ABSTRACT

PHẠM, HARRY TOÀN. Compression Ramp Induced Shock Wave/Turbulent Boundary Layer Interactions on a Compliant Material. (Under the direction of Dr. Venkateswaran Narayanaswamy.).

An investigation into the potential use of soft compliant materials towards unsteady shock load mitigation is made. Compression ramps with different angles are used to generate shock waves impinging on the surface of the compliant layer embedded on a rigid flat plate in a Mach 2.5 flow. A urethane rubber material is chosen as the candidate compliant material for its well characterized material properties and ease of fabrication. Shock boundary layer interactions and fluid structure interactions are analyzed through oil-pigment surface streakline visualization and high-speed pressure transducer measurements. Reductions in the mean separation size are observed by embedding the compliant layer compared to without it. Furthermore, significant reduction in the energy content of the low frequency shock oscillations over the intermittent region was also observed by embedding a compliant layer on the rigid plate.

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Compression Ramp Induced Shock Wave/Turbulent Boundary Layer Interactions on a
Compliant Material

by
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DEDICATION

To my parents.

BIOGRAPHY

Harry Pham was born in Fairfax, VA where he lived for ten years before moving to Winter Park, FL. He attended Stanford University and graduated with a BS in Mechanical Engineering in 2016. During his undergraduate career, his family moved to Wadesboro, NC which partly guided his decision to return to the East Coast and pursue an MS in Aerospace Engineering at North Carolina State University. Upon graduation, he intends to stay within the Southeast region of the United States and work in the field of aerospace.

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Chapter 1

INTRODUCTION

1.1 Shock boundary layer interactions

In supersonic flows, aircraft contours, engine inlets, and maneuvering flaps can create shocks that impinge on aircraft surfaces and interact with the body. These impinging shockwaves affect and are affected by the boundary layer, leading to a phenomenon known as a shock boundary layer interaction (SBLI). Due to increased interest in developing supersonic and hypersonic vehicles in the past several decades, a great amount of work has been done on types of interaction [1, 2]. Figure 1.1 depicts many canonical configurations of SBLI. Extensive research has been done particularly on 2D SBLIs in which the main focus is on the centerline flow away from any corners, and this will be the type of SBLI examined in this study.

On surfaces in viscous flows, impinging shockwaves impose an adverse pressure gradient that the boundary layer must overcome. The impinging shockwave terminates in the boundary layer at the sonic line below which flow is subsonic. This point of shock termination is known as the separation shock foot. The gradual pressure rise in the subsonic

Figure 1.1: Canonical configurations of SBLI. Figure adapted from Gaitonde [2]

region must equilibrate with the abrupt pressure rise in the supersonic region caused by the inviscid pressure jump, and this is achieved by boundary layer thickening and the generation of compression waves within the boundary layer. If the impinging shockwave is weak enough, pressure rise equilibrium above and below the sonic line in the boundary layer can be resolved without the need for flow separation.

If the adverse pressure gradient is strong due to increasing shock strengths, however, flow separation will occur. Fluid momentum within the boundary layer is not sufficient to traverse and overcome the adverse pressure gradient. When this happens, the boundary layer separates and a closed bubble of recirculating flow forms beneath the impinging shockwave. The incoming boundary layer turns and lifts from the wall to pass over the generated bubble, forming a shear layer. For the case of ramp generated SBLIs, this obstruction caused by lifted flow over the separation bubble leads to the formation of a separation shock which coalesces with the inviscid shock generated by the compression ramp. The shear layer eventually gains energy as a result of turbulent mixing with the free stream flow and reattaches to the wall downstream of the separation bubble once

sufficient energy is acquired. The adverse pressure gradient is tied closely to the inviscid pressure ratio of the shock wave, and stronger shocks generated by higher ramp angles lead to an increase in separated flows and larger separation bubbles overall [3].

Boundary layer separation due to shock impingement can cause aircraft buffeting, inlet instability, severe thermal loading (especially in hypersonic flows), and aerostructure fatigue. As previously mentioned, flow separation bubbles will form if the impinging shock is sufficiently strong. These separation bubbles are responsible for unsteady pressure oscillations because they pulse and drive the upstream separation shockwave back and forth on the control surface [4]. Mean pressure loading is generally acceptable on aircraft surfaces; it is unsteady pressure loading that can couple with structural dynamics and cause high-cycle fatigue failures over time.

Figure 1.2: Compression ramp generated SBLI. Figure adapted from Clemens & Narayanaswamy [1]

Figure 1.2 shows a typical 2D SBLI generated by a compression ramp. The separation bubble is marked by the yellow bubble that is predominantly on the brown surface with a small portion of the surface on the ramp leading edge. To cast this figure into a scenario,

the brown surface can represent the wing with the blue ramp representing the wing flap on a supersonic aircraft. This can be envisioned as the bottom surface of a wing, since flaps are generally deflected downwards. Regardless, if the angle of deflection of the flap is large enough, a shock will be generated that impinges on the wing surface. This location of impingement, denoted by L_i in Figure 1.2, is called the intermittent region and is the main area of interest in this study. The separation shock foot spends about 50% of its time oscillating in this region, and this is where the peak root-mean-square (RMS) pressure occurs which has many potential ramifications.

Figure 1.3: Compression ramp SBLI power spectra of unsteady pressure loading [5]. Figure adapted from Clemens & Narayanaswamy [1]

The five graphs in Figure 1.3 show frequency multiplied power spectral densities (PSD) of unsteady energy content on a model surface in a $M_\infty = 5$ flow [5]. Frequency, f , is along the y-axis and frequency multiplied unsteady pressure is on the x-axis. Peaks in each graph show what range of frequencies correspond to the most unsteady pressure loading for each location on the surface beneath the SBLI. In graphs 1, 4, and 5 from Figure 1.3, which portray PSDs for locations upstream and downstream of the intermittent region, most of the frequency content resides at higher frequencies in the 10 kHz to 50 kHz range, with the peak energy occurring at approximately 35 kHz . High frequency energy content in this range is associated with the passage of boundary layer structures, and for locations within the separation bubble, high frequency energy content is generated by the recirculating flow and the shear layer above. In graphs 2 and 3 from Figure 1.3, however, which correspond to locations underneath the intermittent region in the SBLI, shock oscillations and the resulting unsteady pressure loading is greatest at frequencies under 1 kHz . Larger compression ramp angles result in stronger separation shocks and higher magnitudes of low frequency energy content [3].

This low frequency range is known to represent the dominant oscillation frequency of the separation shock foot [1]. This frequency range also corresponds to the range in which aerostructures and aeroshells typically have resonant frequencies that can lead to high-cycle fatigue, also known as sonic fatigue, due to severe aero-acoustic and mechanical vibration loading [6]. As such, impinging shocks can have disastrous effects due to the huge low frequency fluctuating loads they impart on aircraft. For example, consider a situation in which one is attempting to maneuver a projectile or performing an intense, high-g turn in a high-speed aircraft. This action already subjects the projectile or aircraft to maximum loading and stresses, but generated shockwaves that impinge and oscillate on the surface will cause fluctuating pressure loadings that will only add to the overall

load on the aircraft in the worst possible frequency range. This study’s goal is to see if fluid structure interactions can be successfully utilized to mitigate aeroacoustic fatigue problems caused by low frequency shock oscillations.

1.2 Fluid structure interactions

Fluid structure interaction (FSI) over flexible surfaces have ubiquitous occurrences in numerous engineering systems and have been a topic of significant interest over several decades. FSI is characterized by stable or oscillatory interactions between a movable or deformable structure with an internal or surrounding fluid flow. Essentially, fluid flow causes deformations in the structure, and this deformation in turn causes changes in the fluid flow. This interaction loop can result in structural damage and detrimental changes to surrounding flow, and so FSI must be taken into account when designing anything from hydrokinetic energy harvesters, bridges, and artificial heart valves to instrument reeds, wind turbine blades, and supersonic parachutes.

