methodology), the surface plug was illuminated using a combination of 400-nm LEDs and UV-spectrum illumination (black lights) to excite the fluorescent pigment, thereby enhancing streamline visibility. Images of the surface oil flow were acquired throughout the entirety of the wind tunnel run using a camera oriented normal to the test section floor. Pre/post run images for the surface oil flow visualization conducted at testing conditions of $M=2$, $\alpha_F = 15^\circ$, $P_o = 345$ kPa are shown in Fig. 2.4 and 2.5, respectively. Both green and orange pigments were used to increase the color contrasts. Images were acquired at an acquisition rate of approximately 10 Hz using a 4.1-Megapixel (2336x1752) color CCD camera (Prosilica GT 2300C). For the sifting method shown in Fig. 2.5, images were acquired using a 16-Megapixel (4896 x 3264) monochrome CCD camera (Prosilica GT 4905).
2.4 Oil Film Interferometry

Skin friction measurements are a crucial component when attempting to understand any flow-field topology, and provide practical information regarding scaling quantities and viscous drag. Direct and quasi-direct experimental measurements of skin friction are often used in CFD simulation validation and have evolved from single-point surface shear stress measurements [40, 48, 49] to spatially resolved, non-intrusive, optical techniques used to examine two- and three-dimensional flows [17, 39, 64, 61, 62, 78, 105]. Oil film interferometry (OFI) provides a relatively simple experimental procedure that allows for the systematic regional interrogation of complex, high speed flows in an efficient manner. OFI uses the thinning of viscous oils to determine flow induced shear stress distributions acting over a surface. The basic concepts are rooted in the thin oil film equation (Eqn. 2.1), whose expression shows that the wall shear stresses ($\tau_{w,x}$, $\tau_{w,z}$) can be calculated if the height of the oil film ($h$) can be expressed as a function of time (along with having a dependence on the local flow direction and oil viscosity ($\mu$)) [17].

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(\frac{\tau_{w,x} h^2}{2\mu}) + \frac{\partial}{\partial z}(\frac{\tau_{w,z} h^2}{2\mu}) = 0$$  \hspace{1cm} (2.1)
Figure 2.6: Schematic illustrating how the light phase difference, between the reflected and transmitted, produces interference patterns as the oil film thins and how these interference fringes change over time [64].

Interferometry is used to measure the height of the oil film, in which a monochromatic light source is used to illuminate an oil film placed on a highly reflective surface. As shown in Fig. 2.6, the incident light will either reflect off the top surface of the oil film or reflect off the underlying surface; refracting at the air/oil interface when both entering and exiting the oil film. The phase difference ($\phi$) between the reflected and transmitted light will produce an interference pattern, i.e. dark fringes, that will develop over time as the oil film thins. Eqn. 2.2 shows how the phase difference along with monochromatic light source wavelength ($\lambda$), light angle of incidence ($\theta_i$) and refractive indices for the oil and air, respectively ($n_f$ and $n_a$) come together to calculate the oil film height.

$$h = \frac{\lambda \phi}{4\pi} \left( \frac{1}{\sqrt{n_f^2 - n_a^2 \sin^2 \theta_i}} \right)$$  \hspace{1cm} (2.2)

The calculated oil film height can then be used to solve for the skin friction coefficient ($C_f$) using the modified Garrison/Ackman form equation [63]. Shown in Eqn. 2.3, along with its necessary preliminary estimate in Eqn. 2.4, the modified Garrison/Ackman form factors in the
local streamline spacing \((n)\) and dynamic pressure \((q)\) in addition to the oil film height to iteratively compute the skin friction coefficient.

\[
C_{f,i+1}^{0.5} = \frac{\int_0^x (n/C_{f,i})^{0.5} dx}{h\sqrt{n} \int_0^t (q/\mu) dt}
\]  

\[
C_{f,1} = \frac{\mu x}{q h t}
\]  

### 2.4.1 Experimental Set-Up

Two types of wind tunnel tests were required to acquire all the data necessary to properly evaluate a fluid flow using oil film interferometry. To ensure that the information provided from the two separate wind tunnel tests could be extracted and paired together, the position of both the camera/lens and test section were unchanged once the wind tunnel testing began for a particular set of conditions. The first technique used was the previously discussed sifting method based surface oil flow visualization, used to determine the local flow direction and thereby direction of shear. When conducted carefully, qualitative surface oil flow visualizations (as seen in Fig. 2.5) can be used to produce a quantitative map of the limiting streamlines present throughout the entire flowfield. The second wind tunnel test was used to produce interference patterns necessary for determining the rate of oil film thinning. To produce the fringes, a blue monochromatic light source (*Metaphase* DAL-606 470 nm, 38 W) was placed above the test section and orientated to illuminate the highly polished surface plug in the test section floor. As the light source was equipped with a 50/50 beamsplitter, the 16-Megapixel monochrome CCD camera equipped with a Sigma f/5.6 105 mm lens was arranged as part of an in-line system. A sketch of the in-line arrangement can be seen in Fig. 2.7. A single band of 500 cSt nominal viscosity oil was placed onto the test surface using a straight edge, as shown in Fig. 2.8a. During the wind tunnel test, the camera was recording images at 5 Hz. The interference fringes began to form at the leading edge of the oil film, as shown in Fig. 2.8b. It can be seen that while the oil band spread out from its initial state, it by no means covered the entire flowfield. Therefore, the oil band was systematically reapplied further downstream and multiple wind tunnel tests (~10 – 14 runs) were conducted at identical flow conditions.
Figure 2.7: Schematic showing the in-line orientation used for OFI [13] (not to scale).

Figure 2.8: Illustration of the pre-run oil band and the developed interference fringes. Flow is from right to left.
2.4.2 Data Processing

The general procedure for processing a set of interference fringes is discussed below. The procedure closely follows that originally listed in Baldwin et al. [13]

Photogrammetry. As three-dimensional information, oil film height, was being extracted from two dimensional images special care had to be taken to ensure this was done properly. A two step calibration that would allow for the usage of photogrammetry, the mapping of coordinates of a three dimensional object onto the coordinates of a two dimensional image, was implemented. The first step utilized a stepped calibration block covered in reference markers. An image of the block was taken and used to determine the location of the reference markers in both image and physical coordinates. This information would be used to calibrate the interior orientation parameters that characterize the camera/lens system. Step two of the process used a paper dot array to identify the exterior orientation parameters that orient the camera relative to the fin/wind tunnel floor coordinate system. With a properly calibrated camera it is possible to determine the physical location of any point within the interferogram image. Additionally, as required by Eqn. 2.2, the photogrammetric calibration makes it possible to calculate the angle of incidence/reflection of the illumination source. A more thorough discussion of photogrammetry and the calibration process can be found in Naughton and Liu [61].

Streamline Detection. As stated previously, the local flow direction at any point within the field must be known to accurately determine the skin friction/shear stress at said point. As determining the streamline direction in a highly complex, three-dimensional flowfield would be a tedious endeavor, a systematic procedure was developed to automate the task using the acquired surface oil flow visualizations. The procedure utilized an open-source MATLAB software, PIVLab [91], to compute the flow direction using a cross-correlation-based methodology. After registering every image to account for any wind tunnel vibration and applying a contrast equalization, one final pre-processing step was taken to better isolate the motion between each frame. Subsequent images were subtracted from one another (2-1, 3-2, 4-3, etc.), thereby leaving only the instantaneous leading edge of the respective streamlines and producing differential ‘particle’ snapshots that could be tracked using a PIV-based approach. This technique was referred to as differential surface flow vector (DSFV) processing, but is now referred to as streakline image differencing extraction (SLIDE). The differential images were then processed using a 75% overlap, mutli-pass scheme
that used successively smaller windows. Any sub-pixel estimations were carried out using a two-
dimensional Gaussian-distribution, without interpolation. The resultant vector fields were run through outlier detection to remove any errant vectors and averaged over time to acquire a single vector field describing the streamline behavior. The representative streamlines for a test condition \((M = 2, \alpha = 15^\circ, P_o = 345 \, kPa)\) overlaid on an original surface oil flow visualization can be seen in Fig. 2.9. The figure shows how the freestream vectors begin to turn as they approach the interaction (upstream influence) and coalesce along the primary separation line. Inside the interaction, the flow can be seen to diverge from the surface of the fin near the reattachment zone and converge along the primary separation line.

![Figure 2.9: Representative streamlines extracted from surface oil flow visualizations using SLIDE. Flow is from right to left](image)

**Analysis Lines.** With the interference pattern and the flowfield streamlines it is possible to calculate the oil film height and skin friction. Analysis lines start at a user selected location upstream of the leading edge of the oil film and proceed to slice through the interference pattern along the local streamlines, terminating downstream of the last visible fringe pattern. To show an example of this, the analysis lines from a previously conducted study (in the Pilot Wind Tunnel...
facility) for the same SBLI configuration are shown in Fig. 2.10. This user dictated and vetted approach provides an efficient method to reach a desired interrogation density, allowing for a high level of flexibility that makes the method easily applicable to both simple and complex flowfields alike.

Figure 2.10: Image a) shows an interferogram with the streamline flow directions, and image b) then shows the analysis lines superimposed on top of image a). Flow direction is from left to right.

**Oil Film Processing.** The final step of data processing involves application of equations 2.2-2.4 to the generated analysis lines to output the skin friction throughout the flowfield. The analysis lines are processed on an individual basis that is user guided, allowing for basic parameter tuning to account for variations in fringe frequency and quality (clarity). The green analysis line shown in Fig. 2.10b is used to illustrate this functionality. It can be seen that the fringe crosses a number of fringes that are initially easy to discern, but when traveling along the length of the line they become harder to clearly view. The autospectral density of the fringe pattern along the chosen analysis line, shown in Fig. 2.11a, is able to pick out nine peaks/valleys, though it can be seen based on the signal magnitude that the last four were not as clear. Through spectral analysis, the peak frequency of the input signal (fringe pattern) is determined and used in an interrogation
sine wave, which is then cross correlated to the initial signal remove any false peaks (shown in Fig. 2.11b). If the cross correlated signal accurately represents the behavior of the fringe pattern, as determined by the user, the oil film height and skin friction are calculated (shown in 2.11e and f respectively).

Figure 2.11: Information that results from the complete processing of a single analysis line: a) extracted intensity signal along the analysis line, b) cross-correlation of the original intensity signal and the generated interrogation sine wave, c) light incidence angle as determined from photogrammetry, d) streamline angles as determined from surface oil flow visualization, e) the oil film height, and, finally, f) the skin friction at each fringe. [13]

An example of a fully processed interference pattern is shown in Fig. 2.12, where the analysis was able to determine the skin friction the center of the fringe peaks and valleys (as designated by the blue and black dots). The figure highlights the successful analysis that was able to determine the skin friction over a range of curvatures at variable densities across the length of the interferogram. For reference of the high spatial resolution, the size of adjacent pressure transducer holes have been marked within the figure. While the interferogram was determined to be highly processable, two
region (as denoted by the yellow arrows) were unable to be processed due to a combination of fringe clarity issues and/or insufficient fringes to execute the analysis.

Figure 2.12: Final locations, along analysis lines, of the fringe peaks and valleys determined by the processing suite and user vetting. The height of the oil film and skin friction are known at every light blue or black circle. Yellow arrows indicate regions where skin friction could not be properly extracted (red analysis lines with no light blue/black markers). A white arrow marker has been added to indicate scale with respect to the filled pressure transducer access holes (diameter 1.7 mm). [13]

### 2.5 Steady Pressure Sensitive Paint Technique

Pressure sensitive paint (PSP) is a novel optical sensor that emits variable levels of measurable illumination signal in response to pressure variation when provided a light-based stimulus. Its usage spans from the subsonic to supersonic test regimes [33, 59, 66, 89, 99] and it can be used to measure both mean and fluctuating pressures [22, 42, 43]. A commercially available (Innovative Scientific Solutions Inc., ISSI), reduced temperature sensitivity Binary FIB (Fluoride Isopropyl Butyl) pressure sensitive paint was used to capture the steady pressure field underneath the single
fin interaction. The dual-luminophore paint, when excited, emits both green and red signals. The response of the green (\(\sim 550 \text{ nm}\)) and red (\(\sim 650 \text{ nm}\)) signals is captured using two separate channels of a color CCD camera (ISSI), and the proportional response of the two luminophores permits temperature compensated measurement [67]. The following sections describing the calibration, usage and post-processing of Binary FIB PSP follow the general procedure laid out in Mears et al. [59].

2.5.1 Calibration

![Figure 2.13: Schematic of the chamber (not to scale) used to verify the ISSI provided Binary FIB PSP calibration.](image)

Significant efforts were made to ensure that the empirical calibration provided by the PSP supplier could be consistently reproduced by in-house users. A sealed calibration chamber, shown in Fig. 2.13, was constructed to test painted sample coupons. The temperature of the test coupon was controlled using a Peltier thermoelectric plate, and both the plate and chamber air temperature were monitored using a total of five Omega K Type thermocouples. The air pressure within the chamber was monitored using an Omega PX303-050A5V pressure transducer. A 690kPa laboratory air supply was used to pressurize the chamber and vacuum pump was used to achieve the desired sub-atmospheric pressures. Data was only acquired once both temperature and pressure stabilized.
to steady-state conditions. An air-cooled 400-nm LED (4 W) was used to excite the PSP and the emitted signals were acquired using a 2-Megapixel (1600 x 1200), 14-bit color CCD camera with an attached Nikon f/1.4 50 mm lens. To minimize the light contamination produced by the excitation source, a 495-nm cutoff longpass filter was placed on the end of the lens. The image acquisition software (ISSI ProAcquire) used automatically split every image into its red and green channels, producing two 604x804 images for every image taken by the camera. All subsequent image processing was carried out using in-house codes.

Figure 2.14: Comparison of the conducted in-house Binary FIB PSP calibration and the ISSI provided calibration.

For the PSP calibration, the temperature was held at a constant value while the pressure was varied over a range of expected experimental conditions, covering a spread of approximately 172kPa. The pressure variation was conducted in both increasing and decreasing directions to examine the potential signal hysteresis, as there is an expected signal intensity decay with increasing illumination time (1% per hour, as stated by manufacturer). This process was repeated for multiple temperatures to confirm the previously stated minimal temperature dependency. The results from a simple calibration can be seen in Fig. 2.14, shown in terms pressure ($P/P_o$) and intensity ratios ($I/I_o$), compared to the manufacturer (ISSI) provided paint calibration. The two curves shown from the in-house calibration show that there is little variation in pressure over the tested temperatures. Additionally,
there is an excellent agreement between the in-house calibrations and the ISSI provided calibration, with slight discrepancies observed at high pressure levels.

