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On the Experimental Evaluation of Loss Production and Reduction in a Highly Loaded Low Pressure Turbine Cascade

Philip Steven Bear
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ON THE EXPERIMENTAL EVALUATION OF LOSS PRODUCTION AND REDUCTION IN A HIGHLY LOADED LOW PRESSURE TURBINE CASCADE

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

By

PHILIP STEVEN BEAR

B.S.M.E., Wright State University, 2014

2016

Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Philip Steven Bear ENTITLED On the Experimental Evaluation of Loss Production and Reduction in a Highly Loaded Low Pressure Turbine Cascade BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Mechanical Engineering.

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December 17, 2016
ABSTRACT


Improvements in turbine design methods have resulted in the development of blade profiles with both high lift and good Reynolds lapse characteristics. An increase in aerodynamic loading of blades in the low pressure turbine section of aircraft gas turbine engines has the potential to reduce engine weight or increase power extraction. Increased blade loading means larger pressure gradients and increased secondary losses near the endwall. Prior work has emphasized the importance of reducing these losses if highly loaded blades are to be utilized. The present study analyzes the secondary flow field of the front-loaded low-pressure turbine blade designated L2F with and without blade profile contouring at the junction of the blade and endwall. The current work explores the loss production mechanisms inside the low pressure turbine cascade. Stereoscopic particle image velocimetry data, total pressure loss data and oil flow visualization are used to describe the secondary flow field. The flow is analyzed in terms of total pressure loss, vorticity, Q-Criterion, Reynolds’ stresses, turbulence intensity and turbulence production. The flow description is then expanded upon using an Implicit Large Eddy Simulation of the flow field. The RANS momentum equations contain terms with static pressure derivatives. With some manipulation these equations can be rearranged to form an equation for the change in total pressure along a streamline as a function of velocity only. After simplifying for the flow field in question the equation can be interpreted as the total pressure transport along a streamline. A comparison of the total pressure transport calculated from the velocity components and the total pressure loss is presented.
and discussed. Peak values of total pressure transport overlap peak values of total pressure loss through and downstream of the passage suggesting that total pressure transport is a useful tool for localizing and predicting loss origins and loss development using velocity data which can be obtained non-intrusively.
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NOMENCLATURE

\[ C_x = \text{Axial Chord [m]} \]

\[ S = \text{Pitch [m]} \]

\[ H = \text{Span [m]} \]

\[ \text{Re}_{C_x} = \text{Reynolds Number, } U_{in} C_x / \nu \]

\[ Y_t = \text{Total Pressure Loss, } \left( P_{t,in} - P_t \right) \left/ \left( \frac{1}{2} \rho U_{in}^2 \right) \right. \]

\[ Y_{ps} = \text{Total Passage Loss} \]

\[ \text{BL} = \text{Boundary Layer} \]

\[ \text{FSTI} = \text{Free Stream Turbulence Intensity} \]

\[ \text{PV} = \text{Passage Vortex} \]

\[ \text{SSCSV} = \text{Suction Side Corner Separation Vortex} \]

\[ \text{SV} = \text{Shed Vortex} \]

\[ Z_w = \text{Zweifel Loading Coefficient} \]

\[ U_{in,st} = \text{Inlet Velocity [m/s]} \]

\[ U,V,W = \text{Mean Flow Velocity [m/s]} \]

\[ u,v,w = \text{Reynolds’ Velocity Fluctuations [m/s]} \]

\[ < > = \text{Time Average} \]

\[ \rho = \text{Density} \]

\[ P = \text{Pressure} \]

\[ P_{t,in} = \text{Total Upstream Pressure} \]

\[ P_{t,out} = \text{Total Downstream Pressure} \]

\[ \mu = \text{Viscosity} \]

\[ \lambda = \text{Stagger Angle} \]
$C_{o,s}$ = Secondary Vorticity Coefficient

$C_{\lambda,s}$ = Secondary Swirl Strength Coefficient

$Q$ = Q-Criterion

$\psi$ = Deformation Work

$\delta_{99\%}$ = Boundary Layer Thickness

$\dot{P}_t$ = Total Pressure Transport along a Streamline

$T_u$ = Turbulence Intensity

$k$ = Turbulent Kinetic Energy
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I’d like to start by thanking God for providing me with the opportunity to pursue this degree and all of the related opportunities he has provided along the way. I’d also like to thank him for giving me the drive and the courage to do my best and to follow through to the end. I couldn’t have done it without him. I’d also like to thank my friends and family for putting up with my busy schedule and all the times I had to say no to things so I could work or write. The support they gave me over the course of this degree has been immeasurable.

