ABSTRACT

CHO, WONBEOM. Double-Fin Induced Shock Wave/Turbulent Boundary Layer Interactions over a Cylindrical Surface. (Under the direction of Dr. Venkateswaran Narayanaswamy).

Double sharp-fin induced shock wave/turbulent boundary layer interactions (SBLI) over a cylindrical surface have been scarcely investigated despite its significant influence on the maneuverability of missile-like projectiles. As the importance of the super/hypersonic missiles increases, it is inevitable to understand and resolve the SBLI over cylindrical surfaces. The purpose of this study is to understand the complex flow field of the double-fin induced SBLI over a cylindrical surface using pressure sensitive paint (PSP) measurements. The experiment explores the surface pressure field of the double-fin induced crossing SBLI with a leading edge of 10° at Mach 2.5 freestream flow. Conventional PSP and PC-PSP measurements were performed to obtain the mean and the unsteady pressure field. The interaction of the two shock structures from the two fins showed more complex pressure field than the result of the single fin induced SBLI. Also, due to the influence of the curvature surface, the pressure field was found to have different characteristics from the previous research that was conducted on a flat plate. The cylindrical surface led the shock structure to lose its strength on the surface, which results in comparatively simple interactions at downstream.
Double-Fin Induced Shock Wave/Turbulent Boundary Layer Interactions over a Cylindrical Surface

by
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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Master of Science

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Jack Edwards                  Pramod Subbareddy

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DEDICATION

To my parents and brother.
BIOGRAPHY

Wonbeom Cho, born in Seoul, South Korea, spent his early years having a huge interest in military issues, aircraft, and missile. In the Korea Military Academy, he obtained his Bachelor’s Degree in Weapon Systems Engineering and Military Arts while being more into the weapon systems. After graduated in 2013, he began his first military career on the borderline between the two Korea and continued to serve as a Republic of Korea Army staff officer in the US 8th Army. While he went through his military career, luckily, he could obtain a full financial support from the Republic of Korea Army to study at NCSU for the Master’s Degree. During the path towards the Master of Science in Aerospace Engineering, he could extend his knowledge on high-speed aerodynamics under the direction of Dr. Venkat Narayanaswamy.
ACKNOWLEDGMENTS

First and foremost, I would like to express the deepest gratitude to my advisor, Dr. Venkat Narayanaswamy for his constant guidance, encouragement, and support. I am very fortunate to have him as my research advisor and work in the Turbulent Shear Flow Laboratories. My sincere thanks go out to my advisory committee members, Dr. Jack Edwards, Dr. Pramod Subbareddy for their assistance with my research and their valuable insight and suggestions. I would like to particularly express my sincere gratitude to Dr. Subbareddy for his consistent support and guidance in the computational field. I would like to extend my gratitude to all the colleagues who worked in the Turbulent Shear Flow Lab and the CFD lab during my time as a graduate student. Specifically, Josh, Bala, and Vaibhav this journey would have been impossible without you guys. To my parents and brother, who always support and encourage me, thank you as always. Finally, I wish to thank the Republic of Korea Army for providing me a chance to pursue my academic goal in NCSU.
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CHAPTER 1

INTRODUCTION

1.1 Motivation

As the conventional ballistic missiles have encountered a development of modern missile defense systems, it was an unavoidable consequence that the interest toward super/hypersonic missiles increases. The super/hypersonic missiles do not follow the predictable, conventional ballistic trajectory and can maneuver in flight at high Mach numbers, which allows those missiles to detour the modern missile defense system and the interceptors. This leads to a delay in detection of the threat for the opponents, ended up forcing them to have short decision making time to response. However, there is a significant obstacle to overcome to develop this high speed missile system, the interaction between shock wave and the turbulent boundary interaction on the missile surface.
Shock wave and turbulent boundary layer interactions (SBLI) are observed when shock waves impinge into a surface boundary layer, causing the rapid retardation of the boundary layer and adverse pressure gradient [1]. A shock wave occurs when the flow at high, supersonic speed encounters a change of slope on the surface of a vehicle or an obstacle such as fins. This shock wave, depending on its geometry of occurring location, interacts with the downstream boundary layer flow on the vehicle’s surface, which results in an adverse pressure gradient and leads to flow separation or thickens the boundary layer at the impacted location. This interaction can have a significant effect on aircraft, missiles, or rockets, for example, creating drag rise, adverse aerodynamic loading, high aerodynamic heating, and reduced engine inlet performance [2]. This influence simply degrades the efficiency of the vehicle but turns into a reason for the unstart of a scramjet engine or ends up destroying a vehicle surface by local heat up. Among many catastrophic results, SBLI induced by fins on the exterior of the aircraft or missile has a direct impact on its maneuverability, which seriously lowers its precision and leads to loss of control and waste of thousands of dollars for munitions and undesirable accidents [3].

Since the 1940s, the investigation on SBLI has been widely conducted either by experimental or computational, and the overall progress in SBLI research was well described in books and articles,[3], [4], [5], [6], [7]. Featured as canonical configurations, various types of geometry have been studied [3]. Notably, sharp fin induced SBLIs have been studied in the state of the art, which focused not only on a single fin but also on double fins. Because the geometry of such supersonic projectiles has a cylindrical surface, a better understanding of axisymmetric models is needed. Still, most of it has focused on a flat plane surface. The single- and double-fin induced SBLI over a curvature surface has its importance in direct correlation with the control force of the supersonic projectile performance. However, it was just a few years ago that the 3D
relief effect of a curved surface was investigated by Pickles et al. [8], [9]. More extensive understanding of complex SBLI over cylindrical surfaces is needed.