### 2.5.2 Experimental Set-Up

Once painted, the test model and mounting surface were installed in the PSWT in the manner described in Section 2.2 and shown in Fig. 2.15b. The color CCD camera and filter described in Section 2.5.1 were used for the live experiment, though a Nikon f/1.4 28 mm lens was used to obtain a wider field of view of the painted surfaces. The camera was directed through the test section ceiling optical glass and oriented normal to the test section floor. Two air-cooled 400-nm LEDs, equipped with parabolic diffusers to better concentrate the light, were arranged above the tunnel and aimed at the test section floor, as shown in Fig. 2.15a. The orientation of the LEDs was adjusted to provide an even illumination across the test surface and was checked before every wind tunnel test.

![Diagram of Experimental Set-Up](image)

(a) Orientation of the lights and cameras. (b) PSP painted surface and fin model installed in the PSWT, shown under red illumination to avoid photo-degradation.

Figure 2.15: Experimental set-up of the wind tunnel test section used for steady PSP testing.

To provide validation of the bench top calibration and/or allow for the use of a modified in-situ calibration, the surface plug was instrumented with sixteen ports connected to a pressure scanner. Pressure ports P1-P14 (Fig. 2.3b) lie at a radius of 95% of the fin length (120.7mm) and are present from $\alpha = 12^\circ - 64^\circ$, in $4^\circ$ increments. The two freestream ports, P15-P16, lie directly upstream of
the fin tip. All of the pressure ports were connected to a 16 channel differential Electronic Pressure Scanner (ESP) manufactured by Measurement Specialties. The ESP had a 69 kPa differential range and an accuracy of ±0.03% of full scale (±0.02 kPa). The ESP reference pressure, when not set to ambient conditions, was provided using a Druck DPI 610 Pressure Calibrator (±0.025% of full scale or ±0.17 kPa).

One hundred dark and wind-off images were taken before the start of every test run, and wind-on images were taken once the wind tunnel stabilized at the appropriate Mach number. During steady-state conditions, the LEDs were run in ‘continuous’ mode and the CCD camera acquired images at 10 Hz until 100 images were captured. During this period the ESP acquired data at a rate of 30 Hz.

2.5.3 Data Processing and In-Situ Calibration

To account for vibrations that would cause a misalignment between the wind-off and wind-on cases, all wind-on images were aligned to the average wind-off image using a sub-pixel accuracy image registration scheme. The average dark image was then subtracted from both the red and green channels to reduce signal noise. The red and green channels for both the average wind-off and instantaneous wind-on images were then ratio-ed to produce a “ratio of ratios”, as shown in Eqn. 2.5.

$$\frac{I_o}{I} = \frac{I_o, red}{I, red} \frac{I_o, green}{I, green}$$ (2.5)

Example images of the individual channels used to produce the “ratio of ratios” can be seen in Fig. 2.16. Once put into ratio, any unpainted regions of the images were masked off and the time sequence was then averaged to produce a singular the mean intensity field. The mean intensity fields were then spatially filtered (Gaussian) to assist in noise reduction.

To verify the accuracy of the calibration/provide an in-situ modification to the calibration, the ESP readings were paired with the intensity field. To do this, a 7 x 7 pixel region was placed at the center of each pressure port and the pixels corresponding to the port hole were masked (approx. 3 x 3 pixels). The remaining pixels were run through MATLAB’s outlier detection/removal function to account for any paint chipping that occurred around the edge of the port hole. The remaining pixels were averaged to ascertain the mean pressure around the port, as determined by the PSP.
Figure 2.16: Final (time and spatially averaged) intensity ratio for a $M = 2$, $\alpha = 15^\circ$, $P_o = 345 \, kPa$ flow. Flow is from left to right.
These values \(\frac{I_o}{I}\) were then plotted against the pressure ratio determined by dividing the ESP pressure by reference (atmospheric) pressure measured before the start of each run \(\frac{P}{P_o}\). These ratios were taken from every run, and the resulting curve fit calibration can be seen in Fig. 2.17a. The comparison between the in-situ measurements and those acquired in the separate bench top calibration are shown in Fig. 2.17b. It can be seen that there is an excellent agreement between the in-situ and benchtop calibrations in the low pressure regime, but the two curves begin to diverge in the high pressure regimes. The almost reverse behavior can be observed between the in-situ and ISSI calibrations, with the two curves crossing in the high pressure region. Traditionally, PSP empirical calibrations are modeled as a linear system using the Stern-Volmer equation (Eqn. 2.6)\(^5\)

\[
\frac{I_o}{I} = A(T) + B(T) \frac{P}{P_o} \tag{2.6}
\]

though in this case and others \(^9\) a linear equation does not sufficiently model the observed behavior. Therefore a higher-order polynomial fit was generated from the in-situ data, all finalized pressure fields were produced using the in-situ calibration listed in Eqn. 2.7.

\[
\frac{P}{P_o} = 0.5924 \left(\frac{I_o}{I}\right)^4 - 1.1541 \left(\frac{I_o}{I}\right)^3 + 1.7415 \left(\frac{I_o}{I}\right)^2 - 0.1693 \left(\frac{I_o}{I}\right) - 0.0416 \tag{2.7}
\]
2.6 Fast Response Pressure Sensitive Paint

A commercially available (ISSI), fast response (< 100 µs) pressure sensitive paint was used to capture the dynamics present within the pressure field underneath the single fin interaction. After degreasing all test surfaces using acetone, the two coat paint was applied using an air-powered high volume, low pressure (HVLP) paint gun. The initial white base coat serves to mask any surface staining and cover any surface that would unintentionally fluoresce or reflect light, thereby reducing any excess noise that said reflections would cause. After letting the base coat set for at least one hour, the top coat containing the single red (650-nm) luminophore was applied to the test surface. After 15 minutes, the test surface was ready for additional instrumentation and wind tunnel installation.

2.6.1 Wind Tunnel Set-Up

The physical wind tunnel set-up used for the fast response PSP was similar to the that used for the Binary PSP (shown in Fig. 2.15a), with the camera and light set above the wind tunnel test section. To record the fast response PSP, a Photron SA-Z camera (1024 x 1024 full frame, up to 20 kHz) was used with a Canon f/1.4 50 mm lens. Two separate filters were adapted to the lens, a 610-nm longpass filter to cutoff of the illumination signal wavelength behind a 450-nm longpass reflective filter used to reduce/block any specular reflections from contacting the 610-nm filter. The camera lens was connected to the camera with an ISSI EF Lens Controller, allowed for remote adjustment of the camera focus and aperture. Illumination was provided by 4 ISSI Vortex Cooled 400-nm LED’s (18 W), arranged to provide an even light distribution across the surface.

To verify the PSP readings and provide data necessary for an in-situ calibration, eight unsteady pressure transducers (Kulites) were mounted in both the freestream and interaction regions of the testing surface (as shown in Fig. 2.3b). Transducers K2-K8 (Fig. 2.3b) lie at a radius of 80% of the fin length (101.6mm) and are present from \( \alpha = 22^\circ - 58^\circ \), in 6\(^\circ\) increments. All eight differential pressure transducers, listed in Table 2.2, were provided a reference pressure using a Druck DPI 612 Pressure Calibrator (±0.015% of full scale or ±0.031 kPa g). Signals from the pressure transducers were passed into an NI PXI 4495 equipped with a 0.4535\( f_s \) anti-aliasing digital filter.

Like the Binary PSP, three sets of images must be taken for each wind tunnel test. Dark and wind-off images were taken before at the chosen sampling frequency \((f_s)\), with the lights run...
Table 2.2: Kulites used during fast response PSP testing.

<table>
<thead>
<tr>
<th>Position</th>
<th>Serial #</th>
<th>Pressure Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>7831-3-589</td>
<td>69 kPa D</td>
</tr>
<tr>
<td>K2</td>
<td>7831-3-590</td>
<td>69 kPa D</td>
</tr>
<tr>
<td>K3</td>
<td>7831-3-594</td>
<td>69 kPa D</td>
</tr>
<tr>
<td>K4</td>
<td>8090-5-596</td>
<td>69 kPa D</td>
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<td>K6</td>
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<td>100 kPa D</td>
</tr>
<tr>
<td>K7</td>
<td>8090-5-698</td>
<td>100 kPa D</td>
</tr>
<tr>
<td>K8</td>
<td>8020-4-196</td>
<td>172 kPa D</td>
</tr>
</tbody>
</table>

continuously during the wind-off acquisition. During the live run, the lights were run continuously and the pressure transducers and camera were triggered simultaneously at the same sampling frequency. The pressure transducers acquired data for five seconds while the camera acquired images until its partition was filled (based on camera settings).

2.6.2 Processing and In-Situ Calibration

To begin processing, the dark and wind-off images, respectively, were averaged and the wind-on images were registered to the wind-off mean to adjust for any vibration induced shaking. The dark average was then subtracted from both the wind-off and wind-on before the images were cropped to remove any unpainted areas from the image to reduce the physical size and computational load. Wind-off/on images were ratioed to account for any illumination variations and were then reduced to 25% of their original size to further reduce the computational load of data processing (1024 x 1024 → 206 x 219 resolution). Once in this state, images were ready for the pressure calibration to be applied. Using the average readings of the pressure transducers and a spatial averaging of the time averaged intensity ratio of the surrounding paint pixels, a set of eight points was generated and compared with the ISSI provided fast response calibration. The fast response PSP has a significantly higher temperature sensitivity (relative to the Binary PSP), meaning that applying an inappropriate calibration can significantly effect the accuracy of the final results. The calibrations for two separate wind tunnel runs, during which the camera/pressure transducers were sampled at 10 and 20 kHz respectively, are shown in Fig. 2.18. For the 20 kHz calibration the 25°C curve provided an excellent fit based on the data, however the 10 kHz case is shown to be slightly offset.
of the same curve. An interpolation between the 25°C and 30°C was conducted using the present data curves until a match occurred. A polynomial fit was generated based on the data curves and applied to the PSP data.

![Graphs showing calibration data](image)

(a) $f_s = 10$ kHz Sampling Calibration.  
(b) $f_s = 20$ kHz Sampling Calibration.

Figure 2.18: Comparison of in-situ calibration points to ISSI provided fast response PSP calibration.

## 2.7 Testing Conditions

Shown below in Table 2.3 is a detailed log of all the wind tunnel conditions (Mach number, $M_\infty$, stagnation pressure, $P_o$, and resultant unit Reynolds number, $Re/m$) and the model orientation parameters (fin angle of attack, $\alpha_F$, and the interaction strength, $M_n$) used in the current study conducted in the PSWT. Additionally, the flow diagnostics used in conjunction with each of these test parameters is also shown.
Table 2.3: Experimental test matrix denoting the testing conditions and the accompanying flow diagnostic used.

<table>
<thead>
<tr>
<th>$M_{\infty}$</th>
<th>$\alpha_F$</th>
<th>$M_m$</th>
<th>$P_o$</th>
<th>$Re/m$</th>
<th>SOF</th>
<th>FIB-PSP</th>
<th>FR-PSP</th>
<th>OFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10°</td>
<td>1.26</td>
<td>138 kPa</td>
<td>43.9 x 10^6</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>345 kPa</td>
<td>70.2 x 10^6</td>
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<td></td>
<td></td>
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<tr>
<td></td>
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<td>138 kPa</td>
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<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>345 kPa</td>
<td>70.2 x 10^6</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>20°</td>
<td>1.60</td>
<td>138 kPa</td>
<td>43.9 x 10^6</td>
<td>X</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>345 kPa</td>
<td>70.2 x 10^6</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
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<td>483 kPa</td>
<td>74.7 x 10^6</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td>965 kPa</td>
<td>107 x 10^6</td>
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</tr>
<tr>
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<td></td>
<td></td>
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<td></td>
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<td></td>
<td>965 kPa</td>
<td>107 x 10^6</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1379 kPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
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<td>74.7 x 10^6</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>965 kPa</td>
<td>107 x 10^6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1379 kPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10°</td>
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<td>1517 kPa</td>
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<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15°</td>
<td>1.82</td>
<td>1517 kPa</td>
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<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
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<td>1517 kPa</td>
<td>71.3 x 10^6</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Legend: SOF - Surface Oil Flow, FIB-PSP - Steady PSP, FR-PSP - Fast Response PSP, OFI - Oil Film Interferometry
CHAPTER 3
RESULTS AND DISCUSSION

The following chapter examines the experimental results acquired using a number of global flow diagnostics. Each section primarily describes the findings of a single flow diagnostic technique, listed in the same order as introduced in Chapter 2, with subsequent sections discussing how they connect with previous. Section 3.1 uses surface oil flow visualizations to track changes in prominent features of the interaction footprint which aids in orienting the flowfield in later sections that quantify the global skin friction (3.2), time-averaged (3.3), and unsteady surface pressures (3.4). The work discussed in Section 3.2.1 was conducted in the FSU Pilot Tunnel [13].

3.1 Surface Oil Flow Visualizations

Figure 3.1: Surface oil flow conducted at $M_{\infty} = 3, \alpha_F = 20^\circ$ with denoted flow features. Flow is from left to right.

Surface oil visualizations were initially conducted to characterize the surface flowfield beneath the single fin interaction and determine the expanse of the interaction footprint. The visualizations
illustrate how the global surface footprint of the interaction changes as the geometric and tunnel parameters are varied. A sample of a resultant oil flow visualization, with its prominent flow features marked, for a test conducted at Mach 3 with a fin angle of 20 degrees is shown in Fig. 3.1. These visible features and the theoretical inviscid shock trace (not visible in the surface oil flow) have been marked in Fig. 3.1 and extrapolated to the virtual conical origin (VCO). The examination of parameter variation using surface oil flow visualizations focused predominantly on tracking the primary separation line, which was clearly visible across the entire range of interaction strengths, and the VCO, whose location can be determined using the primary separation line and the inviscid shock trace.