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1 INTRODUCTION

Modern optimization of the Low Pressure Turbine (LPT) section of a jet engine aims to reduce weight while maintaining efficiency. The LPT, which can account for as much as 30% of the engine weight, supplies power to the fan section which produces as much as 80% of the engine thrust. One approach to reducing the LPT weight is lowering solidity. An increase in spacing between blades results in a lower blade count and therefore a lower weight. Lowering LPT stage solidity without compromising performance requires blades with higher lift. Studies of high lift blades ($Z_w > 1.15$ [1]) have shown that the increased loading often comes at the cost of unreasonably high endwall total pressure losses or flow separation. Vortex generator jets have been explored as a means to mitigate flow separation but have a cost associated with the jet mass flow [2]. Front loaded blades are often considered to combat flow separation at low Reynolds numbers but their high stagger angle further aggravates the already high endwall losses. These endwall losses are the result of a junction flow distorted by complicated pressure gradients at the interface of the turbine blade and the endwall. Past studies have explored secondary flow features using a variety of techniques such as: hotwire anemometry [3] [4] [5], total pressure measurements [6] [7] [8] [9], surface oil flow visualization [6] [8] [10] [11] and naphthalene sublimation [12] [13], among others. These studies often look at variations on the secondary flow field under certain changes such as: blade lean [14], blade thickness [15], inlet skew [16] [17] [18], blade peak loading location [19] [20] [21], incidence angle [22] and passing wakes [23], among others. Past authors have also developed predictions of losses based on flow geometry such as passage vortex penetration height on the suction surface [24] [25] [26].
How the features in a secondary flow interact and generate loss is highly dependent upon blade geometry. Various methods of mitigating these losses have been employed such as suction surface and endwall blowing [27] [28] [29] [30] [31], non-axisymmetric endwall contouring [32] [33] [34] [35], profile contouring or leading edge fillets/bulbs [36] [37] [38] [39] [40] [41] [42] [43] among others.

Past studies have analyzed the loss development in turbomachinery based on the Reynolds stresses and the turbulence production, also referred to as deformation work as it describes the work associated with turbulent deformation of the mean flow [37] [44] [45] [46]. It was found that a local reduction of the Reynolds stresses leads to a local loss reduction. The turbulence production involves Reynolds stress terms that imply conversion of mean to turbulent kinetic energy when negative and turbulent to mean kinetic energy when positive. The data indicate both negative and positive regions of turbulence production. Positive turbulence production can be difficult to interpret. MacIsaac et al. [46] noted a correlation between high positive turbulence production and regions of high normal stresses. Sangston [44] mentioned that regions of high turbulence production, either positive or negative, tend to align with regions of high shear strength. In a previous paper [47] comparisons of turbulence production with total pressure loss showed that both negative and positive turbulence production resulted in a total pressure drop, implying that turbulence production is an indicator of loss regardless of sign. A decrease in the magnitude of turbulence production was accompanied by a reduction in total pressure loss. Additionally, the turbulence production caused by shear orthogonal to the flow direction played the largest role in loss production. The present research is concerned with the calculation and interpretation of Reynolds stresses when used to
calculate the local turbulence production inside the cascade. Furthermore, the meaning of turbulence production with positive and negative sign is discussed for various turbulence production terms.

The RANS momentum equations contain terms with pressure derivatives. With some manipulation these equations can be rearranged to form an equation for the change in total pressure along a streamline. The benefit of this formulation is that total pressure gradients can be computed solely based on velocity data, which can be obtained experimentally in a non-intrusive manner with Particle Image Velocimetry (PIV), as opposed to direct pressure measurements which imply using a probe that may disrupt the flow. This formulation is particularly sensitive due to derivatives of the Reynolds’ stress. Small errors in even a single Reynolds’ stress component can lead to important features falling under the noise band. This paper will present this equation and discuss simplifications for the flow field in question. The resulting equation can be interpreted as the turbulent total pressure diffusion or the total pressure transport along a streamline. In dimensional form this equation has units of power per unit volume which can be interpreted as a rate of work density change. The turbulence production is dependent on all components of the Reynolds stress tensor and thus requires an analysis of all tensor components to determine their relative dominance. The total pressure transport directly shows the propagation of loss, thus allowing a more thorough analysis of the total pressure loss caused by the flow structures.