1.2.1 Subsonic FSI

It has long been suggested that compliant surfaces can be favorably used as a form of passive flow control to delay the transition to a turbulent boundary layer and to reduce drag in incompressible flows. This form of flow control has several benefits over other active methods such as suction, gaseous injection, and particle additives due to its simplicity [7]. Kramer suggested in as early as 1960 [8] that ducted coatings could be used specifically for boundary layer stabilization by distributed damping, a process similar to the principle of boundary layer removal. This was inspired by previous studies on possible hydrodynamic drag reduction benefits experienced by dolphins due to their

flexible, compliant skin (see Gray’s paradox). Similar to the benefits realized by natural laminar airfoils today, boundary layer stabilization by distributed damping allows for larger extents of laminar flow over a surface, resulting in less drag compared to that of turbulent flows. Kramer reported a drag reduction of 60% when comparing a rubber-coated experimental model with an uncoated model which was certainly a bold result for the fledgling field of FSI at the time.

Figure 1.4: Potential drag reduction due to transition delay. Figure adapted from Gyorgyfalvy [9]

An analytical study by Gyorgyfalvy in 1967 [9] also proposed the use of a flexible aerodynamic surface as a means to reduce skin friction drag due to transition delay. Gyorgyfalvy found that flexible skins could significantly reduce the amplification of Tollmein-Schlichting waves which would lead to delayed transition, and he attempted

to characterize and parametrize material properties that would produce these favorable conditions. Figure 1.4 shows impressive theoretically possible drag reductions due to transition delay for various airborne and waterborne vehicles. Reynolds number is on the x-axis and the percentage of drag reduction for a flexible surface compared to a rigid surface is on the y-axis. Gyorgyfalvy's analysis suggested transition delays of up to 4 times in air and up to 10 times in water with associated drag reductions in skin-friction drag to be 80% and 90% respectively.

However, a common trend quickly observed in early and even later studies involving FSI is that it is a field full of potential but also conflict. While the theoretical benefits of compliant materials are many, there has been much frustration in choosing and applying material properties correctly for favorable conditions and outcomes. An interested reader will find Gad-el-Hak's work provides a good summary of the challenges faced by FSI researchers over the decades [10]. Many experiments that attempted to replicate Kramer's initial findings from his 1960 work showed no significant drag reduction, and Kramer's results were largely believed to be in error. Carpenter & Garrad [11] did a detailed analysis of Kramer's experiments nearly 30 years later and found that while Kramer's coating did have a marginal effect in delaying transition, any unfavorable factor, such as a bad junction between a rigid surface and a compliant surface, could be enough to negate any beneficial FSI effects. They proposed this as the reason as to why Kramer's experiment could not be easily replicated for the same results. Gyorgyfalvy also stressed many times within his study that the positive effects were only possible with proper selection of the flexible surface characteristics. Indeed, his analysis showed that while material properties could be chosen to allow for favorable flow conditions, if chosen incorrectly, they could easily provide conditions even worse than conditions provided by a rigid surface.

Part of the headache experienced by researchers in FSI is due to the nature of a

compliant material; it encompasses such a broad range of possible materials with an equally broad way to model and apply them. Understanding how these materials perform in and interact with varying regimes of flow can lead to better applications, and care must be taken in choosing compliant material properties correctly so that the desired benefits outweigh any adverse effects. Proposed benefits of FSI in subsonic regime such as boundary layer transition delay are not easily transferable to the supersonic regime due to the high Reynolds number of such flows. The closest hint towards a possible benefit from a supersonic perspective would be to utilize compliant surfaces as a dampener of some form. Perhaps the greatest takeaway for this study from taking a look at subsonic FSI is to keep in mind that FSI can be just as detrimental as it can be beneficial.

1.2.2 Transonic FSI

In the transonic regime, one of the most prevalent applications of FSI is through the use of shock control bumps (SCB) to mitigate impinging shockwaves, reduce drag, and delay the onset of buffet for transonic wings [12]. Large extents of favorable pressure gradient on the upper surface of transonic wings allow for supersonic flows of up to $M = 1.4$ which must terminate with a near-normal shockwave on the wing surface. This resulting shockwave presents an adverse pressure gradient that can degrade the health of the boundary layer, cause flow separation, and incur large drag penalties. SCB are a form of flow control that uses flexible plates to deform and create a bump beneath impinging shockwaves. They can be created either passively through a panel that deflects due to the surrounding flow or actively through the usage of actuators placed beneath the panel that deflect it in a controlled manner [13].

Figure 1.5a shows the flow structure of a SCB on a transonic airfoil, and Figure 1.5b

Figure 1.5: Operation principle of SCB on a transonic wing regarding a) shock structure and b) total wake pressure. Figure adapted from Bruce & Colliss [12]

shows the drag reduction in the wake for an airfoil with a SCB compared to a clean airfoil. SCBs operate by smearing the structure of the impinging, near-normal shockwave on the wing surface to create a bifurcated shock structure. This two-legged shock is also known as a λ -shock. The leading edge of the SCB generates an oblique shockwave that forms the front leg of the λ -shock. A series of compression waves may be generated as well in lieu of the oblique shock, but in both cases, this smeared shock structure gradually decelerates the supersonic flow compared to the flow deceleration achieved by a near-normal shock. The weakened shock structure results in reduced stagnation pressure losses as well as lower drag values on the surface.

One caveat of SCB is that their efficiency is highly dependent on the state of the incoming boundary layer and shock impingement position. Furthermore, while they do beneficially mitigate the effects of near-normal shockwaves, the geometry of SCB are generally detrimental to boundary layers. Bruce & Babinsky did a study in 2012 [14] on 3D SCB and performed measurements including schlieren photography, surface oil flow

Figure 1.6: Effect of shock position on SCB in $M_\infty = 1.3$ flow for a) $x_s/\delta_0 = 5$, b) $x_s/\delta_0 = 7$, c) $x_s/\delta_0 = 9$, d) $x_s/\delta_0 = 11$, e) $x_s/\delta_0 = 13$, and f) $x_s/\delta_0 = 14$. Figure adapted from Bruce & Babinsky [14]

visualization, pressure sensitive paint, and laser Doppler anemometry. Schlieren imaging of a SCB in a $M_\infty = 1.3$ flow at six different shock positions are depicted in Figure 1.6. Shock location is represented by x_s/δ_0 where x_s is the streamwise shock position relative to the bump tip and δ_0 is the incoming 99% boundary-layer thickness. The strength of shock bifurcation can be seen to depend heavily on shock location, and the adverse effect of the bump geometry can be seen in the thickening of the boundary layer past the bump with the eventual formation of a shear layer as marked in Figure 1.6f. However, Jinks et al. [13] recently investigated in depth both passive and active flow control methods using SCB, and they recommend additional actuators or limit stops to maintain optimal shapes even when in off-design performance conditions. Overall, there is strong evidence towards SCB as a successful application of FSI in the transonic regime.

1.2.3 Supersonic FSI

In supersonic flows, previous research into FSI has focused on panel flutter caused by events such as turbulent jet impingement [15] and shock impingement on flexible, compliant surfaces. As this study will be on the effect of FSI on SBLI, focus in this section will be on studies involving shock impingement on flexible, compliant surfaces. Studies of this nature are not as extensive as those involving panel flutter, but researchers have made strong contributions in recent years. Of the studies involving shock impingement, most of the research has been focused on studying FSI on a thin panel subjected to shock oscillations to model realistic situations that occur in outer shells and control surfaces of high speed platforms [16].

Figure 1.7: PSD of shock position. Figure adapted from Daub et al. [17]

Daub et al. [17] performed experiments with a fast-moving shock sweeping across an elastic surface in a $M_\infty = 3$ and 4 flow to study the oscillations of the elastic panel excited by the flow field and vice versa. High-speed pressure transducers and high-speed schlieren imaging were used to analyze the flow field, and high-speed capacitive sensors and laser distance sensors were used to measure panel deflection. The elastic panel was demonstrated to have a static and dynamic influence on the behavior of the separated region as well as the flowfield topology compared to results from a rigid panel used as a reference case. Figure 1.7 shows the PSD of shock positions for a $M_\infty = 3$ flow with an oblique, impinging shock generated by a 20° ramp. The separation shock had a larger low-frequency movement on the elastic panel, and schlieren imaging also showed that the separation area on the elastic panel was much larger than the separation area on the rigid panel. From an application standpoint, both results indicated a negative influence due to the FSI.