To develop super/hypersonic missiles, it is inevitable to understand and resolve the fin induced SBLI over cylindrical surfaces. In this present study, the overall objective is to widen the understanding of the fin induced SBLI over the cylindrical surface by an experimental method. Crossing SBLI induced by two sharp fins was investigated in the NCSU supersonic wind tunnel using the PSP measurement technique. Using two different types of PSP, the mean and the unsteady pressure field were obtained to improve the understanding of the effect of the geometric features.

1.2 A Sharp fin induced shock wave and boundary interaction

The downstream of the flow field affected by a sharp fin has been investigated in much of the literature [10]. The shape of flow past a sharp fin forms a swept quasi-conical flow symmetry. As shown in Figure 1.1, this series of radial line forms from VCO (Virtual Conical Origin) except around the region of the leading edge of the fin [11]. When the flow field is seen from the trailing edge of the model, a gamma-shape of the shock waves is visible. The shock wave induced by a sharp fin interacts with the boundary layer flow, which results in bifurcating two shocks (separation shock and reattachments shock) encompassing the conical flow. This conical flow consists of two separation lines and two reattachment lines. The shape and development of this
region depend on the shock strength that changes with the speed of freestream and the angle of the leading edge of the fin.

Figure 1.1 Surface and flow features of fin-generated SBLI, including upstream influence (UI), separation line (SL), reattachment line (RL), and virtual conical origin (VCO). The right image shows the sketch of the $\lambda$-shock structure. (adapting from [12])

At a certain Mach number, an increase in the leading edge angle leads to the strength of the shock wave, which leads the SBLI to enter on another phase of the flow field [10]. As the shock becomes intense, the following developments in the flow field appear; the first separation, the first reattachment of the separate flow, the second separation beneath the flow between first separation and reattachment region, and the second reattachment [13]. The slipstream from the triple points of the gamma-shape shock is the reason to evolve this new reattachment. As the slipstream impinges to the near root of the fin, the unsteady pressure increases at the region of contact. When the momentum of this impinging flow reaches a certain level, the flow runs below the vortex stream that developed in advance and forms another separation and reattachment region.[14]
As shown so far, most of the research has focused on SBLI on a flat surface. However, SBLI on a 3D geometry was conducted as well using axisymmetric structure. In the recent study by Pickles et al. [8], the investigation focused on the differences of SBLIs over fin-on-cylinder and fin-on-flat plate. As seen in Figure 1.2, the fin induced SBLI showed different trends at downstream. Simply, the straight radial lines of the separation and reattachment lines change to the curved lines, which is caused by the curved surface. The shock structure maintains its pressure on the flat plate as the flow goes downstream. In contrast to the planar fin SBLI, curvature structure leads the inviscid shock to lose its influence on the surface due to the geometric 3D relief as the flow goes further. Hence, the inviscid shock that occurred at the leading edge of the fin becomes weaker towards the cylindrical surface, which resulted in changes to the loci of separation and reattachment, as shown in Figure 1.2. The series of straight radials was not visible over the cylinder surface. Due to the 3D relief of the structure, the inviscid shock dissipated along the cylindrical surface, and its compression on the surface boundary layer decreased, which led to the different SBLI from the planar fin SBLI. When the flow was visualized by Surface Streakline Visualization [15], the constant growth of the separation flow along with the downstream on the flat plate was not shown on the cylindrical surface.

Figure 1.2 Top view schematics of the separated flow in planar fin SBLI versus fin-on-cylinder SBLI (adapting from [8]): (a) planar fin SBLI; and (b) fin-on-cylinder SBLI. The shaded orange region portrays the separated flow in both figures.
The figure 1.3 shows the mean pressure field over the two different surface: (a) on a flat plate, and (b) on a cylindrical surface. The $x$-axis is the distance from the fin leading edge, and the $y$-axis is the distance from the fin root. Since it was unwrapped, ‘s’ of (a) indicates the unwrapped distance from the fin root. The mean surface pressure field showed that the pressure contour is consistent with the other measurement result; the peak of the wall pressure around the fin leading edge became weaker over the curvature surface while it lasted over a flat plate in Figure 1.3 (b). Also, the upstream influence line forms a curved line showing that the pressure decrease continuously while the shock structure moves downstream.

![Figure 1.3 Unwrapped mean surface pressure field of the (a) fin-on-cylinder SBLI and (b) planar SBLI. The black dashed line denotes the blue/green interface loci that correspond to the first noticeable surface pressure rise from the SBLI. The dash-dot line is the theoretical location of the inviscid shock. Adapted from reference [8]](image)

While the structure of the flow field shows the difference, the same phase evolves as the shock increases. As the strength of the inviscid shock from the leading edge of the sharp fin increases, the SBLI shows specific regimes: first separation and reattachment, second separation, and reattachment [14]. According to [15], the regimes still exist over the cylindrical surface, and only the difference was the decay of the shock intensity over the curvature surface.
1.3 Crossing shock wave and boundary interaction by two fins

A missile-like projectile is provided maneuverability by controlling the surface, such as canards, wings, and tail fins. Since multiple fins work together, the investigation of the flow field between two fins may follow the steps of a single fin induced SBLI. Crossing shock wave and turbulent boundary layer interaction is one of the canonical features in the history of the SBLI study. However, those studies have focused on the phenomenon of the flat plate because this is considered a relevant research field for the development of hypersonic aircraft systems such as scramjet engine [16], [17]. Typically, the two-fin induced SBLI applies to an inlet of a scramjet engine, nozzles, combustors, and fins on a surface, either within or outside of a high-speed aircraft. Considering the geometry of inlets, this crossing SBLI would be a big reason for efficiency decrease in propulsion system and, moreover, unstart of the engine, which could result in an undesirable accident [6]. Therefore, a number of experimental and computational studies have focused on the double-fin generated crossing SBLI [3], [18], [19].