3.1.1 Primary Separation Line

The position of the primary separation line for multiple Mach numbers, fin angles and Reynolds numbers is shown in Fig. 3.2. The breadth of the current data set facilitates the examination of each parameter in isolation, allowing for a clear discernment of how each parameter affects the global surface flowfield. When varying only the fin angle, it can be seen that the span of the interaction footprint (as measured by an arc between separation line and the fin) increases when the fin angle of attack ($\alpha_F$) is increased. This is a result of the strengthened adverse pressure gradient, which causes a larger separation bubble to form. This behavior can be seen when comparing Figs. 3.2b - 3.2d. When varying only the Mach number the interaction footprint appears to compress inward towards the fin with increasing Mach number, as seen between Figs. 3.2a and 3.2c. This is consistent with inviscid compressible flow theory as an increase in Mach number causes the shock angle to reduce, producing the resultant shift towards the shock generator (fin). These findings related to respective effects of Mach number and fin angle variation are consistent with previously published literature [56, 55, 79].

While these trends have been well documented, the independent influence of the Reynolds number has not been as thoroughly studied. To the authors’ knowledge, no other parametric studies have been conducted on the single fin SBLI in which only the unit Reynolds number was changed for a single test model. Achieved through an adjustment of the blowing (stagnation) pressure, Reynolds number sweeps were conducted for multiple fin angle/Mach number combinations; with only minor changes in the incoming boundary layer thickness (Table 2.1). Shown for all Mach number/fin angle combinations in Fig. 3.2, it can be seen that an increase in unit Reynolds number causes
the primary separation line to shift downstream; while the general shape stays relatively constant. In all cases, the largest shift in position occurs between the lowest and middle Reynolds number tested, while the position shift between in the middle and highest Reynolds number appears to be noticeably smaller. While all the cases have shown these general Reynolds number trends, it would appear that the Mach number, fin angle, and resultant interaction strength exert some influence on the Reynolds number affect. When the interaction strength is increased from Fig. 3.2b - 3.2d, it appears that the extent to which the separation line shifts between the middle and upper Reynolds

Figure 3.2: Effect of Reynolds number on the primary separation line obtained using surface oil flow on the PSWT floor

(a) $M_\infty = 2, \alpha_F = 15^\circ, M n = 1.42$

(b) $M_\infty = 3, \alpha_F = 10^\circ, M n = 1.38$

(c) $M_\infty = 3, \alpha_F = 15^\circ, M n = 1.60$

(d) $M_\infty = 3, \alpha_F = 20^\circ, M n = 1.83$
number examined reduces. Fig. 3.2d shows that the separation line corresponding to these two Reynolds number are essentially invariant. These findings related to the primary separation line shift, which does not appear to linearly correspond to Reynolds number variation, imply that the effects observed may become less significant at very high Reynolds numbers. The downstream shift of the separation line with increasing Reynolds number may relate to the near-wall boundary layer becoming ‘fuller’. When observed closely, Fig. 2.2 shows that the near-wall momentum increases with Reynolds number which allows for an enhanced ability to resist flow separation (denoted by the shifting separation line position). This line of thinking will be further examined using the mean pressure fields presented in Section 3.3.

To determine whether this behavior holds true for smaller scale interactions (i.e. smaller boundary layers), surface oil flow visualizations from previously conducted experiments on a raised flat plate in the same facility [14] were re-examined. The flat plate generated a boundary layer thickness of approximately 3mm, estimated using the methodology outlined in Van Driest[95], which provided roughly a five fold geometric variation when compared to the boundary layer thickness seen on the floor (approximately 15mm). The primary separation lines from the current experiment were plotted against one another with available identically matching conditions, with the exception of Mach 3 at $\alpha_F = 20^\circ$ and $22^\circ$, in Fig. 3.3. The flat plate cases, when normalized solely by the boundary layer thickness, do not collapse on their floor counterparts though they do exhibit similar behavior in terms of all other parameter variation aspects. The flat plate results show minor shifts downstream with increasing Reynolds number. The reduced size in shift, or what appears negligible in some cases, may be attributed to the size of the interaction set-up by the incoming boundary layer as even the floor surface oil flow visualizations exhibited only multiple millimeter shifts at most.

In an attempt to collapse primary separation lines of the present cases, equation 1.2 was revisited. For the cases being compared, the identically matching interaction strength values could be leveraged to equate the plate and floor (small and large boundary layer respectively) tests. The inception length could be utilized as the parameter to be matched, thereby allowing the boundary layer thickness and Reynolds number primary drivers of interaction scaling. The semi-empirical exponent applied to the Reynolds number was a product of multiple studies [25, 81] focused on the upstream influence line produced by various swept shock-generators at Mach 3. Subsequent
Figure 3.3: Comparison of the primary separation lines from the PSWT floor ($\delta \approx 15\text{mm}$) and a raised flat plate ($\delta \approx 3\text{mm}$) in the PSWT.

studies [104] have cataloged that a value of 1/3 has provided reasonable success from freestream Mach numbers of 2.25-4. However, Mears [59] found that at Mach 2 a different exponent produced a better alignment between identically matching case pressure fields from different facilities (one being the current experimental data set), most likely due to the shock structure induced leading edge curvature that is more pronounced at lower supersonic Mach numbers. Said non-dimensional scaling is applied to all cases in Fig. 3.4. Each instance, including Fig. 3.4d with its minor angle of attack difference, shows an excellent collapse between cases with matching unit Reynolds numbers.
Figure 3.4: Comparison of the tunnel floor and flat plate interactions utilizing the non-dimensional scaling.

Though focused on the primary separation line as opposed to the upstream influence, this work shows trends similar to those seen in previous works examining Reynolds number effect (between differing boundary layer thicknesses) [82] and broadening the Mach number scope and increasing Reynolds number variability.

### 3.1.2 Virtual Conical Origin

The virtual conical origin presents a discrete quantifiable metric to judge the effect of parametric changes on the interaction footprint. For this discussion, the distance between the VCO and the fin
The distance between the VCO and fin tip is shown by the red arrow.

Figure 3.5: A Schematic illustrating the VCO location with respect to the fin geometry. The distance between the VCO and fin tip is shown by the red arrow.

tip; measured along the inviscid shock line as shown in Fig 3.5; will serve to quantify the extent of the various parametric effects. The distance between the VCO and fin tip is plotted as a function of angle of attack, and color coded based on Mach number/unit Reynolds number, is shown in Fig. 3.6. The figure shows that for a given Mach number, the VCO distance decreases inversely with angle of attack and that there is a diminishing effect on the change in VCO distance at higher angles of attack. When Fig. 3.6 is examined focusing on the trends as a function of Mach number, there appears to be minimal dependence between the resultant VCO distance and Mach number for either the floor or plate surface oil flow visualizations. These findings are consistent with the work of Lu [56], conducted in a relatively smaller wind tunnel facility ($\delta \approx 3\text{mm}$) over a similar range of Mach numbers and angles of attack, who observed that the VCO distance was primarily a function of angle of attack. When examining Fig. 3.6 to ascertain the Reynolds number effect, the figure shows that the VCO shifts towards the fin tip as the Reynolds number increases for a given Mach number/angle of attack combination. Additionally, in most cases the VCO corresponding to the middle Reynolds number lies closer to the VCO corresponding to the higher Reynolds number. Since the VCO is a coordinate origin based on the extrapolation of the primary separation line, whose behavior is best characterized as a shift downstream and has little effect on the extrapolated angle, it makes sense that the VCO moves closer to the fin tip along the unchanged inviscid shock trace.
(a) PSWT Floor, $\delta \approx 15\text{mm}$  
(b) PSWT Raised Flat Plate, $\delta \approx 3\text{mm}$

Figure 3.6: Effect of Reynolds number, $M_{\infty}$ and $\alpha_F$ on the VCO location as determined using surface oil flow.

(a) PSWT Floor, $\delta \approx 15\text{mm}$  
(b) PSWT Raised Flat Plate, $\delta \approx 3\text{mm}$

Figure 3.7: Variation in VCO position with Reynolds number; data includes all Mach numbers (2-4) and angles of attack ($10^\circ - 20^\circ$) tested.

When the results are indiscriminately displayed as a function of the Reynolds number (for all Mach numbers and angles of attack tested), as in Fig. 3.7, no trends of noticeable significance appear. Based on this figure and the cumulative findings based on surface oil flow visualizations it seems that while the Reynolds number does have distinct effects on the interaction footprint, it plays
a secondary role in establishing the interaction footprint when compared to the fin angle of attack and to a lesser extent the Mach number. This is reinforced when observing the effect of interaction strength in a similar manner (Fig. 3.8). Any increase in either the angle of attack or Mach number results in an increase of the interaction strength. An exponential decay in VCO distance observed using either boundary layer scale coincides with the primary/secondary governance of the angle of attack/Mach number, respectively.

Figure 3.8: Variation of VCO position with interaction strength; data includes all fin angles (10° - 20°), Mach (2 - 4) and unit Reynolds numbers (17 x 10⁶ - 108 x 10⁶) tested. A general trend line has been marked with a red dashed line.

3.2 Oil Film Interferometry

3.2.1 Pilot Wind Tunnel

The preliminary study, conducted in the FSU Pilot Wind Tunnel, investigated four regions of the single sharp fin-generated SBLI with flow conditions of $M_\infty = 2$, $\alpha = 15^\circ$ at a unit Reynolds number (Re/m) of 43.9 x 10⁶. These regions are clearly marked on the surface oil flow image in Fig. 3.9. The yellow rectangle is entirely within the region of the flowfield that lies upstream of the interaction. The three red rectangles mark regions of the flow that span the primary separation line, encompassing flow inside and outside the fin-generated interaction. Two of the regions that cross the separation line have significant overlap and will also serve as a measure of OFI’s repeatability,
as they should have matching values even though they were acquired during different wind tunnel test runs. Additionally, the freestream region of the flow should be uniform in both direction and magnitude of skin friction.

![Figure 3.9: The four regions of the fin-generated SBLI that were analyzed with OFI, one completely in the freestream (yellow) and three regions that straddle the primary separation line (red) [13]. Flow direction is from left to right.](image)

The skin friction magnitudes for all four regions are presented as color contours in Fig. 3.10. The origin of the plot lies at the fin leading edge, and the interaction has been scaled by the boundary layer thickness upstream of the interaction ($\delta_{99} \sim 3.5 \text{mm}$). The location of the fin face (black solid line) and the locations of the extrapolated primary separation line (red dashed line) and inviscid shock line (brown dashed line) have also been marked for reference. While the information density of OFI is quite high (illustrated in Fig. 2.12), an interpolation was carried out in regions bracketed by known skin friction values for contouring purposes.

The region of the flow upstream of the interaction, shown in Fig. 3.11, shows excellent homogeneity throughout. The standard deviation of the skin friction values within this region of the flow, normalized by the mean value, is 5.1%. The individual skin friction vectors shown in Fig 3.11 appear to be approximately equal in length and have slight or no curvature. Ideally, these vectors should all be horizontal, pointing from left to right. Some areas in the figure have no vectors, meaning that a measurement of the skin friction could not be obtained at that location. This is due to poor interference fringes and residual PIV particulate from other previously conducted experiments (as seen at $z/\delta \sim -5.5$).
Figure 3.10: Contour plot of the skin friction magnitude extracted in the four interrogation regions shown in Fig. 3.9. The black solid line represents the fin face, the red dashed line denotes separation line and the brown dashed/dotted line marks the inviscid shock location [13]. Flow direction is from left to right.

The three regions of the flow that span both the freestream and interaction region can be observed in Fig. 3.12, where the fin face and separation/inviscid shock lines are demarcated in the same fashion as Fig. 3.10. For all three regions, the lowest skin friction values are present near the primary separation line. When moving towards the fin, the skin friction increases, reaching a maximum in the areas closest to the fin. This trend confirms what was seen earlier in Fig. 2.8, in that an increase in spacing between interference fringes indicates higher shear stress, and by association higher skin friction. The skin friction vectors shown in Fig. 3.12 accurately follow the (expected) streamline directions, as determined by surface oil flow. Vectors in the immediate vicinity of the separation line converge towards this line from either side, and vectors that fall along the separation line run approximately parallel (as seen near $x/\delta \sim 2$). In the upstream region within the interaction, closest to the fin (yellow areas), the skin friction vectors divert
Figure 3.11: Region of the flow that lies upstream of the fin-generated SBLI. This region has excellent uniformity in both magnitude and direction of skin friction [13]. Flow direction is from left to right.

away from the fin. Near $x/\delta \sim 10$, in the green areas, the vectors can be observed to be moving in the direction parallel to the fin. The divergent behavior of the local flow direction seen here corresponds to the relative location of the attachment line. As discussed earlier, the attachment line is a feature that while expected, due to the strength of the interaction ($M_n$), was not able to be observed with the same clarity as the separation line. All these behavioral trends provide confirmation that these preliminary results appear promising and capture the well-known features of this interaction. However, when focusing on the areas of overlap between the two upstream regions, some discrepancies are noted. While the contours and vectors adjacent to the separation line are very similar, discontinuities can be observed within the interaction, most noticeably between $z/\delta \sim -3$ and $-4$.

There are no existing skin friction measurement studies available for the fin-generated SBLI at $M = 2$ and $\alpha = 15^\circ$ (flow/model parameters of the current study). While this will not allow a direct comparison at the same Mach number and angle of attack, comparing the trends of skin friction levels in relation to common features will provide valuable insight to current capabilities
Figure 3.12: Skin friction results shown for regions within the SBLI, illustrated in both contour and vector forms. The features denoted in Fig.3.10 are again present; flow direction is from left to right. Two constant radius curves about the VCO (magenta) have been added to show where information was extracted for comparison to previous studies [13].

of the analysis suite and technique. The contour plot shown in Fig. 3.12 contains two solid arc sections (magenta curves) that span the regions of investigation. These arc sections are of a constant radius about the fin tip; the section closest to the fin tip is at a radial distance of 25% of the fin length, while the second curve is at 50% of the fin length. To better represent these data extraction locations with respect to the single fin SBLI, they will be denoted in terms of inception length ($L_i$). This is due to the fact that the interaction has no inherent associated length scale [11, 79, 80]. Extracted from the surface oil flow, the inception length is the distance from the VCO to the point at which the interaction begins to exhibit conical behavior. The two data sets in Fig. 3.12 lie at approximately $1.00L_i$ and $1.38L_i$, respectively. Traditional skin friction data obtained from a fin SBLI of approximately the same interaction strength was taken at discrete points along a curve of constant radius as shown in Fig. 3.13a [49]. The figure shows
eleven discrete data points gathered using the laser interferometer skin friction meter technique, at $M = 3$ and $\alpha = 10^\circ$. The horizontal axis of the chart shows the (location of each point with) angle $(\beta)$ with respect to the VCO. Additionally, traditional fin interaction features; upstream influence ($\beta_{ui}$), separation line ($\beta_{ps}$), inviscid shock ($\beta_o$) and reattachment line ($\beta_r$); have been marked for reference. Though no inception length could be reliably extracted from the literature, Kim et al illustrated the conical behavior by examining the skin friction along a single angular ray and showed its eventual invariance. Fig. 3.13b also shows the results extracted from OFI measurements plotted in the same manner, along with the associated error. The error denoted at each location (6%) was based upon the average uncertainty of the streamline detection analysis and the skin friction measurement repeatability (determined from processing fringes acquired at various times for a single test run). Although a complete uncertainty analysis is not included in this report, error present in streamline directions is a significant contributor to the overall error.