The present study analyzes the secondary flow field AFRL’s high lift front-loaded low-pressure turbine blade designated L2F ($Z_w=1.59$) with and without the L2F-EF profile contour designed from a low stagger variant of the L2F [37]. The L2F-EF has
been shown to have lower secondary losses than the L2F [37] [44] due to the modification of the development of the passage vortex. Building on previous work that describes the secondary flow field, the current work explores the loss production mechanisms through a linear cascade of low pressure turbine blades. Stereoscopic Particle Image Velocimetry (SPIV) data and total pressure loss data were taken inside and downstream of a blade passage in closely spaced axial planes to describe the secondary flow field. The flow is described in terms of total pressure loss, vorticity, Q-Criterion, turbulent kinetic energy, turbulence production and total pressure transport. Experimental measurements are expanded upon using an Implicit Large Eddy Simulation of the flow field provided by a collaborating researcher [48].

Qualitative and quantitative experimental measurements were acquired in the Air Force Research Laboratory Low Speed Wind Tunnel (LSWT) facility. (see Figure 1-1) The LSWT was configured as a linear cascade of seven L2F LPT blades. A turbulence grid upstream of the blade row increased Free Stream Turbulence Intensity (FSTI) to 3%, and a splitter plate was installed to develop a clean inlet boundary layer for endwall flow studies. The splitter plate is depicted in Figure 1-2. The baseline splitter plate length of 4.83Cx upstream of the leading edge is used for the current study. The inlet flow velocity was set to provide a $\text{Re}_{\text{Cx}}$ of 100,000 based on inlet velocity and axial chord. This was measured using a pitot-static probe positioned $1.5\text{C}_x$ upstream of the leading edge at 50% span. The top of the tunnel upstream and downstream of the cascade is slotted allowing total pressure wake traverses.
Table 1. Linear Cascade Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>Axial Chord (C₉)</td>
<td>0.1524 [m]</td>
</tr>
<tr>
<td>Pitch/Axial Chord (S/C₉)</td>
<td>1.221</td>
</tr>
<tr>
<td>Span/Axial Chord (H/C₉)</td>
<td>4.17</td>
</tr>
<tr>
<td>Measured mean flow exit angle [37]</td>
<td>-58.4°</td>
</tr>
<tr>
<td>Boundary Layer Thickness (δ₉₉₉₉%) [49]</td>
<td>14 [mm]</td>
</tr>
</tbody>
</table>
Recent studies in the LSWT facility have concluded that the L2F secondary flow field is similar to those seen by previous researchers but has some key differences. One difference is the L2F suction side horseshoe vortex disappears much farther forward in the blade passage. Another difference is the L2F has multiple complicated interactions at the suction surface to endwall interface that result in additional flow features not seen with lower lift blade profiles [39].

The L2F has a high stagger angle to reduce the midspan profile loss. Lyall posited that the high secondary loss associated with the high lift L2F profile was not directly due to its front loading but rather due to its high stagger angle. Lyall [37] developed a low stagger variant of the L2F designated L2F-LS (low stagger). This profile showed decreased secondary losses at the endwall but increased profile losses. In an attempt to combine the good performance of the L2F at midspan and the L2F-LS at the wall, an endwall fillet for the L2F was generated from the L2F-LS profile by blending the L2F-LS into the L2F shape at the endwall. This profile contour was designated the L2F-EF (endwall fillet). The L2F-EF profile demonstrated a 5.2% reduction in total passage loss at Re\(_{\text{C}_x}\)=100K. [49]

Following the same concept, two additional profile contours have been designed as modifications to the L2F-EF contour. The L2F-EB is a bulb design using the L2F-LS shape as the bulb shape. At Re\(_{\text{C}_x}\)=100K the L2F-EB shows a 3.2% reduction in total passage loss. The L2F-EB performs best at lower Re\(_{\text{C}_x}\), indicating a sensitivity to the inlet boundary layer thickness [49]. The L2F-EF2 is a modified L2F-EF with the leading edge aligned with the flow stagnation line. The L2F-EF2 shows a 4.7% reduction in total passage loss at Re\(_{\text{C}_x}\)=100K. All three profile contour designs are depicted in Figure 1-3.
In order to more fully understand the differences between the L2F and its profile contours, various measurement data were acquired for comparison. Multiple sets of SPIV measurements were taken on closely spaced planes in the aft section of the passage and downstream of the blade row [47] [39] [50]. The aft of the passage contains a complicated region of three dimensional flow caused by the interaction of the passage vortex and the blade suction surface (SS). Measurement planes downstream of the blade row are used to compare loss evaluation techniques and their value in further reduction of losses. The SPIV planes were spaced so as to provide uniform final vector spacing in all three dimensions. These closely spaced planes enable calculation of out-of-plane velocity derivatives using a stereoscopic PIV system instead of a tomographic PIV system or CFD. The out-of-plane derivatives are useful in calculating loss production parameters such as turbulence production and total pressure transport.