Figure 1.4 shows the schematic of the canonical experimental model of the crossing SBLI. The crossing SBLIs were investigated, changing the angle of the leading edge. From the earliest studies in this field, the angle of attack of the fin leading edge was set to have either symmetric or asymmetric angles [20], which allowed one to study the interaction not only by identical shock strength but also by a different one. Development of experimental techniques and computations capacity enabled aerospace researchers to capture complex 3D flow with the conventional 2D measurement. Furthermore, some studies have focused on the control flow of the crossing SBLI,
exploiting conventional bleed to reduce the influence of SBLI or vortex generators and micro jet [21].

Figure 1.4 Schematic of the double-fin generated crossing shock-wave/turbulent boundary-layer interaction over a flat plate. (adapting from [22])

The crossing SBLI features are exhibited in Figure 1.5. This surface streamline was obtained based on the experiment using the oil flow visualization method [22]. The research was conducted at incoming Mach number of 5 with two different symmetric fin angle (18°, 23°). As shown in the figure, the downstream from the two fins shows more complicated flow patterns than from a single fin induced SBLI. Not like the single fin induced SBLI, the crossing SBLI forms complicated streamlines due to the interaction of the two shocks from each fin. The two shocks reflect from each other and reflect again on the fin. Along this streamlines, the maximum pressure and heat transfer values are located slightly downstream of the location where those inviscid shocks are crossing [23], and this increases along with the shock strength[24]. Also, the
unsteadiness significantly increases at this location as the crossing inviscid shocks get stronger [25].

![Figure 1.5 Surface streamline topology of crossing SBLI at Mach 5; 18° × 18° (left), 23° × 23° (right) (adapting from [22])](image)

Except for the difference above, the flow pattern from an individual fin is similar to the one from a single sharp fin induced SBLI. As the shock strength increases, additional separation and reattachment line appear, just as the case of a single fin induced SBLI has the series of regimes, between the prior separation and reattachment lines [22]. As shown in Figure 1.5 of 18° leading edges, S1 is the line of primary separation, and R1 is the line of reattachment, which also occurred in weak SBLI of a single fin. Also, the phenomenon in which second separation and reattachment lines are not present here is the same as the weak SBLI case. The notable difference at the downstream is that the separation, S2 and the reattachment, R2 are formed around the centerline. At the centerline, vortices occur due to the impinging flow from each fin, which results in the
separation and reattachment. At the far downstream, the third separation, S3 and attachment, r3 are visible. When the angle of leading edge increases to 23 deg, the flow field changes in the same manner as the single fin SBLI. Additional separation and reattachment occur between the primary separation and reattachment lines (S4 and R4). Due to the increase in the impinging angle, the crossing shock interacts more upstream. It forms Mach stem at the centerline, which also causes separation along with the crossing inviscid fin shocks [26].

The pressure field in Figure 1.6 shows similar characteristics with the surface streamline pattern. The figure shows half of the flow field. The x-axis indicates the distance from the centerline, and the y-axis does the normalized pressure. Most of all, the pressure gradient is vulnerable to the inviscid shocks; the pressure increases at the loci where the inviscid shock influences. The compression to the surface from individual shocks are lower than the intersecting shock at the centerline. Thus the pressure distribution shows its highest value at crossing location around the centerline. Also, around loci, where reattachment is expected, a slight pressure rise is observed as well [20]. Along the path of the reflected shocks, additional pressure rise can be found at far downstream in Figure 1.6 (e) while forming ‘M’ shape of pressure distribution. It is not presented in Figure 1.6, but this trend of pressure rise can be observed even at far down stream, and additional pressure jumps appear as the shock hit the fin wall again [25].
Figure 1.6 Spanwise pressure distribution in the $18^\circ \times 18^\circ$ interaction at Mach 5 from [22]; The dotted line was from computation, and the circle was from experiment.

In addition to the hypersonic experimental condition above, a similar result could be found in the earlier studies [27], [28] at lower Mach number. In Figure 1.7 from [28], the pressure increased due to fin generated shock and continued to climb up after the shock intersecting at the centerline at Mach 2.95. This trend was also observed in the higher Mach number experiment on the previous page. To be clear, the previous example was conducted over $18^\circ$, which showed similar pressure decrease after the pressure peaked on the $11^\circ$ test in Figure 1.7. Also, the spanwise pressure distribution showed similar physics from the hypersonic studies [27]. Throughout the entire geometry, the highest pressure value was found at the centerline, as shown in Figure 1.7 as well [27]. This indicates the crossing shocks had more robust compression on the surface than the
single shock. Moreover, the pressure distribution forms ‘M’ shape at the far downstream as the crossing shocks move towards each fin [27].