Due to the difference in angle of attack and Mach number, the size of the respective interactions (range of $\beta$ angles covered) will be significantly different, and as such the location of features and trends will not have matching angular values. However, the observed trends in both interactions can still be compared. Both plots of Fig. 3.13 show similar behavior when examining the region of the flow between the upstream influence line and the primary separation line. A local minimum is apparent at the line of primary separation in all data sets, and the skin friction increases when moving from primary separation towards the upstream influence (direction of increasing $\beta$). A peak is observable in the Kim’s data near the upstream influence line, after which the skin friction reduces once in the freestream region of the flow. Based on the extent of the oil fringes in the current work, only the behavior inside of the interaction is considered. For reference, the average freestream skin friction value of 0.0015 (see Fig 3.11) has been marked on Fig. 3.13b. When moving towards the fin from the primary separation line, in the direction of decreasing $\beta$, the skin friction values begin to increase. Proceeding onward, the skin friction curves begin to exhibit differing behaviors. The Kim data plateaus to a maximum skin friction in the region of the reattachment line before decreasing in the region immediately adjacent to the fin. The data of the current study gathered at 1.38$L_i$ increases in a fairly monotonic fashion until termination, in contrast to the 1.00$L_i$ data that plateaus before increasing rapidly up to the fin. The differences seen between the
two cases of the current study should be minimal based on their location inside the conical portion of the interaction, based on surface oil flow.

Figure 3.13: Plot a) shows legacy skin friction data [49] collected using LISF. Plot b) shows skin friction data from the current study at two different radial distances using OFI. Reference features of the fin-generated SBLI have been marked for reference along the bottom axis of each plot. Additionally, the average freestream skin friction value has been marked along the right axis of plot b [13].

Figure 3.14: Plot combining all three skin friction data sets using a simple dimensional scaling parameter, allowing for direct comparison. This scaling aligns the inviscid shocks of each interaction to $\beta - \beta_o = 0$ [13].
In an attempt to better compare the interactions to one another, a simple dimensional scaling is applied in Fig. 3.14, in which the inviscid shock location ($\beta_o$) has been subtracted from each angular location. This scaling aligns the inviscid shocks of all data sets to $\beta - \beta_o = 0$. The condensed nature of Fig. 3.14 highlights the previously mentioned similarities and discrepancies present. Further studies into the flow physics present in each particular case are needed to explain the differences in behavior, but overall the preliminary results shown in this study are quite promising for the progression of this particular implementation of OFI for use in complex supersonic three-dimensional interactions.

### 3.2.2 Polysonic Wind Tunnel

The preliminary study conducted in the FSU Pilot Tunnel [13] illustrated that OFI could be expanded from its previous usage in 2-D flows to a complex supersonic 3-D flow. The results extracted from the test case proved to be qualitatively consistent with the expected flow physics and quantitatively matched experimental results from another comparably sized ($\delta$) test facility [48] at a similar interaction strength. Therefore a second study was conducted in the FSU PSWT to examine what affects a significantly increased boundary layer thickness would induce. The larger Mach number operational envelope also offered the ability to reproduce more experimental test cases that have been previously studied, both for cases that match identically and for cases that match only in interaction strength. The PSWT cases examined here are listed in Table 2.3.

![Figure 3.15: Surface oil flow visualization of a $M_\infty=2$, $\alpha_F = 15^\circ$ flow and the location of discrete skin friction data points extracted from the flowfield (blue stars). Flow is from left to right.](image-url)
Figure 3.15 shows the surface oil flow visualization used to extract the local flow direction throughout the flowfield, using the SLIDE methodology, from a $M=2$, $\alpha_F = 15^\circ$ flow. The figure also shows the locations where skin friction data was extracted from various bands of oil overlain on top of the visualization, as noted by the blue stars. Compared to the Pilot Tunnel study, the PSWT study used a more systematic approach to oil band placement that resulted in a larger coverage area. As with the previous study, care was taken to ensure that the analysis encompassed the transition from the freestream region, across the primary separation and well into the interaction region. Additional efforts were made to probe as close to the fin as possible. The surface oil flow visualizations and data extraction locations for all cases examined in the PSWT can be found in Appendix B.

(a) $M_\infty=2$, $\alpha_F = 15^\circ$, $M_n=1.42$

(b) $M_\infty=3$, $\alpha_F = 15^\circ$, $M_n=1.60$

(c) $M_\infty=3$, $\alpha_F = 20^\circ$, $M_n=1.83$

(d) $M_\infty=4$, $\alpha_F = 20^\circ$, $M_n=2.14$

Figure 3.16: Skin friction fields produced for each set of test conditions.
The resultant skin friction fields for each of the four sets of test conditions examined are shown in Fig. 3.16. As with the Pilot Tunnel study an interpolation was conducted between discrete data points to produce continuous contour plots, however due to the area of coverage and the data density the interpolation was carried out using the entire data set, as opposed to individual bands from each test run. To better marry the data extracted from different oil bands a Gaussian smoothing (window size of approximately 5mm x 5mm) was applied to the interpolated field. While some minor non-physical behavior can be seen (patchiness and/or minor gaps), each of the fields present exhibits the qualitative trends expected for the single fin SBLI, based on previous works. The skin friction appears to decrease to a global minimum in the vicinity of the primary separation line (as determined from surface oil flow visualizations), this trend is most easily seen in the Mach 2 case due to the higher freestream skin friction values. When moving inward toward the fin, the skin friction levels begin to increase and reach a global maximum near the fin surface. As mentioned earlier, comparable experimental data sets are available for each test case shown in Fig. 3.16. Discrete LISF studies conducted in the conical region for the same Mach number and fin angle are available for the cases shown in Figs. 3.16b and 3.16d. Similar studies, though for cases that match only in terms of the interaction strength, are available for the cases in Figs. 3.16a and 3.16c [48]. Finally, the test conditions used for the previously discussed Mach 2 Pilot Tunnel study identically match those used in the PSWT.

Building on the basic analysis used in the preliminary OFI study, the work conducted in the PSWT incorporated the effects of oil temperature and viscosity in determining the overall uncertainty present in the skin friction measurements. Described in Naughton and Brown [60], the oil temperature and viscosity were determined to be the dominant sources of error in oil film measurements. The temperature of the oil is traditionally assumed to match that of the underlying surface, and based on this temperature the oil viscosity can be tabulated from the manufacturer’s specifications. The current work had no means to measure the surface temperature during wind tunnel runs, so the adiabatic wall temperature was used. As indicated in Eq. 3.1, the adiabatic wall temperature is a function of the Mach number, static air temperature, and recovery factor (r).

\[ T_{aw} = T_\infty \left(1 + r \frac{\gamma - 1}{2} M_\infty^2 \right) \] (3.1)

While the Mach number and static temperature were measured during wind tunnel tests, the recovery factor is selected based on a range of values associated with turbulent compressible flows.
from literature [76], \( r = 0.92 \pm 0.03 \). The oil temperature, viscosity, and skin friction were calculated using the range of recovery factors to produce the uncertainty bars seen in all subsequent plots. The current methodology is limited to assuming a constant recovery factor (surface temperature) across the test surface. The examination of the skin friction over the selected range of recovery factors provides a reasonable estimate that encompasses a majority of the potential surface temperatures.

![Figure 3.17: Radial progression of the skin friction across the interaction for flow at \( M_\infty = 2, \alpha_F = 15^\circ \).](image)

To appropriately evaluate to the comparable data sets, skin friction data needed to be extracted from the OFI produced fields in a similar manner. Figure 3.17a shows seven circular extraction arcs (red) overlain on the Mach 2 skin friction field, spaced 12.7mm apart and centered about the fin tip. The skin friction magnitudes were extracted every 0.5\(^\circ\) and then re-oriented into the coordinate frame centered on the VCO. Figure 3.17b illustrates the effect of increasing radius on the extracted data. As expected, it is clearly observable that as the radial distance from the fin tip increases, the skin friction curves begin to more closely resemble one another until they collapse into a fairly consistent shape (i.e. begin exhibiting conical symmetry). For the inter-facility comparisons, skin friction data from the furtherest downstream positions were extracted. Multiple curves in close proximity (6.35mm spacing) were used to help account for some of the previously mentioned non-physical trends.
Figure 3.18: Comparison of experimentally measured skin friction at identically match test conditions ($M_\infty=2$, $\alpha_F = 15^\circ$) between the FSU PSWT ($\delta \sim 13\text{mm}$) and FSU Pilot Tunnel ($\delta \sim 3.5\text{mm}$).

The plot in Fig. 3.18 shows how these skin friction curves compare to the results from the Pilot Tunnel study. For consistency, all data shown in this section, whether having identically matching conditions or not, are shown using the angular scaling of $\beta - \beta_o$. In the angular region where data from both studies is present the skin friction curves show an excellent agreement. After coming to a global minimum at the approximate position of the primary separation line ($\beta - \beta_o = 5$), the skin friction curves proceed in an almost identical manner towards the fin surface, reaching similar peak values.

Figure 3.19 examines how the four cases in PSWT ($\delta \sim 13-19\text{mm}$) compare to previously published literature [48] from the Penn State Gas Dynamics Laboratory ($\delta \sim 3\text{mm}$). In the first case (Fig. 3.19a) the skin friction magnitudes and trends exhibit an excellent agreement except near the outer boundary interaction and the near the fin surface. As this case compares looks at differing flow conditions that produce the approximately the same interaction strength, minor differences
in skin friction magnitude in the freestream and near the fin are not completely unexpected. It is generally known that the freestream skin friction decreases with increasing Mach number. Additionally, it has been seen in pressure studies making similar comparisons [9, 14] that the inviscid pressure ratios across a shock are not equal for flow conditions that produce matching interaction strengths. Therefore, it is possible that the maximum skin friction values should not be expected to match. When looking at the other case that compares different flow conditions in Fig. 3.19c,
many of the previous statements still apply. Within the interaction, both cases see a local hump in skin friction produced by the secondary separation \( (\beta - \beta_o = 6) \). Between the freestream and inviscid shock \((\beta - \beta_o \geq 0)\) the two cases align well, but when continuing towards the fin the Mach 4 case shows a larger increase in magnitude. While the two cases see exhibit the peak skin friction value at the same angular location, there is again a notable magnitude difference between the two.

The two comparisons that look at identically matching flow conditions, Figs. 3.19b and 3.19d, show similar behaviors to one another. Both comparisons show consistency in the skin friction values in the freestream regions and along the interaction boundary, but in both instances the data from the smaller facility increases in skin friction at a higher rate. When observing the region between the inviscid shock and fin \((\beta - \beta_o \leq 0)\) the difference in skin friction magnitude becomes more noticeable, and while the respective cases peak at the same angular location there is a marked difference in magnitude, with the stronger interaction presenting a much larger difference.

In general, the examination of matching/similar strength test cases made between a larger boundary layer facility (PSWT) and smaller boundary layer facilities (FSU Pilot and PSU) compare reasonably well. In all cases the data shows a better agreement in the region between the freestream and the inviscid shock \((\beta - \beta_o \geq 0)\), as compared to the region between the inviscid shock and the fin. The magnitude of the difference closer to the fin was seen to increase with increasing interaction strength. As the peak skin friction value appeared at the same angular location for each comparison, it raises a question of whether the flow had fully-developed (conically) at the extraction locations in the PSWT or whether the finite fin length effects had begun to exert influence. To test these hypotheses a longer and taller fin, to increase the likelihood of achieving a semi-infinite infinite interaction as well, fin would need to be produced to repeat all tests. Finally, the additional case comparisons allotted by the PSWT gave additional credence to the \( \beta - \beta_o \) scaling, similar to that seen in Alvi [7] and Arora et al [10], used to compare matching interaction strengths in the preliminary Pilot Tunnel study. The two cases examined (Figs. 3.19a and 3.19c), while differing some in magnitude, show the same behavioral trends in their respective comparisons. The same test cases scaled angularly using \( \beta \), \( \beta - \beta_o \), and \( (\beta - \beta_o)/\mu \) respectively are shown in Appendix B to highlight this point.
3.3 Time-Averaged Surface Pressure Distributions

3.3.1 Effect of Reynolds Number

To measure the mean surface pressures, an array of pressure ports both upstream of the fin tip and within the interaction region (shown in Fig. 2.3b) were connected to an electronic pressure scanner. The pressure port locations were determined to be sufficient for the wide range of planned test conditions and interaction extents. To investigate the Reynolds number effect, wall pressures were normalized by the freestream static pressure and the dynamic pressure, respectively. The normalized pressures, shown in Fig. 3.20, have been plotted as a function of angular position ($\alpha$) of the pressure ports centered about the fin tip. This reference frame is chosen to unambiguously denote that the pressure was measured at the exact same location during each test. The measurement uncertainties in these parameters is well within the size of the symbol shown in these plots. Typical results presented in Fig. 3.20 show an excellent collapse in the central portion of the interaction ($\alpha = 20^\circ - 40^\circ$) using either normalization, but this breaks down when observing either in the region closest to the fin ($\alpha < 20^\circ$) or in the region of the separation/upstream influence lines ($\alpha \geq 45^\circ$).
Both regions illustrate that the lowest Reynolds number tested exhibits the highest normalized pressures, and as the Reynolds number increases there is a decrease in normalized pressure. This behavior is much easier to see on the outer portion of the interaction. The outer most pressure port ($\alpha = 64^\circ$) lies in the freestream for all three Reynolds numbers, but when moving inward a divergence between the three cases is first seen at $\alpha = 60^\circ$ and proceeds to increase to a maximum at approximately $\alpha = 55^\circ$. After this point the discrepancies between the pressure curves begin to diminish, with a re-convergence occurring at approximately $\alpha = 44^\circ$ as the interaction approaches the inviscid shock location (approx. $39.1^\circ$ for this case). This illustrates that while there is a Reynolds effect on the pressure field, it appears predominately restricted to the periphery of the interaction. The regions of divergence are consistent across all strengths tested in this experiment and was seen for a smaller incoming boundary layer is the previously conducted work [14]. This behavior is consistent with the shifting interaction footprint size as discerned from the surface oil flow results, as the further reaching expanse of the interaction footprint associated with lower Reynolds numbers would cause the initial pressure rise from the freestream condition and subsequent climb to occur at locations farther away from the fin.