Spottswood et al. [18] performed similar experimental studies of a shockwave impinging on a flexible panel placed in a $M_\infty = 2$ flow to better understand the fluid dynamic and structural coupling of a compliant panel at high speeds. Using simultaneous high-speed pressure sensitive paint (PSP) and high-speed 3D digital image correlation (DIC), the authors observed significant changes between the natural and FSI-forced resonance frequencies and vibrational modes depending on the magnitude of structure and fluid-dynamic coupling. Figure 1.8 depicts the deflected shapes produced by applying modal analysis on the DIC data. Panel center displacement is on the y-axis and frequency is on the x-axis. Peaks in the PSD represent operational deflected shapes. Frequencies for these shapes can be seen to differ from the frequencies of the unstressed panel modes also denoted on the x-axis. Gogulapati et al. built upon the work done by Spottswoods et al. [16] by creating computational models in ABAQUS and NASTRAN to study the static

Figure 1.8: Panel center displacement power spectral density and full-field displacement based operational deflected shapes. Figure adapted from Spottswood et al. [18]

and dynamic response of the same panel. Computational results showed good agreement with Spottswoods experimental results, but discrepancies arising from sources such as experimental error and modeling approximations necessitate the need for continued work in this area to better understand panel response due to FSI.

Figure 1.9: Steady RANS streamwise velocity contours for a) undeformed surface, b) max deflection into flow on a deformed surface, and c) max deflection out of the flow on a deformed surface. Figure adapted from Brouwer et al. [19]

Brouwer et al. [19] also performed Reynolds-Averaged Navier-Stokes based computational studies on the static and unsteady interplay between surface deformation and shock-induced separation on a panel in supersonic flow. They observed that static surface deformations resulted in significant increases and decreases in the mean size of the shock-induced separation bubble while unsteady surface deformations only had a marginal effect on the separation bubble. Figure 1.9 depicts streamwise velocity contours for three different steady RANS results in a $M_\infty = 3$ flow with L representing the deforming length. The undeformed surface in Figure 1.9a showed a separation length of $0.183L$, while the separation lengths for the 2D surface undergoing mode 1 oscillations in Figure 1.9b and Figure 1.9c were $0.097L$ and $0.430L$ for the max deflection into and out of the flow re-

spectively. Separation size was also found to be highly dependent on which modal shapes were being excited due to the effect of the changes in curvature at the location of shock impingement on the surface.

Figure 1.10: Elastic panel showing normal mode 3;1. Figure adapted from Daub et al. [17]

Overall, every work observed that FSI is a very real phenomenon with very real effects that must be taken into consideration when developing supersonic and hypersonic flight vehicles in shock dominated flows. Generally, it was found that FSI had a negative impact if you let the system naturally play out unchecked. The common denominator in all of these studies was that the compliant materials in question were thin, flexible panels that had modes of vibrations as can be seen on the elastic panel in Figure 1.10. Modal vibrations cause the panel to sinusoidally bulge into the flow and out of the flow, and this occurs globally on the surface of the panel both upstream and downstream of any shock impingement. In true fluid structure interaction form, impinging shockwaves coupling with the elastic modes of panels can lead to modal excitations and accelerated fatigue while the same modal vibrations greatly influencing surface flow can lead to non-optimal flow conditions.

1.2.4 Computational FSI

Research into computational fluid dynamics and computational structural dynamics have advanced greatly in the past few decades, but the intersection between the two with FSI is still developing. Coupling the two methods is a challenge, and the trade-offs in terms of computational cost and accuracy are particularly severe [20]. Models must be able to move back and forth between the structural changes caused by fluid forces and the flow changes caused by structural deformation. Figure 1.11 shows the general flow diagram of computational FSI and the iteration loop involved. With so many methods to combine the two solvers as well as to model compliant materials, there is generally no agreed upon theoretical framework to study FSI [21]. At present, many theoretical studies in the interaction between compliant materials and flows provide computational results that require experimental validation and vice versa, such as with the previously mentioned studies by Spottswood et al. [18] and Gogulapati et al. [16]. The results from this study will provide yet another set of data to validate (or to be validated by) computational FSI, albeit with a much different type of compliant material.

Figure 1.11: Coupled FSI flow diagram. Figure adapted from Kamakoti & Shyy cite kamakoti

1.3 Motivation

The above discussions show that the FSI over flexible surfaces have very real, measurable effects that can be tailored for significant practical gains, and without any intervention, can also result in several detrimental effects. In this study, a new class of FSI is investigated that occurs between an unsteady shock wave incident on a soft compliant surface. Potential applications of such interactions range from dampening panel and control surface loading, reducing aerodynamic drag, and minimizing aeroacoustic fatigue caused by SBLI. The soft surface to be investigated is more similar to the compliant materials studied extensively in subsonic FSI than the panel studies found in supersonic FSI. The largest difference is that, unlike flexible panels, the soft surfaces deform locally under stress without a macroscale global structural response.

This study will focus on the FSI between a shock wave and a rubber surface, which is chosen as the soft surface candidate. Comparisons of surface streakline visualization and wall pressures beneath shock-induced separation over rigid and rubber surfaces are made to bring out the changes on the SBLI caused by FSI. Secondary investigations are made into the changes on the SBLI and FSI on a panel surface as well. It should be noted that this study is intended to obtain a basic understanding of the FSI phenomenon with a soft surface and its impact on the global mean and unsteady flow field; this study does not imply that the chosen rubber material is relevant for practical applications. Instead, the understanding into the FSI obtained from this work is intended to inform the design and application decisions when more appropriate materials are pursued.

Chapter 2

EXPERIMENTAL SETUP

2.1 Wind tunnel facility

All experiments were conducted in the North Carolina State University supersonic wind tunnel facility. The NCSU supersonic wind tunnel, depicted in Figure 2.1, is a blow down-type variable Mach number wind tunnel from Aerolabs LLC with an operating Mach number range of 1.5 to 4.0. Flow is from left to right in the orientation of the tunnel in Figure 2.1. The Mach number is controlled through a block number that changes the size of the converging-diverging nozzle upstream of the test section. The wind tunnel is capable of up to eight seconds of run time depending on the Mach number and stagnation chamber pressure setting. The wind tunnel is operated through a computer with a custom LabVIEW VI that controls the length and stagnation chamber pressure for each run. A PID controller varies a hydraulic valve to achieve a constant stagnation chamber pressure. The wind tunnel test section has a square cross section of $150\text{ mm} \times 150\text{ mm}$ and a length of 650 mm . Two removable aluminum sidewalls that house quartz windows provide access to the tunnel for set up as well as optical access during experiments. Experimental models

can be mounted on a customizable plug in the tunnel ceiling or on a modified sidewall depending on the needs of different measurement methods and the desired viewing angles. Downstream of the test section is an oblique shock diffuser, and the outcoming flow exits through the roof of the facility into ambient air.

Figure 2.1: NCSU Supersonic Wind Tunnel

2.2 Free stream conditions

For the present study, the freestream Mach number, M_∞ , was fixed at 2.5. The stagnation chamber pressure, p_{01} , was held constant at 556 *kPa* (80.7 *psi*) for the duration of each run corresponding to a test section static pressure, p_∞ , of 33 *kPa* (4.7 *psi*) calculated through the isentropic flow relations. This results in a freestream velocity, u_∞ , of 589 *m/s* with velocity variations from test to test estimated to be at $\pm 5\%$. Table 2.1 lists the freestream conditions for all experiments in this study. For a complete derivation of

Table 2.1: Incoming free stream flow characteristics. Table adapted from [22]

Parameter	Value	
M_∞	2.5	
p_∞	4.7	<i>psi</i>
T_∞	138	<i>K</i>
ρ_∞	0.818	$\frac{kg}{m^3}$
u_∞	589	<i>m/s</i>
μ_∞	9.53×10^{-6}	$\frac{kg}{ms}$
Re/L	5.1×10^7	m^{-1}

each free stream value for the NCSU supersonic wind tunnel at Mach 2.5, see [22].