![Inviscid Shock](image)

**Figure 1.7** Surface static pressure along the centerline of the symmetric interactions at the various fin angle (adapting from [28])

In the present experiment, the objective was to measure the crossing SBLI between two fins on a cylindrical surface. Whereas the previous studies on a flat plate had their objective at high speed inlet development, the presented research is more adaptable to the exterior aerodynamics and has a direct relation with the maneuverability of munitions. By making a comparison with the previous studies on a flat plate, the surface pressure field was measured by pressure sensitive paints. Also, the previous research of a single fin on a cylinder could be extended to the interaction between multiple fins. Since most of the missile is controlled by the multiple fins, this research is more practical approach to understand real world of super/hypersonic aerodynamics.
CHAPTER 2

EXPERIMENTAL METHODS

2.1 Wind Tunnel Facility

All the tests were conducted in the NCSU Supersonic Wind Tunnel, shown in Figure 2.1, to evaluate the crossing shock-wave and boundary layer interactions on a cylindrical surface. This is a blowdown tunnel from Aerolabs LLC and has a square test section of 150 mm X 150 mm X 650 mm. The Mach number range is 1.5 to 4.0, which is controlled through the block size of the nozzle chamber at the upstream of the test section. A run-time and stagnation chamber pressure are controlled via a LabVIEW VI, and a constant flow lasts up to 8 seconds. A proportional-Integral-derivative hydraulic valve controller ensures the tunnel to maintain a constant stagnation chamber pressure. The two sides of the test section have windows providing optical access, and these removable walls can be modified depending on experimental purposes. In this experiment,
the model was mounted on one of the sidewalls, and the images were captured through the window of the other wall.

![Image](image_url)

**Figure 2.1** NCSU supersonic wind tunnel

### 2.2 Freestream Condition

For this research, the freestream was set at Mach 2.5, and its stagnation pressure and temperature were fixed at 450 kPa and 300K, respectively. By using isentropic relations, this resulted in a freestream unit Reynolds number of $5.3 \times 10^7 / \text{m}$ and a freestream temperature of 140K. In order to determine whether a fully developed turbulent boundary layer exists ahead of the fins, the freestream boundary layer was found using the Van Driest method (II) [29]. The characteristics of the incoming boundary layer are shown in Table 2.1.
Table 2.3 Characteristics of the incoming boundary layer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>2.5</td>
</tr>
<tr>
<td>$u_\infty$</td>
<td>580 m/s</td>
</tr>
<tr>
<td>$T_\infty$</td>
<td>130°C</td>
</tr>
<tr>
<td>$Re / m$</td>
<td>$5.3 \times 10^7 /m$</td>
</tr>
<tr>
<td>$Re_\theta$</td>
<td>15000</td>
</tr>
<tr>
<td>$\delta_{99}$</td>
<td>6 mm</td>
</tr>
<tr>
<td>$\theta$</td>
<td>0.28 mm</td>
</tr>
<tr>
<td>$C_f$</td>
<td>0.0017</td>
</tr>
</tbody>
</table>

2.3 Experimental Model

Following the previous experiment of the one-fin cylinder [15] in the lab group, the 2-fin cylinder adopted the same dimension on its cylinder part with the one-fin cylinder to readily compare the result from each other as show in Figure 2.2. Also, this allowed to skip the investigation on the boundary-layer, which was found by Pickles et al. [8] to have a 6 mm thickness at about 290 mm downstream of the cylinder leading edge. The pair of 1 inch height fins has half angle of 10° and 20° at its leading and trailing edge, respectively, so that the fin can be mounted inversely to have either angles as its leading edge. The fin has its height of 4 time-taller than the incoming bl thickness, which does not influence the SBLI on the cylinder surface [8]. The width of each fin was 0.38 inches which was 5.4 times smaller than the half-cylinder diameter of 2 inches. The gap between the two fins was 1.25 inches along the cylindrical surface, which corresponds to the region of interest of this experiment where the two shocks intersect with the turbulent boundary layer. The length of the fin is 4.25 inches, and 12.45 inches from the leading edge of the half-
The fin becomes parallel with the inflow direction from 2.01 to 3.01 in from its leading edge and diverges.

Figure 2.2 Configuration of the two fins on a cylinder

2.4 Conventional and Fast Pressure Sensitive Paint Measurement

The surface pressure field of the test model was obtained by the Pressure Sensitive Paint (PSP) technique. The two types of PSP were applied to the test model; UniFIB, a single-luminophore PSP produced from ISSI Inc., and PC-PSP (Polymer/Ceramic PSP) that was mixed in the wind tunnel. The characteristics of PC-PSP, luminescent intensity, pressure and temperature sensitivity, and response time, are affected by its materials and mixing ratio [30]. The PC-PSP used in this experiment was made base on the research suggesting the proper portion of its
compound [31]. The mixing ratio of the PC-PSP is shown in Table 2.2. According to the manufacture, the UniFIB has 0.8% per kPa pressure sensitivity in 0 – 200kPa with the 300ms of response time. The degradation rate is 1% per hour, which showed a reliable test result in a couple of days if the paint was not exposed to UV. On the other hand, the PC-PSP was quoted having a pressure sensitivity of 0.62% per kPa and a time response of 11.6 µs by Y. Egami. A significant disadvantage is the PC-PSP degradation rate of 23.3% per hour, which works as an obstacle to follow the same experiment approach of using UniFIB.