To provide insight on the problem at a much higher spatial resolution, mean pressure measurements were acquired throughout the entire flowfield using Binary FIB PSP (acquired during the same test run as the transducer measurements). The pressure port information was used in conjunction with the PSP across every test to generate an in-situ calibration, as described in Section 2.5. Figure 3.21 shows a comparison of the pressure scanner and PSP measurements across all three Reynolds numbers of the previously discussed example case. The PSP values extracted around each pressure port show an excellent agreement with the pressure scanner measurements for each Reynolds number, providing confidence in the measurements that will take place throughout the rest of the pressure field. In addition, it has provided quantitative information in the fin interference and inception flow regions where conventional pressure port measurements were not possible due to mounting restrictions.

To better correlate the pressure differences present as a result of Reynolds number variation, Fig. 3.22 shows the pressure maps for three Mach number/angle of attack combinations (with varying interaction strengths) in which three Reynolds numbers were examined. For each respective combination, the pressure field corresponding to the lowest Reynolds number appears as the denoted
Figure 3.21: Comparison of mean surface pressure distributions obtained using conventional pressure ports with those obtained using PSP.

color map (designated by the accompanying color bar) and has gray isolines. The pressure contours of the middle and highest Reynolds number appear as black and red dashed isolines, respectively, with the numerical value of each isoline matching for all three Reynolds numbers. Displaying the data in this manner will better highlight the spatial variations between each pressure field for a given Mach number/angle of attack combination. For the previously discussed case of $M_\infty = 2$, $\alpha_F = 10^\circ$ the lowest values isoline for the lowest Reynolds number can be seen close to the pressure port that is second furthest away from the fin (P13), while the red and black isolines corresponding to the other Reynolds numbers appear adjacent to the next inner-most pressure port (P12). When moving towards the fin, the spacing between the isolines of the respective Reynolds numbers begin to slowly decrease, approaching what appears to be their smallest difference roughly between ports P5-P8. This agrees well when comparing to the pressure transducer measurements, as the pressure field is showing its minimal difference in the vicinity of the inviscid shock. However, this region may not be converging as well as expected from the pressure transducers due to the nature of PSP,
Figure 3.22: Quantitative investigation of Reynolds number effect on the entire pressure field using PSP for three separate interaction strengths.

as PSP is an optically based technique and the camera is looking through the inviscid shock in this region, causing an increase in noise within the region due to minor optical aberrations. Between this region and the fin, the spacing between isolines begins to once again increase, though not to the same levels as those present at the outer edges of the interaction.

When looking at the two higher strength interactions ($Mn = 1.42$ and 1.83), the general trends in Reynolds number observed match those seen for $Mn = 1.26$. Noticeably though, as the interaction strength increases the spacing between isolines (especially those between the middle and high Reynolds numbers) is significantly reduced. For the highest strength case, $M_\infty = 3$, $\alpha_F =
20°, the isolines for all three Reynolds numbers appear nearly identical for a large portion of the pressure field, even near the outer bounds of the interaction. The behavior shown by these quantitative pressure fields mirror those observed using surface oil flow measurements. Although varying the Reynolds number distinctly impacts the pressure distributions across the various interaction strengths, it appears that weaker strength interactions are relatively more receptive. The Reynolds number is clearly a secondary factor in governing the interaction footprint as compared to the fin angle of incidence and freestream Mach number. Additional experiments at $M_\infty = 3$, $\alpha_F = 10°$ and 15°, respectively, would be beneficial data sets to assist in further examining these assertions.

3.3.2 Inter-facility Scaling

![Figure 3.23: Comparison of global mean pressure fields for the matching interaction ($M_\infty = 2$, $\alpha_F = 15°$, $Re/m = 43.9 \times 10^6$) taken in the FSU Pilot Wind Tunnel ($\delta = 3.5 \text{mm}$) and the FSU PSWT ($\delta = 13 \text{ mm}$). Matching pressure value isolines have been color coded between the two facilities. Images recreated from Mears [59].](image)

The global discernment of the mean pressure allotted by PSP allows for an earnest investigation into the influence of individual facilities and the validity of results acquired within them, an important objective of the present study. Previous discussions (including those written by the current author) have predominantly relied upon data that lie outside of the inception region allowing for the utilization of the conical assumption/simplification and reference frame. Full-field data representation allows convenient probing both inside and out of the inception region as well as the ability to forego the simplified reference frame and the ambiguity of accurately positioning...
the frame center (VCO). Figure 3.23 shows the PSP generated pressure fields from the floors of the PSWT and FSU Pilot Wind Tunnel [59], respectively. The incoming boundary layer of the two facilities, run using both the same test conditions and air source, varies in boundary layer thickness by a factor of almost 4 ($\delta \approx 13\text{mm and 3.5mm}$). Isolines of matching pressure values from both the PSWT (solid) and Pilot Tunnel (dashed) have been color coded to allow for easy comparison. The unscaled flowfields (Fig. 3.23a) show no particular agreement in the alignment of their pressure contours. When replotted using the same geometric Reynolds number scaling applied to the surface oil flow, the two fields show a significantly increased resemblance. Focusing on the region upstream of the respective finite fin effects, as seen in Fig. 3.23b, there is an excellent alignment of the pressure contours from the outer periphery of the interaction to the region adjacent to the fin face. The two pressure fields highlight the achievable repeatability of the fin-tip nearfield between variable sized facilities using appropriate scaling.

Figures 3.24 and 3.25 expands upon the applicability of scaling between facilities by using the discrete pressure port locations from Baldwin et al. [14] and Lu [56], respectively to guide extraction from the corresponding PSP pressure fields of the current work. With the fin leading edge as coordinate system origin and using Eqn. 3.2, the physical location of each pressure port $(x_1, y_1)$ was used to determine where to extract data from the PSP pressure field $(x_2, y_2)$. The inverse tangent of the respective x and y coordinates was then evaluated to determine the angular location ($\alpha$) with respect to the fin leading edge.

$$
\left( \frac{x_1}{\delta_1} \right) Re^{0.7}_{\delta_1} = \left( \frac{x_2}{\delta_2} \right) Re^{0.7}_{\delta_2} \quad \text{and} \quad \left( \frac{y_1}{\delta_1} \right) Re^{0.7}_{\delta_1} = \left( \frac{y_2}{\delta_2} \right) Re^{0.7}_{\delta_2}
$$

Figure 3.24 compares selected cases collected from the floor and a raised flat plate from the PSWT over a range of interaction strengths from weak to moderate (1.27-1.60). The measurement uncertainties in the flat plate pressures (Plate) are within the size of the symbol shown in these plots. With the proposed scaling applied to the PSWT floor and flat plate data, it can be observed that some regions of the flow collapse within the margin of measurement uncertainty while others exhibit a distinct difference in pressure magnitude. In all cases, the data sets involving the larger incoming boundary layer (floor) exhibited the initial pressure rise at a wider angular value. This difference in the angular instance of initial pressure rise may be attributed to differences in the boundary layer profiles between the PSWT floor and raised flat plate. As stated earlier, when compared to an
Figure 3.24: Comparison of surface pressure distributions of varying incoming boundary layer using Reynolds number based scaling, \((x/\delta)Re_\delta^{0.7}\) and \((y/\delta)Re_\delta^{0.7}\).

equilibrium boundary layer, the PSWT floor exhibits a minor momentum deficit. In the case of a flat plate with fuller boundary layer profile, the interaction periphery (upstream influence/primary separation) would have shifted downstream resulting in a lower angular value. However, boundary layer for such a case was not measured to confirm this hypothesis.

The pressure arrays align well once the pressure rise becomes linear or the initial plateau has been reached but diverge when approaching the fin. For the two stronger cases \((M_\infty = 2 \& 3, \alpha_F = \)
the PSP is noticeably different in terms of the pressure drop in the immediate vicinity of the fin present on the flat plate. The cause of these differences is likely related to the development of near fin flow features and/or the finite length of the fin used in the current experiments. The pressure drops that occur near the fin for the plate data in Figs. 3.24b and 3.24d are consistent with the similar scale ($\delta$) flows studied in literature [14]. The pressure drop is related to the change in flow direction that occurs at the primary reattachment line, in conjunction with the overlying slip line seen in Fig. 1.5, where flow moves towards either the fin or the SBLI-induced separation vortex. Based on the Mach number and fin configuration in these cases, they are expected to exhibit a reattachment line, however, when observing the surface oil flow in Figs. 2.4 and 3.1 (stronger interaction than cases being discussed, $M_n = 1.83$) neither visualization definitively shows a reattachment line. In the authors’ opinion this leads to two, non-exclusive possibilities on why the reattachment lines influence is not exerted on the pressure field. The first being that the reattachment line has not sufficiently ‘emerged’ from the fin root within the experimental domain due to the size of the boundary layer. Referencing Fig. 1.5, the reattachment line is extrapolated to the VCO through the fin geometry. The current extraction location may not be far enough downstream for the feature to ‘emerge’ from the fin or the feature may be very close to the fin root to be noticeable. The second possibility is that the finite fin effects that result from a discrete geometry impede the development of the reattachment line. The finite fin effects restrain the further development of the SBLI footprint in the inner portion of the interaction, exemplified by the contour levels (bright yellow) that close into a contained packet against the surface of the fin. A longer fin would delay the onset of this bubble to a location further downstream, and as the name implies, an infinitely long fin would not exhibit this behavior. Further studies, with a longer fin, are needed to better isolate these effects and potentially confirm these possibilities.

The plots in Fig. 3.25 show a comparison of pressure distributions ($M_\infty = 3, \alpha_F = 10^\circ$) extracted from multiple pressure port arrays, at different radial distances from the fin tip, at the Penn State University (PSU) Gas Dynamics Laboratory ($\delta \approx 3\text{mm}$) [56]. While the PSU unit Reynolds number ($58.9 \times 10^6$) was not explicitly matched in the PSWT, it did fall between two unit Reynolds numbers that were tested ($37.3 \times 10^6$ and $74.7 \times 10^6$). Therefore, data was separately extracted from the two pressure fields for comparison. The plots list the radial distance for the original pressure port locations as well as the radial extraction distance for the corresponding pressure field cases.
Figure 3.25: Comparison of surface pressure distributions \((M_\infty = 3, \alpha_F = 10^\circ)\) from PSWT obtained using PSP \((\delta \approx 17\text{mm})\) with data from the Penn State Gas Dynamics Laboratory \([56]\) \((\delta \approx 3\text{mm})\) taken at various radial lengths from the fin leading edge using Reynolds number based scaling, \((x/\delta)Re_\delta^{0.7}\) and \((y/\delta)Re_\delta^{0.7}\).

Based on the scaling factor. The first two plots show an excellent agreement between all three cases examined, though it is interesting to note how the Reynolds number scaling affects the radial extraction distances, being approximately 1.5 and 2 times the original pressure port radius. The behavior seen in the last two plots shows a bit more variability. The lower Reynolds number data set matches the trends seen in the data from PSU, though a slight divergence in the pressure values appears between the inviscid shock \((\alpha = 27.4^\circ)\) and the fin face. The higher Reynolds number data set matches lower Reynolds number almost identically until a drastic drop off in pressure occurs near the fin. Looking at the radial extractions the answer becomes clear, the extractions taken for the higher Reynolds number take place at distances \((r = 145\text{mm} \text{ and } 151\text{mm})\) beyond the end of the fin \((r = 127\text{mm})\). For this reason they have been denoted with dashed lines in the figure. It is interesting that the interaction region between the inviscid shock and the outer interaction boundary continues to hold its shape, enough to align with other data sets, even well beyond the trailing edge of the fin.
3.4 Unsteady Surface Pressure Dynamics

To examine the unsteady dynamics on the surface underneath the single fin interaction, a combination of high-frequency pressure transducers and fast response PSP was utilized. As mentioned in Section 2.6, the pressure transducers serve to produce an in-situ calibration of the PSP and to locally confirm the accuracy of the pressure fluctuations/spectra observed by the PSP so that the rest of the pressure field may be examined with a reasonable level of confidence. The acquisition triggers of the pressure transducers and high-speed cameras were synchronized and the sampling frequencies were matched for two separate tests ($f_s = 10$ kHz and 20 kHz). Due to increased noise (or reduced signal to noise ratio) in the 20 kHz tests, only the 10 kHz PSP will be examined in this work, therefore the discussion of the pressure transducer results will be limited to the same frequency regime ($10 \text{ Hz} \leq f \leq 5,000 \text{ Hz}, 2.5 \times 10^{-4} \leq St_\delta \leq 0.126$).

3.4.1 Unsteady Pressure Distributions Measured Using High-Bandwidth Pressure Transducers

Eight Kulite pressure transducers were installed in the test model as seen in Fig. 2.3b (labeled K1-K8) at a radius of 101.6 mm about the fin tip. In the current work a single test case was examined ($M_\infty = 2$, $\alpha_F = 15^\circ$, $Re/m = 43.9 \times 10^6$), selected to identically match test conditions achieved in work previously conducted in the FSU Pilot Wind Tunnel [10, 59]. Marked surface oil flow visualizations in Fig. 3.26 identify both features of importance and the location of instrumentation relative to them (pressure transducer upstream of the fin tip not shown). The figure shows that one transducer lies within the intermittent region between the upstream influence and separation lines, one transducer is in the immediate vicinity of the separation and inviscid shock lines respectively, and the rest of the transducers present within the interaction region lie generally underneath the separation vortex.