2.3 Experimental models

A few experimental models were made for this study. The rationale for choosing the 2D ramp-generated SBLI configuration is the availability of extensive literature on separation shock loading over rigid surfaces, which provides a great starting point to compare the results with adding the compliant insert. The two predominant models used to compare the SBLI and FSI characteristics over a rigid surface and a compliant surface will be referred to as the all-steel model and the rubber-insert model respectively throughout this paper. In addition to these two models, an acrylic-insert model and a panel model were created and tested. However, a majority of the results focus on the all-steel model as well as the rubber-insert model, with results from the acrylic-insert model and panel model providing secondary contributions and insight. The SBLI in this study is generated through three different compression ramps of 16° , 20° , and 24° .

2.3.1 All-steel model

The experimental all-steel model is a flat plate machined out of low carbon steel. The model, depicted in Figure 2.2, is 355 *mm* (14") long, 100 *mm* (4") wide, and 10 *mm* (0.375") thick. An arrow detailing flow direction is included for orientation of the model with respect to the tunnel flow. The model was placed in the wind tunnel freestream flow at a zero angle of attack. The entire model was lifted 25 *mm* into the test section away from the tunnel wall through the usage of two mounting struts to prevent any interference by the tunnel boundary layer. The six holes along the outer edges of the model are used to securely attach the model to the struts. They are counterbored to allow the heads of the mounting screws to sit flush with the surface of the model to prevent unwanted shock structures off the screw heads. The two struts are then fixed to the previously mentioned customizable plug that can be mounted on the tunnel ceiling or on the modified sidewall. A sharp leading edge with the angled side facing downwards towards the tunnel wall was machined to minimize any unwanted shocks that could reflect and impinge on the area of interest of this study. Along the surface of the flat plate, a 2D boundary layer developed and naturally transitioned into a fully developed turbulent boundary layer well upstream of the test region. The two oval slots at the downstream end of the flat plate are used to mount the compression ramps which will be discussed in detail in a later section.

2.3.2 Rubber-insert model

The experimental rubber-insert model is nearly identical to the all-steel model. The main difference, which allows for the eventual comparison of an SBLI over a rigid surface and a compliant surface, is the inclusion of a recess milled out of the flat plate surface to accept the rubber-insert. This recess is highlighted in blue in Figure 2.3. The recess is

Figure 2.2: All-steel experimental model

240 *mm* long, 76 *mm* wide, and 2 *mm* thick. It was milled symmetrically about the midspan with the leading edge of the rubber surface with respect to the incoming flow located 75 *mm* downstream of the overall model leading edge. This was due to physical constraints determined by the angled cut on the backside of the flat plate.

Figure 2.3: Rubber-insert experimental model

The recess was filled flush with ReoFlex 50. ReoFlex 50 is a non-porous, liquid ure-

thane rubber product from Smooth-On Inc. with a Shore hardness of 50A. The steps to apply this material is similar to that of an epoxy. A 1:1 ratio of the two liquid components is thoroughly combined, and care is taken during the mixing process to ensure that no air bubbles are incorporated into the mixture which would lead to microbubbles that increased surface roughness. After mixing, the solution is poured flush into the recess while the model is on a level surface. The rubber is then left to harden over a few hours. To ensure that the rubber was fully cured, rubber-insert models were left for at least two days before any further modification were made for experiments. One advantage of this rubber is that there is negligible shrinkage upon drying. This particular rubber mixture is often used for production casting and naturally bonds to the flat plate once dry. For all the experiments in this study, the rubber surface was not externally pre-stressed. Further, schlieren imaging was performed to identify the presence of shock/Mach waves that may emanate from an uneven surface finish. No waves were detected within the rubber surface, confirming that the surface is indeed smooth and even.

It should be noted that this rubber material is only chosen as the candidate soft surface to get a basic understanding of a soft surface's effect on the mean and unsteady flow field. The hope is that with the understanding obtained from this work and future works involving a soft material in supersonic flows, material scientists will be able to engineer a material specifically made for load mitigation purposes. An additional benefit of using this particular product is that it is part of a family of liquid urethane rubbers provided by Smooth-On Inc. that have different Shore A hardnesses. This will allow for future investigations on the impact of scaling rubber hardnesses on the FSI in supersonic flows.

The acrylic-insert panel used the same low-carbon steel flat plate with the recess that was used for the rubber-insert model. For experiments involving the acrylic-insert model,

an acrylic plate is inserted into the recess and bonded to the flat plate using superglue. The acrylic insert is cut using a laser cutter to have the same dimensions as the recess to allow for a flush surface. In addition to a flat plate recessed model that could accept a 2 *mm* insert, another flat plate model was made with a recess of similar dimensions in length and width but with a recess thickness of 4 *mm* to accept inserts twice as thick. This allowed for investigations into the effect of scaling compliant material thicknesses.

2.3.3 Panel model

The experimental panel model was made to allow for comparisons between the rubber-insert model and the more common type of compliant material typically found in literature regarding compliant materials in supersonic flows: panels. The panel model has the same overall dimensions as the previously described flat plates. The back of the flat plate was milled down to nearly the thickness of the plate to leave a thin panel on the flow side surface. The panel is centered symmetrically about the midspan and is 210 *mm* long, 70 *mm* wide, and 0.75 *mm* thick with slight corner fillets. The top surface of the panel model looks identical to that of the all-steel model in Figure 2.2, however, the bottom surface depicted in Figure 3.8 shows the panel surface highlighted in blue. The panel leading edge with respect to incoming flow is located 95 *mm* downstream of the overall model leading edge. The mounting process is the same for the panel model as it was for the all-steel and rubber-insert models.

This model design was inspired by the work done by Spottswood et al. [18] to allow for a panel flush with the surface of the model and fixed along all four sides without the need for any clamps or rivets. The backside of the panel in that study was not exposed to the flow because the surface of their panel was flush with their wind tunnel wall, and

Figure 2.4: Panel experimental model, bottom view

they were studying the SBLI over the wind tunnel boundary layer. This configuration was not possible for the experimental set up for this study, however, because the model is held 25 *mm* into the wind tunnel to allow for a clean boundary layer over the flat plate. To provide a controlled environment on the bottom of the panel, a larger recess highlighted in red in Figure 2.2 was milled around the panel to accept a backplate. The backplate fits flush in this recess with a rubber gasket to prevent any interferences due to the channel flow between the flat plate, wind tunnel wall, and mounting struts. The backplate is held in place by the mounting struts which sandwiches it to the model recess when the model is attached to the struts. Two small holes were drilled on either side of the panel model to allow for a rudimentary method of pressure equilibration during initial experiments. Holes were also drilled into the backplate which allowed for pressure transducers that could measure the pressure in that chamber. These holes also allow for an eventual way to impose and hold a specific pressure in the chamber to allow for different pressure differentials.

Table 2.2: Panel model frequencies

Mode	Frequency (Hz)
(1,1)	868
(2,1)	967
(3,1)	1149
(4,1)	1422
(5,1)	1790
(6,1)	2248

The panel was designed to have modal frequencies under and within the 1 kHz range which is typical of the resonant frequencies of aeroshells and aerostructures. A modal analysis was done using ANSYS Workbench, and the first six modes of vibration are listed in Table 2.2. In general, low frequency vibrational modes occur on panels with large surface areas and small thicknesses. The maximum length and width of the panel for this study were set based on the physical constraints imposed by the flat plate model. As such, the panel thickness was the main variable used to drive the vibrational modes down to the desired frequency range. The first three modal shapes are depicted in Figure 2.5.

Figure 2.5: Panel model modal shapes for mode a) (1,1), b) (2,1), and c) (3,1)

Table 2.3: Ramp configurations and inviscid pressure ratios

Ramp angle	p_2/p_1
16°	2.6
20°	3.2
24°	4.0

2.3.4 Compression ramps

The SBLI for each model is generated through three different compression ramps with angles of 16°, 20°, and 24°. The ramps were made of low-carbon steel and attached to each model using two screws through the pair of oval slots shown in Figure 2.2 and Figure 2.3. Figure 2.6 shows an experimental configuration of the rubber-insert model with the 20° compression ramp mounted. The 24° ramp face is on the opposite end of the ramp block, and the compression ramp angles were varied between test cases and not actively during the experiment. The ramp leading edge was located 300 *mm* downstream of the flat plate leading edge where a fully developed turbulent boundary layer was incident on the oblique separation shock generated by the ramp. Table 2.3 shows the three ramp configurations as well as the corresponding inviscid back pressure ratios, p_2/p_1 , at $M_\infty = 2.5$ flow.