Table 2.4 PC-PSP Components

<table>
<thead>
<tr>
<th>Component</th>
<th>amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminophore</td>
<td>Ru(dpp)3</td>
</tr>
<tr>
<td>Polymer</td>
<td>Single component RTV</td>
</tr>
<tr>
<td>Particle</td>
<td>Boron Nitride Particle</td>
</tr>
<tr>
<td>Solvent</td>
<td>Toluene</td>
</tr>
</tbody>
</table>

The two pressure sensitive paints are sprayable and were applied to the test model right before the experiment. The painting process requires several steps. Black Krylon layer is the first coats on the experimental model, which helps the following layer, FIB Base Coat, being applied well. As the second coats, the FIB base coat (ISSI Inc.) was used on the black Krylon layer to provide a uniform, smooth surface by masking either stains or machining imperfections of the test model. Also, this white base coat helps pressure sensitive paint to increase the intensity response signal as well. As the topcoats, UniFIB, or PC-PSP was applied on the test model to be ready for the experiment. The base coat and both PSP were applied using a high volume, low-pressure airbrush, and set to have a constant pressure of 10 psi. In every step, the paints were applied to have at least 6 layers. For PC-PSP, its performance is significantly degraded once the compounds
are mixed [31]. Thus, the paint was applied right before the wind tunnel run once every experimental setup was finished.

The painted test model was excited by two water-cooled 20W UV lamps (LM2X-400 LED). Since the paint has a low luminescent intensity and the images are captured with a high frame rate, the two lamps were used during recording. The image was captured by a CCD camera (FASTCAM SA-X2) in conjunction with a Nikon 50mm telephoto lens and a 600nm long-pass filter. The camera was controlled via the Photron FASTCAM Viewer (PFV) software, and the aperture was set to f/1.2 to obtain bright images. The frame rate was 60 fps for the UniFIB test and 8,000 fps for the PC-PSP test. The camera can take images up to 12,874 per record, which corresponds to less than 2 seconds for the PC-PSP test.

**Figure 2.3** Schematic of set up for PSP experiments. View from the top
The calibration data was adapted from the previous research of Pickles [32]. His calibration was conducted using a pressure cell on the test section, and the calibration curve was obtained as a form of the Stern-Volmer equation in (2.1). However, for PC-PSP, it was not able to conduct in the same way because of its rapid degradation. Among several error source of using PSP, there are two major limitations in the characteristic of PSP; Its temperature sensitivity and degradation of the luminescence intensity[33]. Particularly, the luminescent intensity of PC-PSP rapidly decayed in a short time period (-23.3%/h) that it is essential to minimize its degradation [31]. In the temperature wise, the Stern-Volmer coefficient in (2.1), the relation between intensity and pressure, changes by the surface temperature [34], which can be the most dominant error source in PSP measurement. However, the temperature dependency was found to be negligible as in situ calibration applied in the research where the same mixing ratio of the compounds was used [35]. Also, the degradation of PC-PSP is considerably fast; thus, the PC-PSP coated test model was calibrated in situ instead. The in situ calibration directly matches the luminescent intensity ratio with the pressure pixel by pixel. A mean pressure field was obtained in advance with known calibration curve data from Uni-FIB. This process was implemented right before the main PC-PSP experiment to ensure a consistent experiment condition. This reference mean pressure field was obtained using 200 images from pre- and post wind-off images and wind-on images, respectively. Then the knowing pressure curve is applied to the intensity ratio of PC-PSP that was made by dividing wind-off and wind-on images of PC-PSP. The obtained calibration curve is stated as follows: A second order polynomial form of the Stern-Volmer relation:

\[
\frac{I_{ref}}{I} = A + B \left( \frac{P}{P_{ref}} \right) + C \left( \frac{P}{P_{ref}} \right)^2
\]  

(2.1)
The given Uni-FIB calibration curve shows the coefficient of $A = -0.0503$, $B = 0.4613$, and $C = 0.5734$. The PC-PSP calibration curve was turned out to have the coefficient of $A = -0.562$, $B = 1.373$, and $C = 0.01808$.

![Figure 2.4 The raw camera view of UniFIB.](image)

Post processing of the PSP was done using an in-house Matlab code. This measurement has the possibility to introduce a discrepancy between wind-on and wind-off images due to the influence of wind tunnel testing; thus, an image registration process is essential. In remove noise from the wind tunnel vibration, the reference mean image was made using the 200 images captured from pre-wind-off and post-wind-off to reduce the error. Then the images were cropped into the region of interest, and the fin portion was masked to reduce unnecessary computing. From the following step, the mean pressure field and the unsteady pressure field require different processes. In order to obtain a mean pressure field, 200 images were averaged, which corresponds to about 3 s. The averaged image was divided by the wind-off image to find the intensity ratio. The calibration curve, then, was applied to this intensity ratio pixel by pixel. To acquire unsteady pressure fields, there are additional processes required. Once the image registration is done, a pixel binning was implemented in $9 \times 9$ pixels, before processing the whole sequence, since it is too expensive to
process even one sequence over 8,000 frames. Next, the mean wind-on images were divided by
the mean wind-off image to obtain an intensity ratio. The known calibration curve from UNI-FIB
was applied to this intensity ratio, which enables each pixel to have the relation between pressure
and intensity as stated above during the explanation of the calibration method. Lastly, the found
calibration was applied to all the instantaneous images.
CHAPTER 3

RESULT and DISCUSSION

3.1 Pressure Field Measurement in Crossing SBLI over a Cylindrical Surface

To measure the pressure field of crossing SBLI over a cylindrical surface, the PSP experiments were conducted at a Mach number of 2.5 with the two fins having a leading edge angle of 10°. To compare with the previous single fin SBLI by Pickles [8], the dimensions of the test model were consistent with the single fin model except for adding one more fin and fixing the two fins on a different angle: ±45° from the centerline. The region of interest is where the crossing shocks generated from the two fins interact with the turbulent boundary layer over a cylindrical surface. Since the surface is curved, the unwrapped images were processed by
\[ \theta^\circ = \tan^{-1}(y/z) \]

where \( y \) is the vertical distance measured from \( z = 0 \). The unwrapped mean pressure field using Uni-FIB is presented in Figure 3.1. The centerline of the surface corresponds to \( 0^\circ \), and the middle points of each fin are fixed \( \pm 45^\circ \) from the centerline. The \( x \) axis of the plot indicates the distance from the leading edge of the cylinder. The data was normalized by the undisturbed free stream pressure, \( p_\infty \), forward of the interaction region. The pressure field was limited to angles of \( \pm 60^\circ \) to reduce the error coming from the distortion of view angle around \( \pm 90^\circ \).