The root mean square (RMS) of the mean subtracted pressure fluctuations measured by the high-frequency pressure transducers (Kulites), as calculated using Eq. 3.3 [15], are shown in Fig. 3.27.

$$\sigma_P = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - \bar{P})^2}$$

Normalized by the local mean pressure ($P_{\text{wall}}$), the RMS pressures represent the relative energy/unsteadiness exhibited throughout the flowfield. The data has been organized by both the
Kulite number and the angular location with respect to the VCO (for those within the interaction) to better identify the quantitative values with the flow features present. The plot in Fig. 3.27b shows that the peak unsteadiness is seen in the vicinity of the inviscid shock line ($\beta_0$), and then tapers off when moving away from the inviscid shock in either direction. A peak in the vicinity of the inviscid shock line corresponds well with the transducer study conducted by Arora et al [10], as those points near the feature lie underneath the separation bubble vortex core. Additionally, the same study and studies of matching interaction strengths [6] identified that the rear shock lies almost directly below the mean location of the inviscid shock using above surface visualization techniques, meaning that it may contribute to the RMS values seen here. However, the peaks seen in the previous study near the intermittent region (generated by the separation shock) and near the reattachment line (not seen in the current surface oil flow) are not present. This may due to the spatial resolution of the interaction region interrogation and this conjecture can be easily evaluated.
Figure 3.27: RMS of the pressure signals measured by each kulite ($f_s = 10$ kHz), organized by both Kulite number and position within the interaction flowfield.

by the PSP.

The power spectral density (PSD) for each transducer is shown in Fig. 3.28, shown with respect to both frequency and Strouhal number. Calculated using Eqn. 3.4, where $R_{xx}$ is the autocorrelation function of the signal, the PSD illustrates the distribution of energy across the frequency band examined.

$$ G_{xx}(f) = 4 \int_0^\infty R_{xx}(\tau) \cos(2\pi f \tau) d\tau \quad (3.4) $$

In terms of overall energy, the region investigated in the freestream boundary layer (K1) appears to have the least while the signals measured in the vicinity of the inviscid shock (K5 and K6) appear to have the most. The total energy seen in each spectra curve mirrors the behavior trends seen in Fig. 3.27, this make sense as the RMS pressure is equal to the square root of the integrated area underneath the spectra curves. When looking at each curve, none of them have any significant peaks that would indicate a particular tone of interest or resonance. However, there is a notable elevation in power in the low-frequency regime ($10$ Hz $\leq f \leq 100$ Hz, $2.5 \times 10^{-4} \leq St_{\delta} \leq 2.5 \times 10^{-3}$).

While the lack of discrete peaks is expected in 3-D SBLI, the presence of the higher energy, low-frequency content (below $St_{\delta} \sim 0.01$) is somewhat surprising as it is more significant in 2-D SBLI and previous 3-D SBLI studies have explicitly discussed the distinct lack of meaningful contribution from this frequency band. In some cases seen, the energy contained in the low-frequency content
Figure 3.28: Power spectral density of the respective Kulite signals.

(evenly f = 30-90 Hz) looks to be approximately an order of magnitude higher than across any other portion of the frequency band investigated.

To determine if there was any meaningful relationship between any of the respective transducer signals, the coherence was calculated between every transducer. Shown as the square of the cross-spectral density divided by the product of the two respective power spectral densities in Eqn. 3.5, the coherence function gives a measure of how statistically similar two signals are.

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)}$$

The function can have a result between zero and one (0 ≤ γ² ≤ 1). When two time signals are completely uncorrelated γ² = 0, and when γ² = 1 the two signals are said to be perfectly correlated or linearly related [15]. Figure 3.29 shows four representative cases in which the signal from a transducer is compared to all other transducer signals, including itself. The four cases shown represent distinct regions throughout the flowfield, they include: upstream of the fin tip (freestream), the transducer lying closest to the fin, underneath the inviscid shock/vortex core, and the intermittent
Figure 3.29: Coherence ($\gamma^2$) seen between Kulites at locations of interest throughout the flowfield.

region between the upstream influence and primary separation lines. Upon first observation of all four regions two trends become obvious; when correlated with itself the coherence is equal to one (which is expected), and that above a frequency of 100 Hz ($St_\delta = 2.5 \times 10^{-3}$) no signal consistently exceeds the threshold of interest ($\gamma^2 > 0.2$). Conversely, 100 Hz and below shows significant coherence levels between various signals that range from $0.3 \leq \gamma^2 \leq 0.9$. Each of the four cases appear to consistently exhibit one of two behaviors; either a relatively flat plateau between the frequencies of 30-90 Hz or two distinct peaks in the vicinity or 30 Hz and 90 Hz respectively. The coherence between the signal upstream of the fin tip (K1) and all other signals appears to decrease
with distance from the fin face, with the first three transducers registering at $\gamma^2 \geq 0.6$ while the rest predominantly lie below $\gamma = 0.4$. This may indicate that the low-frequency content is more prevalent near the fin face and/or away from the separation and rear shock motion. Moving to transducer closest to the fin (K2), the coherence between it and K3 peaks near $\gamma^2 = 0.9$; likely due to a combination of low-frequency content and the general proximity of the two measurement locations. Aside from this nearest neighbor and the already observed signal in the freestream, the rest of the coherence values are relatively more subdued. The signals nearest to the inviscid shock (K6) and in the intermittent region (K8) both exhibit the dual peak structure in the low-frequency regime for all of their signal comparisons, with no coherence levels exceeding 0.6. As the coherence seen between the inviscid shock and all other signals look to collapse, it raises the question of why. Is there potentially some global unsteadiness, that while it does not correlate as high as other signals observed, associated with the inviscid/rear shock, that is consistent through out the field?

### 3.4.2 Validation of Fast Response PSP

The high-frequency pressure transducers served to both acquire meaningful dynamic information from various regions of the flowfield and to confirm that the behavior described by the fast response PSP was accurate. After processing the data in the manner described in Section 2.6 (ratio images and apply in-situ calibration), the pressure fluctuations from the transducers and the local PSP were compared. For reference, the transducers were approximately 3 x 3 pixels in size (in the PSP images) and the region used for local data extraction was a 7 x 7 square centered on the transducer (with the center 3 x 3 masked out).

After aligning the pressure fluctuations of the transducers and PSP via cross-correlation, the respective time histories were examined as shown in Fig. 3.30. In all eight cases shown, the PSP is able to excellently match the behavioral trends seen in the transducer signal (across 0.2 sec, first 2,000 samples), though the PSP appears to report slightly smaller magnitudes of fluctuation compared to the transducers. Due to issues with illumination sources cutting out during test runs, only 17,000 of the acquired 50,000 images ($f_s = 10$ kHz) were used when comparing transducer and PSP data. Unless otherwise stated, all further values calculated from transducer or PSP data used 17,000 samples for consistency.

The RMS pressure and PSD of the respective signals were examined to determine if the total energy present and its distribution across the frequency band were comparable. Figure 3.31 shows
Figure 3.30: Time history of pressure fluctuations measured by each Kulite and the surrounding PSP.

Figure 3.31: RMS of the pressure signals measured by each Kulite and the surrounding PSP, organized by both Kulite number and position within the interaction flowfield.

that the magnitude of the RMS pressure measured by the PSP is in most cases lower than that of the transducers, however the physical trends in the data match well across the interaction region. When comparing the PSD, the two measurement techniques show an excellent agreement across the
entire frequency band. The only notable difference between the transducer and PSP signals is the magnitude seen. Below a frequency of 100 Hz the PSP signal has a higher magnitude, this behavior reverses when examining frequencies above 100 Hz for all cases. This behavior is most pronounced in the case of the first transducer (K1), where it appears that small fluctuations produced in the mid/upper portion of the frequency band (f > 100 Hz) give the PSP trouble. Additional information regarding the direct characterization of the relationship between the transducer signals and the surrounding PSP (Coherence, Gain and Phase) can be found in Appendix D.

Figure 3.32: Power spectral density of the pressure signals measured by each Kulite and the surrounding PSP.

The final assessment made to determine the validity of the PSP results (compared to the transducers) was the examination of coherence levels seen between various regions of the flow using only PSP. Figure 3.33 probes the same four regions of interest that were shown in Fig. 3.29. Similar to the transducer comparison, the PSP shows very little statistically significant coherence levels in the frequency band above 100 Hz. When looking at the low-frequency content between the freestream and near fin regions the peak coherence levels appear to approximately match in magnitude at 90 Hz, though the content about 30 Hz seems to be somewhat muted in the PSP.
Figure 3.33: Examination of the coherence present throughout various regions of the interaction using PSP immediately surrounding Kulites. The regions examined here mirror those probed in Fig. 3.29.

cases. Similar behavior is seen in the other two cases on the other side of the interaction region, with the peaks near 90 Hz appearing well defined while the content near 30 Hz (while still there) materializes itself in a noisier fashion than seen in the transducers.

Based on the evaluation of the cross-region coherence measured solely using PSP and the direct comparisons made between transducers and the local PSP, the field can be reasonably probed using the calibrated fast response PSP. The rest of this section will make use of fast response PSP
throughout the entire flowfield.

### 3.4.3 Global Surface Pressure Dynamics

**Full Field Examination.** As with the BiFIB PSP used in Section 3.3, fast response PSP offers incite into the unsteady dynamics present in regions that have been previously unstudied due to either limitations in sensor density and/or sensor invasiveness. Figure 3.34 shows both the time-averaged and RMS pressure fields produced using fast response PSP. The time-averaged pressure field shown in the figure corresponds extremely well, in terms of both magnitude and shape, with the BiFIB pressure field generated for identical test conditions. The RMS pressure field highlights traditionally unseen behaviors upstream of the fin tip, in the inception region, and in the conically developed region.

![Figure 3.34: Time-average and RMS pressure fields produced using fast response PSP.](image)

Four distinct phenomena stick out when observing the flowfield, with two being prevalent in the inception region and two being having a larger reach. The first notable feature is elevated RMS levels along the length of the inviscid shock line, easily denoted as such as it clearly runs between transducers K5 and K6 in Fig. 3.34b. While the inviscid shock can be observed in the time-averaged field due to the optical aberrations that result due to density variations, the resultant feature in the RMS field is caused by the motion of the inviscid and rear shocks. The presence of this is expected due to the findings seen in the transducer measurements. The second omnipresent feature is the
demarcated boundary of the freestream and the interaction regions, running from the fin tip to the edge of test surface. While the surface oil flow used to guide the placement of sensors showed that the outermost sensor (K8) was placed at the interaction periphery, the influence of the steady and unsteady pressure field reaches out further and was therefore missed in previously discussed measurements. This increase in flowfield unsteadiness at the interaction boundary is caused by the separation shock motion.

While the aforementioned flow features have been discussed in previous conical region discrete sensor surveys, the features present in the inception region have only been shown experimental by Mears et al and Mears [59, 58]. Conducted at identical flow and test conditions, the work by Mears was conducted in the FSU Pilot Tunnel ($\delta = 3.4$ mm). Directly upstream of the fin tip is a band of increased unsteadiness that runs along the interaction periphery (i.e. intermittent pressure regime). Mears [58] described this shape as similar to a bow-shock, like those induced by blunt fin and cylinder in supersonic flow. The finite thickness of the fin produces this "quasi-2-D" interaction that can only be sustained immediately upstream of the fin. It was proposed that the crossflow component of velocity that comes about as part of the open separation bubble sweeps the pressure fluctuations induced by the curved shock region towards other portions of the interaction. Finally, the highest pocket of unsteadiness seen anywhere in the interaction lies at the fin tip itself and are possibly a resultant of the unsteadiness generated by the curved shock lying just upstream.

The presence of the four regions of elevated unsteadiness appearing in both the Pilot and Polysonic Wind Tunnels (matching approximately in magnitude) indicate that the dynamics are inherent to the interaction. Similar comparisons between facilities of differing scale, over a wider range of test conditions, should be examined to more concretely confirm the exhibited robustness.

**PSP Arc.** With the enhanced spatial resolution provided by the fast response PSP, the initial transducer arc can be re-examined in a more thorough manner to provide insight into the flow dynamics and alleviate any concerns brought about by the spatially limited instrumentation. To do this psuedo-transducers were constructed from PSP clusters to fill in gaps between physical sensors and to extend the interrogation arc both towards the fin and into the freestream region. The placement of the these clusters is marked on both the time-averaged and RMS pressure fields in Fig. 3.35. Black dots represent where PSP surrounding a transducer is used, with data being extracted from these locations in the same manner used during the PSP validation. The red dots
Figure 3.35: Location of PSP data extraction points used to increase the spatial resolution of the installed pressure transducer arc.

indicate locations where no physical sensors are present, therefore a 3 x 3 cluster of PSP pixels (approximate surface area of a Kulite) is used.

The RMS pressure curve, reproduced using only PSP, along with the original transducer measurements are shown in Fig. 3.36. As seen during the PSP validation, the RMS pressure magnitudes reported by the PSP are generally lower than that of the transducers but they reliably reproduce the same trends seen between the same bounds. The RMS pressure reaches local minima near the fin and the surface oil denoted intermittent separation, while a global maximum is achieved in the vicinity of the inviscid shock location. When sweeping out from the fin face to the edge of the initially examined region a sawtooth pattern appears, this is most likely non-physical and caused by the alternating spatial extraction of the PSP data (around transducers or in open space). When moving beyond the limits of the transducer instrumented region towards the boundary periphery and beyond a number of new attributes appear. From the surface oil flow intermittent region the RMS pressure increases until it plateaus at a local maximum on the edge of the interaction. Continuing outward, an immediate drop-off occurs and the pressure stabilizes once the interrogation points lie beyond the extent of the interaction’s reach (i.e. freestream).

When compared to the work of Arora et al [10] conducted in the FSU Pilot Tunnel at identical testing conditions (transducers only), the current work aligns well. While the magnitudes don’t
identically match, due to the larger frequency band examined and integrated over by Arora et al, both flows show peaks in RMS pressure at the edge of the interaction and near the inviscid shock. The two studies differ however in the near-fin region, as the pressure in the current work continues to drop until the fin is reached while the previous study increases up to the fin after dropping off. Arora et al coincides with Garg and Settles [38] in this increase induced near the reattachment line and fin/floor junction. As stated earlier, none of the surface oil flow visualizations in this work have definitively shown a mean reattachment line. Additionally no studies above the tunnel surface (PIV, PLS, etc.), which may may aid in discerning the whereabouts of the reattachment location, have been carried out in the PSWT for any configuration of the single fin interaction.