These three ramp angles were chosen for a number of reasons. The inviscid pressure ratio varied by almost 50% which provides an appreciable range to elucidate the effect of SBLI strength scale up. The goal of this study was to examine the effect of compliant materials on features such as separation length, and Dolling & Or [3] reported no mean separation in a $M_\infty = 3$ flow at compression ramp angles below 12°. For a compression ramp angle of 12°, the mean separation was reported to be 0.2δ . The three chosen ramp angles should then induce discernable, large-scale flow features in SBLI for comparison.

Figure 2.6: Rubber-insert model with the 20° compression ramp mounted on top

Finally, extensive work with these ramp angles have been done previously by Funderburk, another member in the research group, in a 3D SBLI configuration with compelling results [23] which allowed for a strong start to the investigation undertaken by this study.

2.4 Experimental Methods

2.4.1 Surface Streakline Visualization

Surface streakline visualizations were performed for each ramp angle and model to provide a qualitative understanding of the mean surface flow features associated with the SBLI. A slow drying mixture of mineral oil and DayGlo Rocket Red pigment is used for this method. The pigment fluoresces red when illuminated by an ultraviolet light, and this is provided by a uvBeast UV LED flashlamp during experiments. Figure 2.7 shows the set up for this form of measurement in the NCSU supersonic wind tunnel. This figure is adapted from Funderburk [22], and it should be noted that the model sidewall shown in the schematic are not present for this study. To provide a good contrast with the red

pigment, all of the model surfaces were painted with a flat black background using a latex enamel spray paint from Krylon, Inc. The compliant surface of the rubber-insert model necessitated the use of a self-etching primer coating before the latex coating to prevent the paint from cracking and peeling. Both the primer and the top layer of paint are assumed to have a negligible effect on the compliant rubber surface in this study.

Figure 2.7: Schematic of set up for surface streakline visualization experiments. Figure adapted from [22]

The visualization procedure is as follows: The pigment-oil mixture is mixed and painted on the model in the area of interest before the run. During the run, this area is illuminated with the UV light source and recorded using a DSLR camera controlled on a PC remotely. Flow shear drags the pigment-oil mixture across the surface of the model during the run to provide qualitative images of iso-shear contours. Before the ability to

mount models on the sidewall, previous flow visualization techniques for top mounted models in this tunnel involved a fast drying mixture of aluminum oxide and kerosene oil. Images from these experiments had to be taken after the run when the model could be removed. Mounting the models on the custom sidewall allowed for a top down, normal view of the surface of the model through the opposing side window. This allowed for the surface streakline visualization experiments to be recorded over the duration of the entire run to prevent any distortions from facility shutdown. About 100 images, obtained over three seconds of steady state tunnel operations, were extracted from the video and averaged for further analysis. For reference, every surface streakline visualization experiment had a test duration of six seconds.

2.4.2 Wall Pressure Measurements

In addition to surface streakline visualization, high-frequency wall pressure measurements were made to provide quantitative information of the SBLI pressure field. Kulite Semiconductor Products, Inc. model XCQ062-15A high frequency response transducers were used for this study on only the all-steel model and the rubber-insert model. The transducers have a nominal diameter of 1.7 mm , an effective frequency response of 50 kHz , and a manufacturer quoted uncertainty in instantaneous pressure of 170 Pa . The transducers were mounted flush with the surface of the flat plates along the plate mid-span extending from the incoming boundary layer through the ramp leading edge.

The transducers are mounted inside a bored out 4-40 socket head cap screw using JB Weld epoxy steel resin with the transducer tip flush with the tip of the screw. Tapped 4-40 holes were machined through the flat plate experimental models to allow the transducer tips to be completely flush with the model surface during runs. It should be noted that

the transducers are not moving with any rubber deformation motions as they are screwed to the steel plate underneath. Normal screws were put in the transducer locations before the liquid rubber was poured so that there were through holes in the rubber insert for the transducer-mounted screws. The transducer leads ran out the back of the model, through a shielding strut that was the same height as the mounting struts, and through a hole in the tunnel plug that the mounting struts are attached to. The leads are connected to a ten channel Vishay Measurements model 2350 amplifier which boosted each signal for increased resolution. Using a Stanford Research Systems SR600 low-pass filter, the signals were then low-passed at a frequency of 25 kHz . Afterwards, the signals are digitized at a rate of 100 kHz using a National Instruments, Inc. model 9215 analog-to-digital converter and recorded using a custom LabVIEW VI.

Figure 2.8: Top-down view of transducer positions

Figure 2.8 shows a top-down view of the flat plate models with transducer locations highlighted in white. Flow is from left to right with the ramp leading edge at $x = 0$ *mm* and the model mid-span at $y = 0$ *mm*. The transducers were spaced 4.5 *mm* apart due to constraints placed by the 4-40 screw head. However, this spatial resolution could be effectively doubled by moving the leading edge of the compression ramp downstream by approximately 2 *mm*. Shifting the ramp leading edge does change the development length of the incoming boundary layer before it encounters the incident separation shock; however, the change in boundary layer thickness is assumed to be negligible over the additional 2 *mm* distance.

An in-house MATLAB code developed by Funderburk [22] was used to process the acquired pressure data. Mean pressure profiles were computed by taking an average and standard deviation of the pressure signals of each transducer for a given test over a two second period, where the rolling standard deviation of the wall pressure in the incoming boundary layer was less than 5%. Two seconds of test time corresponded to 8×10^5 total data points for each transducer. Frequency multiplied power spectral densities of wall pressure fluctuations were computed over this two second time period using Welch's method of windowed Fourier transforms with a window size of 5000 samples and 50% overlap between windows. Three runs were done for each transducer location of interest, and the results presented for the mean pressure profiles and the power spectral densities are averaged from these three separate runs.

Chapter 3

RESULTS AND DISCUSSION

3.1 Boundary layer profile

To begin, a boundary layer measurement was taken of the incoming flow over the all-steel model with no compression ramp present. The boundary layer is attained through floor-normal pitot sweeps at the center span location ($y = 0 \text{ mm}$) at a location approximately 50 mm upstream of the leading edge of the compression ramp. A custom pitot probe was utilized for this test as well as a separate rigid model with a slot to accommodate the stem of the pitot. The pitot is held in place using a Newmark Elements linear actuator and allows for controlled translation of the pitot height relative to the flat plate surface between runs. The pitot pressure tube is connected to a Kulite Semiconductor Products, Inc. model ITQ-1000-100A transducer. The incoming signal is amplified and digitized at a rate of 200 Hz before being recorded. For an in-depth description of the boundary layer measurement set up and methodology used, refer to [22].

The resulting boundary layer for the all-steel model is depicted in Figure 3.1. Pitot sweeps were performed starting outside the boundary layer and moving inwards in incre-

ments of 1 *mm*. Below $z = 4$ *mm*, steps were taken in 0.5 *mm* increments to refine the near wall velocities. Free stream velocity was approximately 600 *m/s*, and the resulting $\delta_{99\%}$ boundary layer occurred at approximately 4.5 *mm* where the velocity was 595 *m/s*. At the time of this writing, a rubber-insert model that can be used for a boundary layer measurement is still under development.

Figure 3.1: Boundary layer profile for the all-steel model

3.2 Surface streakline visualization

Oil-pigment surface streakline visualization was first used to identify salient flow features within the SBLI. Primary focus is on the difference in response between the SBLI on the all-steel model and the rubber-insert model. The acrylic-insert model and the panel model are used to provide secondary insights. Length scales determined through measurable distances on the model, such as the distance between counterbored holes, were added along the axes for comparison purposes. In all the following figures of surface streakline

visualization with length scaling, it should be noted that the images are not depicting the actual recorded fluorescence of the UV pigment. During processing, the images have been normalized by the max intensity of each image, and a color map gradient was chosen that approximates the color of the visualization pigment used. For reference, a single, raw image extracted from the recording is shown in Figure 3.2a from an experiment set up consisting of the all-steel model with a 20° compression ramp. Figure 3.2b shows the time-averaged image of the same experiment. Flow is from left to right, and the compression ramp leading edge is at approximately the horizontal midpoint of each image.