![Figure 3.1 Mean Pressure Field using Uni-FIB](image)

In Figure 3.1, the freestream flow goes from right to left. The theoretical inviscid shock (I.S.) trace was calculated and overlaid on the mean pressure surface. The notable pressure gradient
is observed where the blue contour turns into the green contour, at the locus of upstream influence (U.I.). As seen in a single fin on cylinder surface [15], the green iso-contour region starting from the leading edge showed a curved shape due to the 3-D relief effect of the curvature surface. Without a flow visualization experiment, it is hard to specify the location of the separation and reattachment lines. However, virtual separation and reattachment lines can be expected according to the single fin SBLI research of Pickles [8]. From right to left, as the flow moves closer to the fin root, the pressure contour evolved from green to yellow, which indicates the primary separation and the reattachment, respectively. This mean pressure field from $x = 0$ mm to $x = 25$ mm, is consistent with the findings in the test using a $10^\circ$ leading edge of a single fin on a cylindrical surface [22]. With this $10^\circ$ leading edge, a comparatively small shock strength, a second separation and reattachment are not generated, so only primary separation and reattachment lines should appear.

The notable difference from the single fin test was that the canonical flow structure lasts only until the crossing shocks intersect at the centerline ($x = 25$ mm). Whereas the single fin induced SBLIs showed curved iso-contour shape without intersecting other flows, the double fin induced SBLIs converged and exhibited the pressure jump at the centerline in Figure 1.7. The yellow contour along the streamwise direction, lasted from $x = 25$ mm to $x = 65$ mm at the centerline. This trend is presented using the pressure profile at the centerline in Figure 3.2. The $x$-axis is the distance from the fin leading edge, and $y$-axis is the normalized pressure. The rapid pressure increase started at $x = 25$ mm forms the plateau up to $x = 65$ mm, and the pressure decreased gradually. It cannot be determined how the pressure peaked at the centerline without an examination of the flow mechanism. It is not known how the two inviscid shocks intersect and affect the curvature surface around the centerline. However, it is obvious that the two intersecting
shocks compress the surface again after losing their influence on the surface due to the 3-D effect of the curvature structure.

![Figure 3.2](image)

**Figure 3.2** Pressure profile at the centerline, $\theta = 0^\circ$

There are still noticeable distinctions from the previous double fin induced SBLI on a flat plate. The crossing shocks induced by the 13°-leading edge of two fins generated only primary separation and reattachment lines without additional separation and reattachment around the fins [22]. This absence of the new lines is because small vortices composed of other separation and reattachment lines are not generated in weak shock waves [22]. In this experiment with a 10°-leading edge of the two fins on a cylindrical surface, this small shock induced SBLI is applied, and this phenomenon is observed at the single fin case as well. The pressure gradient at U.I. did not decrease until it showed its peak around the fin root.

Furthermore, a second pressure peak was not visible in the entire pressure field, although it was found that the second pressure peak appeared around centerline in the double fin induced SBLI over flat plate [20]. Figure 3.2 shows the absence of the second pressure peak around the centerline far downstream. Also, the centerline pressure did not increase as in the case of the flat
surface in [28], [22]. Instead, a high pressure portion appears along the centerline and maintains its pressure in the x-direction for about 30 mm. In the flat plate condition, the crossing inviscid shocks from a pair of fins reflect from each other and move downstream towards the fins. On the fin surface, these shock waves bounce back to the centerline and interact again around the downstream centerline, which compresses the surface at far downstream [20]. However, the two inviscid shocks in the present experiment lost their influence on the surface while moving over the curvature surface due to 3-D relief of the curvature structure. It can be assumed that the crossing shock reflected at the centerline and moved back towards each fin but, the pressure on the surface from the shocks seemed significantly reduced. It was hard to find any pressure rise along the virtual line of reflecting shocks which existed in the flat plate case. Also, even if the crossing shocks bounce back to the fin, the shock would meet the fin at 45°; thus, the shock is not expected to move back to the centerline and form a second pressure peak.

Detailed pressure distribution at various cross sections is presented in Figure 3.3. The x-axis is the polar angle from the cylinder centerline, and y-axis is the normalized pressure. The pressure profiles between the two fins were obtained at 10, 25, 40, 50, 70, and 90 mm from the fin leading edge, and median filtering was applied. From x = 0 to 25mm, the pressure profiles were consistent with the trends of the earlier research with a single fin; the overall pressure distribution at each cross section gradually decreased along the spanwise direction. This decreasing pressure peak shows the 3-D relief effect of the curvature surface, leading the shock strength on the surface to decrease with downstream distance. The normalized pressure from the inviscid shocks decreased from $2 P_\infty$ to $1.6 P_\infty$ at $x = 10$mm to 40mm.