Content across the resolvable frequency band was once again explored by examining power spectral density of each pseudo-sensor and the coherence between them. Shown in two plots, due to the number of spectra shown, Fig. 3.37 shows the PSD for every signal extracted from the PSP. Figure 3.37a shows the climb in energy present in each spectra when moving between the fin face and the inviscid shock, while Fig. 3.37b highlights the decrease, minor recovery and subsequent drop-off seen across the span between the inviscid shock and the freestream region. The increased
Due to the large number of points investigated, a systematic approach was used to investigate the coherence seen between each region of the interaction. Based on the RMS pressure plot seen in Fig. 3.36 four regions of interest were identified: the inviscid shock line, the intermittent separation region, the interaction boundary, and the freestream region. Two more regions of interest were considered based on results seen in single fin literature, the near-fin region (i.e. fin/plate junction) and the region of the flow under the separation vortex where the reattachment line may traditionally be found. Each of these regions and their approximate angular location are listed in Table 3.1. In a similar naming convention used with the physical pressure transducers, all PSP patches used for coherence comparisons have been denoted P1 (closest to the fin) through P23 (farthest from the fin). These designations are listed on each plot along with the respective angular position. The most interesting results seen from the all encompassing coherence study are displayed in Figs. 3.38 -3.40, while the rest can be found in Appendix D. The figures show six plots (one for each region of interest) which contain three points from each region, both for visual clarity and to provide multiple confirmations of the physical behavior observed.
Table 3.1: Regions of interest to examine coherence and their approximate angular location.

<table>
<thead>
<tr>
<th>Region of Interest</th>
<th>( \beta(^\circ) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near Fin</td>
<td>31</td>
</tr>
<tr>
<td>Under Vortex</td>
<td>37</td>
</tr>
<tr>
<td>Inviscid Shock</td>
<td>44</td>
</tr>
<tr>
<td>Intermittent Separation</td>
<td>52</td>
</tr>
<tr>
<td>Interaction Boundary</td>
<td>58</td>
</tr>
<tr>
<td>Freestream</td>
<td>68</td>
</tr>
</tbody>
</table>

Comparisons of patch P1, the point closest to the fin/floor junction, to the rest of field are shown in Fig. 3.38. As expected, with this and all cases, the point that lies closest (P2) to the anchor point of the investigation sees elevated coherence levels across the entire frequency band. When looking at the other regions, all regions but the interaction boundary show significant coherence \( (\gamma^2 \geq 0.6) \) at approximately 80-90 Hz. The freestream region shows the highest coherence to the fin/floor junction, which is consistent with the previous transducer/PSP results, however these points are at a significantly different (spanwise) location when compared to the transducer lying just upstream of the fin tip. This would indicate that the frequency content throughout the freestream region is reasonably consistent. By contrast, when considering the near-fin region to that of the interaction boundary the signals are almost completely uncorrelated, across both the low \( (St_\delta < 0.01) \) and mid-frequency \( (0.01 < St_\delta < 0.2) \) regimes (region thresholds used by Adler and Gaitonde [4]).

The coherence of levels seen between patch P9 (inviscid shock) and the rest of the arc shows behavior that was missed due to the angular spacing of the physical transducers. Points near the interaction boundary and the intermittent separation both show statistically significant coherence in the mid-frequency band. Additionally, when this relationship present in the mid-frequency content appears, the low-frequency region looks to be completely uncorrelated. This gives the impression that there is correlated motion between the inviscid shock region and the separation shock intermittent separation/boundary regions. This same behavior was exhibited across a similar \( St_\delta \) range in the smaller FSU Pilot Tunnel by Arora et al [10]. With the aid of additional above surface visualizations used in the work, the authors deduced that the coherence corresponded to a correlated motion between the separation and rear legs of the \( \lambda \)-shock. When comparing patch
Figure 3.38: Coherence between PSP patch P1 (near-fin) and all other PSP patches
Figure 3.39: Coherence between PSP patch P9 (inviscid shock) and all other PSP patches
Figure 3.40: Coherence between PSP patch P17 (Interaction Boundary) and all other PSP patches
P9 to the three remaining regions, low-frequency behavior consistent to the previous findings is present while the mid-frequency content is once again absent.

The final focal point of interest is PSP patch P17 which lies on the interaction boundary. As one of the more prominent features seen in the full-field RMS pressure map (Fig. 3.34b) along with the mid-frequency coherent content, the region merits secondary investigation. Upon inspection the previously established mid-frequency relationship with the inviscid shock appears, but aside from that most regions appear to be mostly or completely uncorrelated. The two regions closest to the fin and the freestream region show no statistically significant levels across the entire frequency band. Activity seen at patches P7 and P15 are a resultant to the proximity of the inviscid shock and intermittent regions, respectively. The only other notable coherent features are the low-frequency plateaus present in patches P13 and P14 (the RMS pressure local minima).

Conical Extractions. The final portion of the unsteady dynamics investigation focuses on a larger section of the field and the application of the conical assumption that has been successfully utilized for simplifying the evaluation of the time-averaged flowfield. As done in this work and other 3-D SBLI studies, high-frequency surface pressure transducers have been most commonly placed within the conical region to avoid the uncertain influence of inceptive effects. These have produced a tremendous knowledge base but have missed some notable features at the front of the interaction, as illustrated by the fast response PSP. An experimental study conducted by Schmisseur and Dolling [77] examined the dynamics produced by a single fin at various angles of attack in a Mach 5 flow. The work showed that the mean and RMS pressures collapsed into quasi-conical symmetry. While only a single set of flow/geometric conditions was examined here, the present conditions produced a significantly lower interaction strength ($M_n = 1.42$) than any of the cases present in the Mach 5 study ($M_n = 2.14 - 3.18$).

A large set of pseudo-transducers were generated throughout the entirety of the interaction region, from the inception region to the fin tail, to probe the flow. Thirteen radial arcs were drawn about the fin tip with a constant radial spacing of approximately 9.2mm (10 pixels) between each arc. Sensors on each arc, 3 x 3 pixels in size, were placed along rays emanating from the VCO, as determined from surface oil flow visualizations, with an angular spacing of three degrees between them ($\beta = 29^\circ - 68^\circ$). Care was taken to ensure that some rays emanating from the VCO aligned with particular features of interest (i.e. inviscid shock, interaction boundary). The grid of PSP
sensors can be seen as dark squares in Fig. 3.41. All radial values listed in this section correspond to the fin tip, not the VCO.

Figure 3.41: RMS pressure field marked with the location of each data extraction made for investigation.

Extractions of both the mean and RMS pressures at various radii are shown in Fig. 3.42. To more cleanly visualize the trends seen when moving downstream, data from every other radial arc is shown. As expected the mean pressure converges into conically symmetric behavior as the radial distance from the fin tip increases. The flow appears to begin exhibiting radially invariant behavior approximately 69 mm from the fin tip, though the exact radius at which this behavior starts may be closer to the fin tip based on extraction resolution. As was seen in Section 3.3, the conical behavior begins to breakdown (near the fin surface) when the extraction radius approaches the fin tail and the finite fin effects take hold. Extremely similar trends are seen when looking at the RMS pressures, with interaction dynamics exhibiting conical behavior at approximately the same radial distance seen in the time-averaged pressures. This gives credence to the application of the conical
assumption to pressure fluctuations for weaker interaction strength cases than those examined in Schmisseur and Dolling [77]. Experimental tests should be conducted across a range of weaker and stronger interaction strengths to more concretely confirm this and to more thoroughly examine if mean and unsteady pressure fields begin displaying conically symmetric behavior at the same spatial instance.

Figure 3.42: Extractions made along arcs to examine the effect of increasing radius on both mean and RMS pressure.

To observe the conical behavior with regard to the entire frequency band, the power spectral density and coherence along the length of and across the span of the interaction were investigated. Measured along angular rays corresponding to the six regions of interest, Fig. 3.43 shows the effect of increasing radius on the resultant spectra. Except for those extractions made farthest upstream, the energy spectra collapse onto one another in a conically symmetric manner. Compared to the point where conical behavior is first exhibited in the mean and RMS pressures (r = 69.3mm), the spectra actually appear to collapse at a shorter radial distance (approximately r = 50.8mm) from the fin tip. The coherence was measured between the regions of interest at different radial distances to confirm that the behavior observed with the single transducer/PSP arc is conical and not an anomaly. Figures 3.44 and 3.45, using the inviscid shock and freestream region as the respective anchor points, examine the spanwise coherence at four different radii. The mid-frequency content seen in the relationship between in the inviscid shock and the interaction boundary first
Figure 3.43: Examination of the effect of radial distance on the power spectral density.
appears in the plots showing $r = 60$ mm, beyond this radius the behavior is consistently seen. The seemingly omnipresent low-frequency content becomes more prominent and stabilizes across the interaction the further downstream the interrogation shifts. When examining the coherence along the length of the inviscid shock, shown in Fig. 3.46, it appears that there are no coherence structures present along the entire length of the feature. However, the levels of coherence between neighboring extraction points increases when shifting from the inceptive region to the conical region.
Figure 3.44: Effect of radial distance on the coherent structures seen between the inviscid shock ($\beta = 44^\circ$) and the rest of the interaction.
Figure 3.45: Effect of radial distance on the coherent structures seen between the freestream region ($\beta = 68^\circ$) and the rest of the interaction.
Figure 3.46: Examination of the coherent structures present along a single ray emanating from the VCO along the inviscid shock ($\beta = 44^\circ$). Each plot shows the coherence between the listed anchor point and all other extraction locations along the ray.
CHAPTER 4

CONCLUSIONS

The interaction footprint of the single fin generated SBLI was studied using multiple of state-of-the-art global flowfield diagnostics to investigate the topological characteristics and dynamical flow physics. The focus of the work was to examine the effect of incoming flow conditions, fin orientations, and other scaling parameters on the flowfield involving 3-D SBLI. Based on the capabilities of the research facility, the current work was able to explicitly study the Reynolds number effect on 3-D SBLI in a manner that no previous study has, as the unit Reynolds number within this single facility could be varied by almost an order of magnitude. Extractions from surface oil flow visualizations showed that there was a distinct shift in the most prominent and distinguishable features of the SBLI footprint. As the Reynolds number was increased, the primary separation line showed an enhanced ability to resist flow separation thereby shifting the position of the SBLI feature downstream and reducing the overall expanse of the interaction footprint. When examining the Reynolds number effect across the range tested, it became apparent that the interaction became relatively less sensitive at higher Reynolds numbers. While the Reynolds number caused distinct changes to the position of the primary separation line, it should be considered a secondary factor in shaping the interaction footprint as compared to the fin angle of incidence and the freestream Mach number (i.e. the interaction strength). Weaker interactions are relatively more susceptible to changes in the Reynolds number as compared to stronger interactions.

The investigation of surface oil flow features was expanded using mean pressure distributions, measured using both discrete pressure transducers and PSP that were acquired simultaneously. The global pressure fields showed that flowfield variations caused by Reynolds number changes were observed to be larger in magnitude near the inner/outer regions of the interaction and smaller in the vicinity of the inviscid shock. A quantitative confirmation of the diminishing sensitivity of SBLI to the increasing Reynolds number and its relation to interaction strength was also illustrated by the pressure fields. The enhanced understanding of these parameters will aid the planning of future experimental and numerical studies and be able to more properly adjust Reynolds number
selection for increased efficiency in resource allocation. Continuing this work, expanding both the range of interaction strengths tested and increasing the resolution of Reynolds number sweeps conducted will ideally lead to the derivation of empirically driven formulations. Formulations such as these would be able to provide predictive capabilities over a wide range of conditions for use by the SBLI and high speed aerodynamics communities.

The second major aspect of this study was to investigate the effects of the facility on the validity and repeatability of the results. The focus of the investigation was not the quality (i.e. turbulence levels) of the incoming flow but the incoming boundary layer thickness, as the boundary layer thickness becomes a limiting factor in terms of usable experimental area (sidewall effects) and can be a geometric constraint when designing test models. A significant amount of previously published data was available to make both direct (identically matching test conditions) and indirect (nominally similar interaction strengths) comparisons to the measurements made in the current work. Global skin friction data acquired in the FSU Pilot Wind Tunnel using OFI compares favorably to results from the Penn State Gas Dynamics Laboratory, having approximately the same boundary layer thickness, using LISF. This comparison highlighted both the promising nature of the experimentally simpler (new to supersonic speeds) technique and the excellent cross facility match; which led to the expanded study conducted in the PSWT. Data from the fully-constructed PSWT skin friction fields showed reasonable agreement to those collected in the two smaller wind tunnel facilities. For most of the cases studied, the region between the inviscid shock line and the outer periphery compared favorably, however, there is a minor divergence in magnitude close to the fin face. While achieving a global maximum in skin friction at the same angular location, the overall magnitude and rate of increase often varied. This behavior became more pronounced as the interaction strength was increased. While there are differences in the skin friction magnitudes, the angular scaling used \((\beta - \beta_o)\) appears to provide an adequate vehicle for conducting indirect mean skin friction comparisons within the conical region. In comparing the mean pressure measurements conducted in various facilities, nearly identical trends were observed. The pressure differences in the near fin region are less pronounced for weaker strength interactions, though for the stronger cases the PSP flowfield does not reflect the expected reattachment effects and/or significantly undershoots the anticipated theoretical pressure ratio. These results may be attributed to the combination of a thicker incoming boundary layer inducing a larger inception region and the onset
of finite fin effects, as illustrated by the pressure fields. Further study is necessary to better isolate these effects and address said issue. Based on the observations made in this study, it appears that separate empirical relations may be necessary to account for the explicit boundary layer and the Reynolds number effects, respectively.