Figure 3.2: Surface streakline visualization images of the rigid model, Mach 2.5 with a 20° compression ramp with a) a single image and b) a time-averaged image

3.2.1 All-steel model

Ensemble-average, top-view surface streakline images of the SBLI at ramp angles of 16° , 20° , and 24° are shown in Figure 3.3 for the all-steel model. The ramp leading edge was at $x = 0 \text{ mm}$ with flow from left to right in the positive x -direction. The separation locus, identified by the start of pigment accumulation, is marked with a light blue dashed line. This marking system will be carried out for the rest of the surface streakline visualization images. Pigment accumulation occurs because the surface flow is no longer moving downstream at this point, causing all the upstream pigment to accumulate in this bright band. The separation bubble is marked by the dark band downstream of the separation locus. Recirculating flow in the separation bubble causes pigment to migrate upstream towards the area of pigment accumulation, causing the bubble to render dark in the averaged image due to a lack of pigment. At the separation location, pigment is whisked away from the surface and reattaches at a downstream point on the ramp face (not shown) to close the separation bubble.

The separation length, L_{sep} , was determined for different ramp angles and is defined in this study as the distance between the mean separation line and the ramp leading edge. As expected, L_{sep} increases with increasing ramp angle due to the strengthening inviscid shock and resulting adverse pressure gradient. The separation bubble required to resolve the adverse pressure gradient can be seen to increase with shock strength due to the larger dark bands present for higher ramp angles. It can be observed in Figure 3.3a and Figure 3.3b that the separation line is 2D across 80% of the span for the 16° and 20° compression ramp generated SBLIs; however, considerable curvature can be observed for the 24° ramp angle over a larger span in Figure 3.3c. The curvature of the separation locus of the 24° ramp angle does not alter the outcome of this study since the same configuration

Figure 3.3: Surface streakline visualization image of the all-steel model, Mach 2.5 for compression ramp angles of a) 16° , b) 20° , and c) 24°

was used as the comparison bed for all the surfaces considered. Furthermore, only the bottom half of the images ($y < 0 \text{ mm}$) were used for all comparisons to analyze the same region of SBLI over the models.

3.2.2 Rubber-insert model

The effect of having a soft, compliant material beneath the separation shock wave on the mean separation size was studied by carrying out the same surface streakline visualization experiments on the rubber-insert model. All three compression ramp angle configurations are shown in Figure 3.4. The same SBLI characteristics are observed for the rubber-insert model as they were for the all-steel model. Features such as the 2D separation line and the separation bubbles are again observed to increase with higher ramp angle. Interestingly, the separation line is more 2D for the rubber-insert case compared to that of the all-steel case. The curvature seen in the separation line for the rubber-insert 24° case (Figure 3.4c) does not start until $y > 30 \text{ mm}$ whereas curvature can be seen to start for $y > 15 \text{ mm}$ in the all-steel 24° case (Figure 3.3c).

For ease of comparison, the SBLI over the all-steel model and rubber insert model from Figure 3.3 and Figure 3.4 respectively are compared side by side in Figure 3.5 for all three ramp angles. As previously mentioned, only the bottom half of the SBLI for each model are compared, and this is reflected in the y-axis numbering as well. The top halves of the frames in Figure 3.5 corresponds to the SBLI over the compliant, rubber-insert model, and the bottom half of the frame corresponds to the SBLI over the rigid, all-steel model.

Having three ramp configurations allowed for insight on the effectiveness of the compliant effect on mean separation size with increasing shock strength. The inviscid pressure

Figure 3.4: Surface streakline visualization image of the rubber-insert model, Mach 2.5 for compression ramp angles of a) 16° , b) 20° , and c) 24°

ratio varied by almost 50% ($p_2/p_1 = 2.6 - 4.0$) across these ramp angles, and hence, provides an appreciable range to elucidate the effect of SBLI strength scale-up. It can be observed from the separation lines marked in Figure 3.5 that the separation size for all separation strengths decreased for the rubber insert model compared to that of the all-steel model, indicating that the separation bubble has shrunk over the rubber-insert model which is also confirmed by the smaller dark bands for each ramp angle comparison. To provide an approximate quantification of the shrinkage in L_{sep} for 16° , Figure 3.5a shows that the separation line is located at $x = -8 \text{ mm}$ for the all-steel model and at $x = -5 \text{ mm}$ for the rubber-insert model, which shows that the separation size decreased by 38% over the rubber-insert model. Overall, the separation line moved by $\Delta x = -3 \text{ mm}$ (16°), -4 mm (20°), and -4 mm (24°) which correspond to percentage decreases of 38% (16°), 28% (20°), and 23% (24°) in the separation size. The observed magnitude of reduction in mean separation size over the compliant surface remains relatively constant at approximately 4-5 mm. As such, the compliant surface has a lesser percentage effect at higher ramp angles due to the overall increase in L_{sep} for stronger separation shocks.

3.2.3 Thermal effects

Even though individual experiment run times were short at five seconds each, differences in the thermal conductivity between steel and rubber can also contribute to the observed changes in the mean separated flow size. To decouple any effects due to thermal conductivity from the observed FSI, the same surface streakline visualization studies were performed over a 2 mm thick rigid acrylic insert (acrylic-insert model) which replaced the rubber insert. The difference in thermal conductivity between most acrylic and rubber is about 10%, which suggests a very similar heat transfer effect on both surfaces. In

Figure 3.5: Comparison of top-view surface streakline images with rubber surface on top and rigid model on bottom, Mach 2.5 for compression ramp angles of a) 16° , b) 20° , and c) 24°

contrast, the thermal conductivity of steel is roughly two orders of magnitude larger than that of acrylic and rubber.

Figure 3.6 shows the top-down view surface streakline visualization comparison between the acrylic-insert and rubber-insert models for the same 16° compression ramp SBLI. The top half of the frame corresponds to the SBLI over the compliant, rubber-insert model as it did in Figure 3.5, however, the bottom half of the frame now corresponds to the SBLI over the rigid, acrylic model. It can be observed that the mean separation line over the acrylic-insert model was just under -10 mm, which was slightly upstream compared to the all-steel model separation line. Thus, it is clear that the observed reduction in mean separation size is indeed due to FSI with negligible contributions from thermal conductivity differences between the materials.

Figure 3.6: Comparison of top-view surface streakline images with rubber-insert model on top and acrylic-insert model on bottom for a 16° compression ramp angle.

3.2.4 Scaling rubber-insert thickness

Experiments were also conducted on a rubber-insert model that could accept a 4 *mm* thick rubber insert to examine the effect of scaling rubber thicknesses on mean separation. Comparisons are depicted in Figure 3.7 with the 2 *mm* images in the top halves of the frames and with the 4 *mm* images in the bottom halves. While the responses of the SBLI on the 2 *mm* rubber insert and the 4 *mm* rubber insert are largely similar indicating that FSI effectiveness does not scale linearly with rubber thickness, the location of the mean separation sizes were not strictly identical. This is most apparent for the 24° ramp case where the separation length for the 4 *mm* rubber-insert is discernably larger than that of the 2 *mm* rubber-insert at -16 *mm* and -14 *mm* respectively. However, the separation lengths observed over the two different rubber-insert thicknesses were overall still less than that of those observed over the all-steel model. As a reminder, the separation line for the all-steel model for the 24° case was at approximately -18 *mm*. The scale-up of FSI with rubber thickness will be visited in more detail in a future effort.

3.2.5 Panel model

Results involving the panel model are the most recent investigations at the time of this writing. Surface streakline visualizations on the panel model are presented in Figure 3.8 for all three compression ramp angles. The images show a very non-linear response in the separation line across all compression ramp angles. The point of max separation occurs at approximately $x = -16$ *mm*, -22 *mm*, and -34 *mm* respectively for the 16°, 20°, and 24° ramp cases. Curvature in the separation line towards the ramp leading edge is again observed for positive *y*-values as they are in the other surface streakline visualizations; however, the overall extent of separation is much larger with the panel model. There

Figure 3.7: Comparison of top-view surface streakline images with 2 mm rubber insert on top and 4 mm rubber insert on bottom, Mach 2.5 for compression ramp angles of a) 16°, b) 20°, and c) 24°

seems to exist a bulge that is pushing the location of separation shock upstream for $y < 10$ mm. This is apparent especially in Figure 3.8c, and the structure of the bulge fades as compression ramp angle and the overall size of the separation bubble increases.