From $x = 25$mm, however, the pressure around the centerline began increasing and formed the pressure plateau until $x = 70$ mm. As previously shown in Figure 3.2, the pressure along the
centerline reached the peak of $1.7P_\infty$ at $x = 40\text{mm}$ and remained constant until $x = 70\text{mm}$, which is higher than the pressure of $1.6P_\infty$ from the individual inviscid shock just before they intersected at $x = 40\text{mm}$. This manifestation is in contrast to the previous studies of the crossing SBLI on a flat plate [28], [36]. Whereas the pressure peak was found around the centerline over the entire region of interest on a flat plate [20], the centerline pressure ($1.7 P_\infty$) did not overtake the pressure at the fin leading edge ($2 P_\infty$) on the cylindrical surface.

The overall pressure distribution at a cross section shows a reduce profile as the compression of the individual shock decayed along the $x$-direction. As shown in Figure 3.2, no additional pressure growth cannot be found around the centerline in Figure 3.3 as well. Also, the pressure jump was not observed around the fins, which was another distinction from the pressure field of the flat plate research [24], [27]. The crossing shocks were reflected towards the fins and compressed the wall around the fin root on a flat plate, showing ‘M’ shape of the pressure profile. Therefore, the absence of the pressure rise around the fins may be the evidence of the manifestation that the crossing shocks at the centerline did not bounce back to the fins at downstream over a cylindrical surface.
Figure 3.3 Surface pressure distribution at various cross sections.
The unsteady pressure field was obtained using PC-PSP, as shown in Figure 3.4. The scale of the pressure field is slightly different from that of the mean pressure field in figure 3.1. That may be due to the noise when the mean pressure field was obtained; the base layer coat was not uniformly applied to the test model. The y-axis is the polar angle from the cylinder centerline, and the x-axis of the plot indicates the distance from the leading edge of the cylinder. The data was normalized by the undisturbed free stream pressure, $p_{\infty}$, forward of the interaction region. The overall resolution was degraded while the captured images were post processed. Because the collected data (over 10,000 images) were too huge to process, the pixels were binned to save computational cost. The flow field of the present results seemed to be influenced at the upstream; the two fins generated a slightly different pressure field. The pressure pattern was not asymmetric. However, the unsteady pressure field still shows the representative features: its pressure peak around the fin leading edge and pressure rise at the centerline. Also, the two lines of upstream influence from the fin leading edges showed a curved shape. Overall, the unsteady pressure field can be collapsed with the mean pressure field, but additional experiments may be needed to maintain an undisturbed upstream in the future.
Figure 3.4 Unsteady pressure field over a cylindrical surface.

The series of unsteady pressure fields is presented in Figure 3.5. Since the images were captured in 8 kHz, 125 µs gaps exist between each image. The black contour indicates 1.22 $P_\infty$ to help identify high pressure around the fin and centerline. The strong fluctuations were observed while the flow passed the double fins. The red contour around the leading edge fluctuates over time, becoming either narrow or wide. It is assumable that the downstream pressure at the centerline increases and widens its area when the high-pressure around the leading edge dominates.

It is evident that the pressure peak at the centerline fluctuates over time, and the width of the fluctuation is noticeably bigger than the other regions. Also, the pressure rise of the inviscid shock from the bottom fin in Figure 3.5 (b) and (d) seemed to lead the width of the black contour at the centerline to become wider towards the downstream in the next image. According to [25], the crossing SBLI over a flat plate as the unsteadiness increased at the centerline where the two shocks...
intersected. However, it is hard to examine the reason of the unsteadiness of the crossing SBLI in this experiment, and further studies are required to fully understand the unsteadiness in this region.

**Figure 3.5** Series of instantaneous crossing SBLI pressure field over a cylindrical surface. The images were captured at 8kHz (125µs). The black contours indicate 1.22P∞.
CHAPTER 4

CONCLUSION

4.1 Concluding Remarks

In this thesis, SBLIs generated from double fins on a cylindrical surface were investigated through the experimental method. The PSP measurement was conducted to investigate the mean and unsteady pressure field of crossing SBLIs generated by double fins on a cylindrical surface. The pressure field showed the consistent characteristics with the single fin SBLI on a cylinder until the shocks intersect. It was clearly observed the 3-D relief effect of the curvature surface. The inviscid shock became weak over the cylindrical surface, and its compression on the surface formed a curved contour. For the comparison with the double fins on a flat plate, a similar pressure increase occurred around the centerline, but the pressure rise at the centerline was lower than the individual shock. Also, there was no additional pressure peak due to the reflecting shocks at the
downstream. The influence of the curvature structure brought the weakened shock structures, which leads to less complexity in crossing SBLI.

The SBLI has a considerable impact on the performance of missile, aircraft, and rockets flight by influencing the flow field over their cylindrical surface. Specifically, for the super/hypersonic missiles, it is a significant aspect, since the missiles should be able to maneuver in flight at high Mach number. The results presented in this thesis are important by the fact that the practical cylindrical surface and double fins were used to investigate the double fin induced crossing SBLI. Mainly, the crossing SBLI over a cylindrical surface provided insight into the further study of the 3D interactions or control techniques that ultimately, can contribute to the precision and maneuverability of a super/hypersonic missile.