A preliminary investigation into the single fin SBLI dynamics was carried out using simultaneously sampled high-frequency pressure transducers and fast-response PSP ($f_s = 10$ kHz). The transducers served a dual purpose, to make quantifiable measurements throughout the flowfield and provide an in-situ calibration. With the calibration applied to change the illumination intensity variations to pressure, the fast-response PSP showed an excellent local agreement with the transducers, as observed by comparing baseline fluctuations, processed power spectra, and interaction spanning coherence levels. Full-field maps of the flow unsteadiness ($P_{RMS}$) showed elevated levels along the outer boundary of the interaction, on the inviscid shock line and at/immediately upstream of the fin tip vertex, aligning well in the location and magnitude with a similar study conducted in the Pilot Tunnel. Probing the flowfield using the enhanced spatial resolution allotted by PSP showed coherence seen between the inviscid shock and interaction boundary (upstream influence), denoting a physical mechanism of communication that was previous observed in a separate Pilot Tunnel study. Probing along radii emanating from the VCO confirmed that flowfield dynamics (RMS pressure, PSD spectra) exhibit conical symmetry in a fashion well-documented in time-averaged studies. These factors illustrate that the dynamics seen throughout the flowfield are relatively robust and appear regardless of the facility used for study, though additional flow conditions/fin angles should be examined to better supplement this argument. Finally, significant levels of low-frequency content were found in the PSP resolvable frequency band. Energy content in the low-frequency domain, traditionally associated with 2-D SBLI, had previously shown to be relatively insignificant for 3-D SBLI. While it seems that this content is most likely an effect of the increased boundary layer thickness (compared to other works), further study is necessary to pinpoint the driving mechanism and its overall impact.

In summary, the findings of the current work have contributed to the ever expanding knowledge base regarding 3-D swept SBLI. Global flowfield diagnostics provided new insight regarding the roles that Reynolds number and interaction strength play in shaping the interaction footprint. The underlying physics and interaction characteristics, both dynamic and time-averaged, are proven to
be robust when comparing results from facilities differing in size. Finally, additional methods to scale interactions have been illustrated that should aid the facilitation of future experimental and numerical studies.
CHAPTER 5

FUTURE WORK

The work presented showed that significant progress has been made towards expanding the knowledge base on the single fin SBLI and three-dimensional SBLI in general, however additional work is necessary to further answer the questions raised in this study. The continuing work can be divided into that which can be done by further processing and analyzing already acquired data, and that which requires further wind tunnel testing. The fast response PSP data which has been collected provided a figurative goldmine of information and understanding, and still offers considerable depth in what can be extracted from it. Only the surface has been scratched in the investigation of the dynamical characteristics in this study. The high spatial resolution provided by the fast response PSP will hopefully allow for the tracking of structures and other physical mechanisms as they are generated and travel through the flowfield. Conversely, there may be feedback pathways between regions of the flowfield which have yet to be fully recognized, as potentially hinted at by the communication present between the inviscid shock and outer boundary of the interaction. More sophisticated analysis techniques like POD and DMD could surely shed additional light on the subject. Tests conducted at a wider range of flow conditions and fin angles should be run to investigate if the inception region behavior changes with interaction strength and to determine the robustness of the low-frequency content.

Another focus of the current study was to investigate how scales of the interaction change with variation in key parameters and facilities. While new discoveries in regards to the role in which the Reynolds number plays in 3-D SBLI has been revealed, ideally more empirically driven formulations can be derived that would be able to provide predictive characterizations for a wide range of conditions for use by the SBLI and high speed aerodynamics communities. These actions apply not only to the pressure fields, but the global skin friction measured by OFI and other similar techniques.

Finally, two wind tunnel testing techniques are currently under development at FCAAP that would be quite useful for advancing the current study. First, the installation of the necessary equip-
ment required to properly conduct PIV measurements in the PSWT, giving the ability to study the interaction and shock structure present above the test surface. Second, high spatial resolution temperature measurements will soon be able to be acquired using temperature sensitive paint (TSP). Functioning similar to PSP, TSP will give insight into the heat transfer taking place throughout the interaction and provide full-field temperature measurements that will further improve the accuracy of OFI data acquisition through improved oil viscosity calibrations.
APPENDIX A

SURFACE OIL FLOW

Table A.1: Table of test parameters and VCO locations for the PSWT floor.

<table>
<thead>
<tr>
<th>$M_\infty$</th>
<th>$\alpha_F$</th>
<th>$M_n$</th>
<th>$P_o$</th>
<th>$Re/m$</th>
<th>$\beta_o$</th>
<th>$\mu$</th>
<th>VCO</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>15°</td>
<td>1.42</td>
<td>138 kPa</td>
<td>17.6 x 10^6</td>
<td>45.34°</td>
<td>30°</td>
<td>131.2 ± 13.1 mm</td>
<td>13.4 mm</td>
</tr>
<tr>
<td>2</td>
<td>15°</td>
<td>1.42</td>
<td>345 kPa</td>
<td>43.9 x 10^6</td>
<td>45.34°</td>
<td>30°</td>
<td>76.2 ± 7.6 mm</td>
<td>12.9 mm</td>
</tr>
<tr>
<td>3</td>
<td>10°</td>
<td>1.37</td>
<td>483 kPa</td>
<td>37.3 x 10^6</td>
<td>27.38°</td>
<td>19.47°</td>
<td>245.9 ± 24.6 mm</td>
<td>17.0 mm</td>
</tr>
<tr>
<td>3</td>
<td>10°</td>
<td>1.37</td>
<td>965 kPa</td>
<td>74.7 x 10^6</td>
<td>27.38°</td>
<td>19.47°</td>
<td>197.3 ± 19.7 mm</td>
<td>16.4 mm</td>
</tr>
<tr>
<td>3</td>
<td>15°</td>
<td>1.60</td>
<td>1379 kPa</td>
<td>107 x 10^6</td>
<td>32.24°</td>
<td>19.47°</td>
<td>111.8 ± 11.2 mm</td>
<td>17.0 mm</td>
</tr>
<tr>
<td>3</td>
<td>15°</td>
<td>1.60</td>
<td>345 kPa</td>
<td>74.7 x 10^6</td>
<td>32.24°</td>
<td>19.47°</td>
<td>72.1 ± 7.2 mm</td>
<td>16.4 mm</td>
</tr>
<tr>
<td>3</td>
<td>15°</td>
<td>1.60</td>
<td>483 kPa</td>
<td>37.3 x 10^6</td>
<td>37.76°</td>
<td>19.47°</td>
<td>96.6 ± 9.7 mm</td>
<td>17.0 mm</td>
</tr>
<tr>
<td>3</td>
<td>20°</td>
<td>1.83</td>
<td>965 kPa</td>
<td>74.7 x 10^6</td>
<td>37.76°</td>
<td>19.47°</td>
<td>58.9 ± 5.9 mm</td>
<td>16.4 mm</td>
</tr>
<tr>
<td>3</td>
<td>20°</td>
<td>1.83</td>
<td>1379 kPa</td>
<td>107 x 10^6</td>
<td>37.76°</td>
<td>19.47°</td>
<td>63.8 ± 6.4 mm</td>
<td>16.4 mm</td>
</tr>
<tr>
<td>4</td>
<td>10°</td>
<td>1.51</td>
<td>1517 kPa</td>
<td>71.3 x 10^6</td>
<td>22.23°</td>
<td>14.47°</td>
<td>91.7 ± 9.2 mm</td>
<td>19.0 mm</td>
</tr>
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<td>1.82</td>
<td>1517 kPa</td>
<td>71.3 x 10^6</td>
<td>27.06°</td>
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<td>55.1 ± 5.5 mm</td>
<td>19.0 mm</td>
</tr>
<tr>
<td>4</td>
<td>20°</td>
<td>2.14</td>
<td>1517 kPa</td>
<td>71.3 x 10^6</td>
<td>32.46°</td>
<td>14.47°</td>
<td>65.3 ± 6.5 mm</td>
<td>19.0 mm</td>
</tr>
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</table>

Table A.2: Table of test parameters and VCO locations for the PSWT plate.

<table>
<thead>
<tr>
<th>$M_\infty$</th>
<th>$\alpha_F$</th>
<th>$M_n$</th>
<th>$P_o$</th>
<th>$Re/m$</th>
<th>$\beta_o$</th>
<th>$\mu$</th>
<th>VCO</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10°</td>
<td>1.26</td>
<td>138 kPa</td>
<td>17.6 x 10^6</td>
<td>45.34°</td>
<td>30°</td>
<td>83.3 ± 8.3 mm</td>
<td>3.4 mm</td>
</tr>
<tr>
<td>2</td>
<td>15°</td>
<td>1.42</td>
<td>138 kPa</td>
<td>17.6 x 10^6</td>
<td>45.34°</td>
<td>30°</td>
<td>42.3 ± 6.3 mm</td>
<td>3.8 mm</td>
</tr>
<tr>
<td>2</td>
<td>15°</td>
<td>1.42</td>
<td>345 kPa</td>
<td>43.9 x 10^6</td>
<td>45.34°</td>
<td>30°</td>
<td>33.1 ± 3.3 mm</td>
<td>3.4 mm</td>
</tr>
<tr>
<td>3</td>
<td>10°</td>
<td>1.37</td>
<td>483 kPa</td>
<td>37.3 x 10^6</td>
<td>27.38°</td>
<td>19.47°</td>
<td>77.1 ± 7.7 mm</td>
<td>3.1 mm</td>
</tr>
<tr>
<td>3</td>
<td>15°</td>
<td>1.60</td>
<td>483 kPa</td>
<td>37.3 x 10^6</td>
<td>27.38°</td>
<td>19.47°</td>
<td>51.7 ± 5.2 mm</td>
<td>2.9 mm</td>
</tr>
<tr>
<td>3</td>
<td>15°</td>
<td>1.60</td>
<td>965 kPa</td>
<td>74.7 x 10^6</td>
<td>32.24°</td>
<td>19.47°</td>
<td>45.0 ± 6.1 mm</td>
<td>3.1 mm</td>
</tr>
<tr>
<td>3</td>
<td>22°</td>
<td>1.83</td>
<td>483 kPa</td>
<td>37.3 x 10^6</td>
<td>37.76°</td>
<td>19.47°</td>
<td>31.6 ± 3.2 mm</td>
<td>3.1 mm</td>
</tr>
<tr>
<td>3</td>
<td>22°</td>
<td>1.83</td>
<td>965 kPa</td>
<td>74.7 x 10^6</td>
<td>37.76°</td>
<td>19.47°</td>
<td>28.3 ± 3.5 mm</td>
<td>2.9 mm</td>
</tr>
</tbody>
</table>
Figure B.1: Surface oil flow visualizations used in OFI processing. Flow is from left to right.
Figure B.2: Surface oil flow visualizations used in OFI processing marked with data extraction points (blue stars). Flow is from left to right.
Figure B.3: Radial progression of the skin friction across the interaction for all flow conditions examined.
Figure B.4: Comparison of angular scaling for test cases with interaction strengths of approximately $M_n = 1.4$. 

(a) $M=2, \alpha_F = 15^\circ, M_n=1.42$

(b) $M=2, \alpha_F = 15^\circ, M_n=1.42$

(c) $M=2, \alpha_F = 15^\circ, M_n=1.42$
Figure B.5: Comparison of angular scaling for test cases with interaction strengths of approximately $M_n = 1.83$. 

(a) $M=3$, $\alpha_F = 20^\circ$, $M_n=1.83$

(b) $M=3$, $\alpha_F = 20^\circ$, $M_n=1.83$

(c) $M=3$, $\alpha_F = 20^\circ$, $M_n=1.83$
APPENDIX C

TIME-AVERAGED PSP

In the following time-averaged PSP fields, regions that have been masked to remove noise (due to lack of/damaged paint) appear as white.

Figure C.1: $M_\infty = 2$, $\alpha = 10^\circ$, Re/m = 17.6 x 10^6
Figure C.2: $M_\infty = 2, \alpha = 10^\circ, \text{Re}/m = 43.9 \times 10^6$

Figure C.3: $M_\infty = 2, \alpha = 10^\circ, \text{Re}/m = 70.2 \times 10^6$
Figure C.4: $M_\infty = 2$, $\alpha = 15^\circ$, $Re/m = 17.6 \times 10^6$

Figure C.5: $M_\infty = 2$, $\alpha = 15^\circ$, $Re/m = 43.9 \times 10^6$
Figure C.6: $M_\infty = 2, \alpha = 15^\circ, \text{Re}/m = 70.2 \times 10^6$

Figure C.7: $M_\infty = 2, \alpha = 20^\circ, \text{Re}/m = 17.6 \times 10^6$
Figure C.8: $M_\infty = 2$, $\alpha = 20^\circ$, $Re/m = 70.2 \times 10^6$

Figure C.9: $M_\infty = 3$, $\alpha = 10^\circ$, $Re/m = 37.3 \times 10^6$
Figure C.10: $M_\infty = 3$, $\alpha = 10^\circ$, Re/m = 74.7 x 10$^6$

Figure C.11: $M_\infty = 3$, $\alpha = 15^\circ$, Re/m = 74.7 x 10$^6$
Figure C.12: $M_\infty = 3$, $\alpha = 20^\circ$, $\text{Re}/m = 37.3 \times 10^6$

Figure C.13: $M_\infty = 3$, $\alpha = 20^\circ$, $\text{Re}/m = 74.7 \times 10^6$
Figure C.14: $M_\infty = 3$, $\alpha = 20^\circ$, Re/m = $107 \times 10^6$  

Figure C.15: $M_\infty = 4$, $\alpha = 10^\circ$, Re/m = $71.3 \times 10^6$
Figure C.16: \( M_\infty = 4, \alpha = 15^\circ, \text{Re}/m = 71.3 \times 10^6 \)

Figure C.17: \( M_\infty = 4, \alpha = 20^\circ, \text{Re}/m = 71.3 \times 10^6 \)
APPENDIX D

FAST RESPONSE PSP

(a) Kulite/PSP Coherence

(b) Kulite/PSP Gain

(c) Kulite/PSP Phase

Figure D.1: Characterization of the relationships between the Kulites and surrounding PSP. Kulite 1 (K1) phase not shown due to noise.
Figure D.2: Coherence between the under vortex region and all other regions.
Figure D.3: Coherence between the intermittent separation region and all other regions.
Figure D.4: Coherence between the freestream region and all other regions.


BIOGRAPHICAL SKETCH

Andrew Kyle Baldwin was born in Tallahassee, Florida in 1993. Andrew began his tenure at Florida State University in Fall 2011 and earned a Bachelors of Science degree in Mechanical Engineering in Spring 2015 from the FAMU-FSU College of Engineering. For grad school, he joined Dr. Rajan Kumar’s Experimental Aerodynamics Group where he has primarily focused on the study of supersonic flows and three-dimensional shock wave/boundary layer interactions (SBLI). Andrew was awarded his Masters degree in Mechanical Engineering after the Summer of 2018. As a part of his doctoral studies, he co-taught the Introduction to Gas Dynamics course during the Spring of 2020. After the completion of his PhD he intends to continue working for Dr. Kumar as a Post-Doctoral researcher.