Figure 3.8: Top-view surface streakline images of the panel model, Mach 2.5 for compression ramp angles of a) 16° , b) 20° , and c) 24°

Cavity pressure was also measured on the non-flow side of the panel with a transducer. This pressure was not controlled in any way for the current experiments and was allowed to reach rudimentary equilibrium through the two side holes in the model connecting the cavity to the model side surface. The mean cavity pressure was measured to be approximately 49 kPa which is 50% more than the test section static pressure of 33 kPa. This positive pressure differential within the cavity would cause the panel to bulge slightly out into the flow. The panel was designed to have natural frequencies within the

1 kHz range, and shock oscillations in this low frequency range may be exciting modal vibrations as well. A power spectral density graph of the fluctuating pressure within the cavity shows a large peak in energy content at just over 1 kHz with smaller distinct peaks in this range as well. This is another hint that modal vibrations are at play, as the vibrating panel at this frequency would act like a diaphragm pumping the cavity and causing pressure fluctuations. Further investigations are required to get a definitive understanding of this FSI response; however, these results are presented in this study to provide yet another example of FSI having a possible undesirable effect on the flowfield. The larger separation structures seen with the panel model would to higher drag values if this response were to occur on an aircraft control surface.

3.3 Wall pressure measurements

While surface streakline visualizations provide a map of mean flow features, the results observed are largely qualitative even though rough length comparisons can be determined from the effect of the compliant surface. For a more quantitative measurement technique, mean and unsteady pressure profiles measured along the SBLI over all-steel and rubber-insert models were compared to quantify the FSI effect on the pressure field. The results presented here are using 8×10^5 data points over 2 seconds of steady operation and averaged over three separate experiments that were highly repeatable.

3.3.1 Mean pressure profile

Figure 3.9 shows a comparison of the mean pressure profiles along the SBLI over the rubber-insert and the all-steel models generated by a 16° compression ramp. The blue square data points correspond to the pressure profile for the all-steel model, and the

Figure 3.9: Comparison of normalized mean wall pressure normalized of SBLI over steel and rubber surfaces

yellow circle data points correspond to the pressure profile for the rubber-insert model. Error bars are included to indicate the two-sided 99% confidence interval. The error bars pertaining to data for the all-steel and rubber-insert model are colored blue and orange respectively. The measurement domain extends from the upstream boundary layer through 1 *mm* upstream of the ramp leading edge, and the pressure profiles are normalized by the freestream static pressure of the furthest upstream transducer location. The mean pressure trends on the all-steel case show an initial sharp rise in the intermittent region until the mean separation location, followed by a more gradual rise. These trends are in excellent qualitative agreement with 2D SBLI literature at a similar Mach number [3]. Further, the location of inflection from a sharp to gradual pressure rise is very consistent with the mean separation location observed in the surface streakline visualization.

The corresponding trends exhibited with the SBLI over rubber-insert model are very

similar to that of the all-steel model. The most noticeable difference is that the start of the pressure rise in the SBLI occurs about 2 *mm* downstream of the start in pressure rise over the all-steel model. This is consistent with the downstream displacement of separation line over the rubber-insert model observed in the surface streakline visualization experiments. Wall static pressure in the all-steel SBLI increases above the freestream value at a location of $x = -17 \text{ mm}$ whereas the wall static pressure of the rubber-insert SBLI does not measure above freestream pressure until $x = -15 \text{ mm}$. As a result, the initial pressure rise over the rubber-insert model is steeper than that over the all-steel model until the wall pressure of the rubber-insert model matches within 1% of the all-steel at $x = -10 \text{ mm}$, the location of mean separation. Downstream of this location there is hardly any difference between the wall pressures for the SBLI over the all-steel and rubber-insert models because the total pressure rise must eventually match the pressure rise caused by the inviscid shock. It should be noted that the pressure rise does not match the theoretical inviscid pressure rise of $P_2/P_1 = 2.6$ generated by the 16° ramp. This occurs at a downstream attachment location on the ramp face that can't be measured with the current configuration. Overall, there is no more than a 5% difference in the local mean wall pressure at any location within the SBLI. Hence, the resulting mean lift and pressure drag forces caused by the shock interaction should be largely similar, with perhaps a modest dividend on the drag with the rubber-insert model due to the separated flow shrinkage.

3.3.2 Unsteady power spectral densities

The impact of the FSI on unsteady shock oscillations is quantified to explore if placing soft surfaces beneath the separation shock could be used to dampen unsteady shock loading. To address this for the specific rubber surface, high-frequency wall pressure data

was processed to produce power spectral densities (PSD) of wall pressure fluctuations at the intermittent region for the 16° and 20° cases. Figure 3.10 shows the comparison of the frequency-multiplied PSD between the SBLI over all-steel and rubber-insert models for the 16° compression ramp case. The green line represents data for the rigid, all-steel model and the black line represents data for the compliant, rubber-insert model. Again, all the data shown are ensemble averaged over three separate runs, and Figure 3.10a includes the PSD from a single run as well as the three-run ensemble average to illustrate the repeatability of the measurements. The sharp attenuation evident at $f = 25 \text{ kHz}$ in all the following PSD figures is due to the signal being processed through a 25 kHz low-pass filter. The transducer locations predominantly within the intermittent region for the 16° and 20° ramp are at $x = -10.5 \text{ mm}$ and -15 mm respectively.

Figure 3.10: PSD comparison in the intermittent region between steel and rubber surfaces for a) 16° ramp and b) 20° ramp

It can be observed from Figure 3.10 that most of the energy content of the low frequency shock oscillations over the intermittent region of the all-steel model occur between 100 Hz to 3 kHz . The corresponding Strouhal numbers ($St_l = f * L_{sep}/u_\infty$) for both the compliant model and rigid model for this frequency range is approximately between 0.001 and 0.05 and is consistent with 2D SBLI literature [1, 24]. Peak unsteadiness over the all-steel model occurs at St_l of approximately 0.01, and this is in good agreement with literature as well. The corresponding PSD of the SBLI on the rubber-insert model shows significant reduction in the energy content of the pressure fluctuations at both compression ramp angles. The magnitude of energy reduction was between 40% to 50% across a frequency range of 50 Hz to 1 kHz , which spanned most of the low frequency unsteadiness spectrum. The integrated percentage reduction in the unsteady pressure for frequencies less than 1 kHz is 60% for the 16° ramp and 64% for 20° ramp.

The observed reduction in amplitude of the energy signal in the low frequency range indicates that the rubber surface is perhaps providing a damping effect to the shock oscillations. Damped systems generally reduce the natural frequency of that system; however, it can further be observed that the frequency corresponding to maximum energy content shifted to higher values in the SBLI over the rubber-insert model compared to that of the all-steel model. Larger extents of separation induce larger-scale motions of the shock foot [1]. Therefore, decreases in separation lengths result in an increase in the frequency at which max energy occurs due to the smaller-scale shock oscillations. The observed increase in the frequency of peak energy content, which can be seen for both ramp configurations, is then consistent with and provides further evidence towards the reduction in the mean separation size over the rubber surface as seen in the mean pressure profile and the surface streakline visualization images.

Within the 1 kHz to 10 kHz range, the energy of the SBLI over rubber surfaces either

exceeds (16°) or overlaps (20°) with that of the rigid surface. Following this frequency band of energy decrease, an increase in energy content is observed at frequencies above 10 kHz . This high frequency range is associated with the passage of boundary layer structures which causes jitter in the shock motion. In this frequency range, the pressure fluctuations over the rubber-insert model exhibit a higher energy content compared to that of the all-steel model. This higher unsteady pressure loading over the rubber-insert model at frequencies above 10 kHz model is observed at all transducer locations, and there is no explanation for this trend at the time of this writing. However, high frequencies tend to dampen out quickly and generally don't couple with structures. The focus for this study is mainly on the low frequency oscillations that are most caustic to aerostructures, and this is the frequency range where the largest impact of having a compliant surface in the intermittent region is observed.