### 4.2 Future Works

Some obstacles were in the way to study this research. COVID-19 forced many researchers to pause their work and the NCSU supersonic wind tunnel had to stop running, and computational aspect of the research could not finish. The PSP was supposed to measure the crossing SBLI with various leading edge angle, which was the reason why the fin was designed to have 10° and 20° edge, which can be inversely installed on the half cylinder model. According to the research using the flat plate, if the experiment is performed with a 20° leading edge, the shock strength increases, which would result in more complex flow fields such as Mach stem at the centerline[22]. Therefore, studying the crossing SBLI with different leading edge angle may be comparatively easy work in the coincident experiment condition. Moreover, although the results of the crossing
SBLI on flat plate could be understood by reviewing the past literature, the experiment conditions were various in each study. Therefore, complimentary experiment for the double fin on a flat plate would be a good way to validate the double fin on cylinder result.

The crossing shock waves and boundary layer interactions on a flat plate were found to have an intricate 3D flow field by numerous researchers [3]. Considering this complicated flow structure, plenty of research approaches can be performed to study the 3D flow on the cylindrical surface. The present research was only conducted with PSP measurement resulting in 2D pressure field data. Therefore, experiments such as PLS and PIV may elucidate the outer crossing shock structure and can explain how the crossing shocks affect the surface pressure field in this research. Also, a complimentary computation can be performed on the crossing SBLI on a cylindrical surface, which validate numerical method on the crossing SBLI on axisymmetric model.
REFERENCES


APPENDICES
Appendix A

Supplemental Experiments

In this appendix, the author’s previous work is presented. The research was planned to study with a full cylinder model at the early stage. The Schlieren imaging, Surface Streakline visualization, and PSP measurements were performed, but the full cylinder model ended up with the unstart of the supersonic wind tunnel at lower Mach number. Even in high Mach number, the upstream was influenced by reflecting shock from the wind tunnel wall. It is hard to discuss the result from these experiments, so the methodological comments were shown.

Surface Streakline Visualization

Surface Streakline Visualizations (SSV) helps visualize different flow features on a surface, including flow separation and shock formation. In the SSV test, mineral oil that works as the shear driven flow was mixed up with fluorescent dye. The fluorescent dye (DayGlo T13 “Rocket Red” pigment) illuminated as being exited by the 2 20 W UV light sources. The dye is captured as images and movies by CCD Camera with 50 mm f/1.2 lens and 600 nm long-pass filter. Once the model was set up in the test section of the supersonic wind tunnel, the paint was
applied to the test model surface. As the flow was introduced in the wind tunnel, shear driven patterns were formed on the surface; in the region where the driving shear force is weak, the paint accumulates, and where the force is strong, the paint disperses, and these phenomena indicate flow separation and reattachment respectively.

Figure A.1 Instantaneous SSV result induced by 20 degrees double fins on a full cylinder

The upstream was influenced by reflecting shock from the wind tunnel wall and shows weak shock strength at the bottom fin. Although there was the interruption at upstream, the crossing shock showed the two lines at the centerline.

Schlieren Measurement

Schlieren imaging is one of flow visualization technique using the characteristics of light; light is bent depends on a density of fluid they traverse. Schlieren has an advantage of detecting flow around an object, so it was used to capture a shock wave of the leading edge of a test model to figure a test model and a wind tunnel start. The wind tunnel was set to have two transparent
window side walls to allow a parallel-light to go through the test section. An LED light source, a
knife edge and two mirrors were used to provide a parallel light ray condition. The light ray from
the LED passed a knife edge to be focused and reflected by a mirror. The reflecting light passed
the test section and reflected and be focused by another mirror. A DSLR camera collected the light
that passed a slit.

![Schlieren image](image)

**Figure A.2** Schlieren image. The inlet of full cylinder model. A normal shock appears right in front of the
inlet, which indicates the unstart of the test model.
Appendix B

Comparison of the single fin induced SBLI over a cylindrical surface using different geometry

In the previous computation on a single fin induced SBLI over a cylinder from Pickles [32], the bottom side of the grid was set as either outflow or symmetry to evaluate the wind tunnel wall effect in a real experiment. Here, the domain of the computation was made with a half cylinder to find if the difference can be found from the quarter cylinder domain of the previous research. Furthermore, the half cylinder grid allows the extended azimuthal distance to the trailing edge of the cylinder, SBLI at far downstream location was able to investigate.

As shown in Figure B.1, SBLI was visible until it reached the bottom of the half cylinder. It was found that the inviscid shock had an influence on the boundary layer at the bottom of the cylinder, but its strength is not enough to separate the boundary layer. In the quarter cylinder figure, the inviscid shock compressed the surface around the edge of the domain since the wall was set to symmetry assuming the effect of a wind tunnel wall. The Figure B.2 shows the offset density field at $z = 45\text{mm}$, 45mm from the fin leading edge. Whereas the inviscid shock on quarter cylinder seemed to be intense at the bottom wall, the shock structure of the half cylinder kept losing its strength as moving towards the downstream. Since the boundary layer separation was not observed
after $z = 45\,\text{mm}$, it is assumable that the research on SBLI over a cylindrical surface can be investigated with a quarter cylinder.

![Normalized pressure field on (a) half cylinder and (b) quarter cylinder.](image)

**Figure B.1.** Normalized pressure field on (a) half cylinder and (b) quarter cylinder.

![Normalized offset density field at 45 mm from the fin leading edge on (a) half cylinder and (b) quarter cylinder.](image)

**Figure B.2.** Normalized offset density field at 45 mm from the fin leading edge on (a) half cylinder and (b) quarter cylinder. The view is from the trailing edge.
Appendix C

Test Model Drawings

1. Fin
2. Half Cylinder