Figure 3.11: PSD comparison for rubber-insert model with a 16 ramp at a) $x = -12.5\text{ mm}$; b) $x = -17\text{ mm}$

Figure 3.11 shows the comparison of the PSD at two upstream locations for the 16° ramp generated SBLI between the all-steel and rubber-insert models. Figure 3.11a depicts the comparison of PSDs at $x = -12.5 \text{ mm}$ which is the transducer location just upstream of the $x = -10.5 \text{ mm}$ transducer. A similar energy reduction in the low frequency range as well as the shift to higher frequencies of peak energy content for the SBLI over the rubber surface is observed. The intermittent region can span a few millimeters in length and, as a result, traverse over more than one transducer location. Furthermore, the impinging separation shock spends only about 50% of the time oscillating within the intermittent region, and so the resulting oscillation influence can be smeared across a range of transducers. One observation to note is that while the max unsteady energy for the all-steel model has dropped from 0.048 psi^2 at $x = -10.5 \text{ mm}$ to 0.039 psi^2 at $x = -12.5 \text{ mm}$, the max energy over the rubber-insert model has only dropped from 0.028 psi^2 to 0.025 psi^2 over the same location.

The PSD at a further upstream location of $x = -17 \text{ mm}$ is depicted in Figure 3.11b. At this location, which is far away from the influences of the intermittent region, no energy reduction is observed. Indeed, a look at the magnitudes of energy content shows that there is much less energy at this location to begin with. The max observed energy in the low frequency range is approximately 0.004 psi^2 which is one order of magnitude lower than the energy levels seen within the intermittent region. At this location, the biggest observable difference is the increase in energy over the compliant surface at frequencies above 1 kHz . The high frequency energy content generated by boundary layer structures is equal in magnitude to the low frequency energy.

Figure 3.12 shows the comparison of the PSD at two downstream separated locations for the 16° ramp generated SBLI between the all-steel and rubber-insert models. A similar energy reduction and frequency shift in peak energy was again observed with the rubber-

Figure 3.12: PSD comparison for rubber-insert model with a 16° ramp at a) $x = -1.5$ mm; b) $x = -8$ mm

insert model at low frequencies for $x = -8$ mm in Figure 3.12b, which lies just downstream of the peak pressure root mean square (rms) location of $x = -10.5$ mm. No reduction was observed at the $x = -1.5$ mm location in Figure 3.12a for frequencies below 1 kHz. This location is completely underneath the separation bubble, and the power spectra is fully dominated by high frequency content generated by the recirculating flow within the separation bubble as well as by radiation from the turbulent shear layer over the bubble. At frequencies above 10 kHz and before low-pass filtering attenuation, the SBLI over the rubber-insert model exhibits more than twice the energy of the SBLI over the all-steel model. Overall, however, having the SBLI occur over a rubber surface causes significant dampening of the low frequency shock oscillations which is critical to aerostructures that exhibit resonance at this frequency range.

3.4 Discussion

The final question is what mechanisms are causing the observed reduction in the mean separation size and energy content at low frequency shock oscillations in SBLI over the rubber surface. A few proposed mechanisms are listed as follows:

1. Local deformations
2. Changes in $\delta_{99\%}$
3. Distributed damping effect
4. Surface roughness effect
5. Differences in C_f

The second through fifth proposed mechanisms are interrelated and would lead to changes in the boundary layer momentum distribution and turbulent kinetic energies within the boundary layer. The current hypothesis is that the first proposed mechanism, local deformations, has the largest effect on surrounding flow field. The rubber surface forms local deformations beneath the shock wave and the separated flow which in turn potentially forms a partial obstruction to the large-scale shock oscillations. This results in a reduction of unsteady pressure loading in the low frequency range. This hypothesis is also supported by the recent work by Brouwer et al. [19] that showed that the mean separation size responded strongly to the mean curvature of a panel with only secondary influences due to unsteady deformations. The important distinction is that these deformations on the rubber surface are local as opposed to global deformations which would be caused by the modal vibrations of a thin panel. The fact that these deformations are local may make all the difference in the observed fluid structure interaction and differentiates

it from the generally negative effect of FSI seen on flexible panels. Initial calculations based on the mean pressure rise and material properties of the rubber insert approximate the deformations to be on the scale of 50 microns. Pressure fluctuations were approximately 2-5% of the mean pressure depending on surface location which would result in fluctuating deformations of 1-3 microns. Detailed efforts are needed to resolve the actual driving mechanisms and will be the subject of a future investigation.

Chapter 4

Conclusion and Future Works

4.1 Concluding remarks

Experiments were performed to investigate the fluid structure interactions caused by a shock boundary layer interaction unit placed over a rubber surface to explore the potential use of compliant materials towards unsteady shock load mitigation and separation control. Compression ramps of different angles were employed to generate different strength SBLIs whose inviscid pressure ratio varied by over 50%. For all the cases, surface streakline visualization of the SBLI revealed that having a rubber surface beneath the SBLI displaced the separation line downstream by an average of almost 30% compared to the SBLI over rigid surfaces. Experiments over an acrylic surface ruled out differences in thermal conductivities as being the driving factor behind the observed reductions in separation, and experiments over a thin panel surface showed even greater extents of separation relative to that of the rigid surface.

The mean pressure profiles across the SBLI show less than 5% difference between the SBLI over the steel and rubber surfaces, suggesting the mean lift and drag forces did not

change considerably with the presence of the rubber surface. Separated flow shrinkage over the rubber surface should result in smaller drag values, but the effect on skin friction drag is unknown at this time. Trends within the pressure profile also supported surface streakline visualization results that the separation line was displaced downstream over the rubber surface. A strong reduction of 50% - 60% was observed in the energy content of the separation shock oscillations over the intermittent region when the SBLI occurred over the rubber surface compared to the rigid surface. These results provide compelling evidences for the potential use of FSI between shock waves and soft, compliant surfaces for unsteady shock load mitigation.

This type of compliant material is very attractive as a passive form of flow and loading control as it does not require any components for sensing, feedback, or actuation. A realistic application would be to imbed the compliant material as a narrow band along locations where shock impingement is most likely to occur on control surfaces. A large area covered by the rubber-insert was chosen in this study as the effect of the compliant surface on the overall flow field was unknown. However, with results indicating that the most beneficial effects occur over the compliant surface within the intermittent region, applications can be tailored specifically for this area alone.

4.2 Future works

This study was largely exploratory in nature on the effect of a soft, compliant surface on 2D SBLI, and further research is necessary to better understand the fluid structure interactions taking place. As such, there are many possible avenues of investigation that can be explored such as:

1. Digital image correlation (DIC) which can be used to measure surface deformations.

This will provide valuable information on the response of a compliant surface to shock impingement and overall surface flow and allow for a better understanding of the structural side in fluid structure interactions. Obstructions caused by local deformations on the rubber surface can be quantified as well as any vibrational modal excitations on the panel surface.

2. Particle image velocimetry (PIV) which can be used to compare off-body flow structures over the rubber-insert, all-steel, and panel models. At the time of this writing, a PIV system using a double-pulsed Nd:YAG laser is nearing its final stage to being fully incorporated into the supersonic wind tunnel. Such experiments will provide a wealth of information such as insight into the turbulent boundary layer and overall shock structure over each model.
3. Pressure sensitive paint (PSP) which will provide information on the overall pressure field. Mean PSP is currently possible within the NCSU supersonic wind tunnel which will allow for full pressure profiles, and planned implementation of high-speed PSP will allow for in-depth information on the fluctuating pressure field and further verification of reductions in unsteady energy content over the rubber surface. PSP will also greatly aid in understanding the FSI over the panel model, as the nature of a thin panel does not allow for pressure transducers to measure surface pressure.
4. Taking a closer look at scaling rubber thicknesses to see if there is a certain rubber thickness at which optimal results are observed within the intermittent region. Similarly, taking a look at the effect of different rubber thicknesses on the FSI can prove valuable as well. This can be investigated fairly easily because the candidate urethane rubber chosen is part of a large product line of urethane rubber that have varying hardnesses.

5. More investigations with the panel model to fully understand the initial surface streakline visualization results observed. DIC would assist greatly in determining any excited vibrational modes due to shock impingement. Controlling the cavity pressure can also prove to greatly impact the panel response. An interesting pursuit would be to experiment on a model that couples a thin panel with a soft, compliant surface resulting in two different forms of fluid structure interactions.

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