To further explore the loss production mechanisms at work, total pressure loss data was acquired on planes corresponding with the SPIV measurements. The closely spaced total pressure loss planes allowed for calculation of the local pressure gradient. Of
particular interest was the derivative in the exit flow direction. This data also allows the tracking of the total pressure loss development through and downstream of the blade row.

A thorough investigation of the loss production mechanisms requires a thorough understanding of the flow structures present. A surface oil film technique was developed and implemented for the suction surface and endwall surface. This oil flow visualization allowed a qualitative analysis of the flow structures present for the different profile contours.

By using the aforementioned methods and equations to process the various data acquired, a more thorough understanding of the flow field in a low pressure turbine cascade is achieved. The flow structures for a front loaded blade are described along with the variations seen by modifying the geometry with profile contouring. The profile contours have reduced the secondary total pressure loss. Using parameters such as: Reynolds stresses, turbulence production and total pressure transport, the loss development and reduction is described for both the baseline L2F and its profile contoured counterparts.

The body of this Thesis is composed of two main parts: experimental development and setup, and flow structure and loss analysis. The next three chapters describe the development and application of each experimental technique individually. These chapters focus on the apparatus used and their setup, the experimental technique used to acquire the data, and the relevant processing techniques used to refine the data. The following three chapters approach the data interpretation through various parameters. The first describes the flow field and compares the various profile contours. The second presents the Reynolds’ stresses, turbulence intensity and turbulence production and utilizes the
data from the current study to explore its meaning. The third presents the development of the total pressure transport equation and its simplification along with an analysis of the total pressure transport through the LPT cascade.
2 THE SURFACE OIL FILM TECHNIQUE

The Surface Oil Film Technique, also commonly called Oil Flow Visualization, is a flow visualization method that utilizes a high viscosity fluid to indicate fluid shear near a boundary surface. This technique relies on the no slip boundary condition at two interfaces, an oil/surface interface and an air/oil interface. This condition requires that the oil have the same velocity as the surface at the oil/surface interface and the same velocity as the air at the air/oil interface. High velocity air will move the oil further and leave less residue than low velocity air. The high viscosity of the oil allows an imprint of the air flow variations that can be tracked. Different forms of this technique use varied methods to track the oil movement and/or thickness to depict the flow direction and magnitude in a given region [6] [8] [11] [27]. Similar but more complicated techniques such as naphthalene sublimation or particle tracking allow for a more quantitative analysis [12] [13] [51].

The present study utilized a fluorescent dye mixed into mineral oil to track flow features. By illuminating the dye with an ultraviolet light, and photographing it at regular intervals, the features can be tracked throughout development and at steady-state. This chapter discusses the development and application of the Surface Oil Film Technique for low speed applications with a variety of conditions. High speed applications are briefly discussed in work by Wolfgang Merzkirch [52]. This technique allows the qualitative analysis of average flow features on a surface providing meaningful insight to flow field structures quickly and at relatively low cost.

Flow visualization of the secondary flow structures within the low pressure turbine cascade was desired. The two regions of interest were the suction surface of the blade and
the cascade endwall. These two regions differed both in orientation and in surface material and finish. Multiple flow conditions in these regions were of interest. These conditions included the baseline L2F blade along with three profile contours at three different Reynold’s numbers and two inlet boundary layer thicknesses.

Figure 2-1 depicts the flow structures present in the L2F flow field. Multiple dominant features are observed developing through the passage. The first is the passage vortex (PV) which forms as the pressure side leg of the leading edge horseshoe vortex. The cross passage pressure gradient drives the PV across the passage until it interacts with flow features along the suction surface. The passage vortex was observed to lift off from the endwall as it nears the suction surface. The second feature is the corner vortex (CV) which forms as a counter rotation underneath the PV. Another is the suction side corner separation vortex (SSCSV) which forms at the intersection of the suction surface and the endwall near peak suction. This vortex travels downstream against the suction surface moving away from the endwall towards the trailing edge. These features will be described in more detail in Chapter 5.
The initial study utilized a simple mixture Kaydol heavy mineral oil tinted with Spectralite Oil-Glow 44. The oil was applied to the suction surface of the blade or to the endwall using an airbrush. The oil was illuminated using an ISSI high power blue LED light and photographed with a PCO 4000 scientific camera. The light and camera were set up downstream of the cascade for the suction surface cases (see Figure 2-2) and above the tunnel for the endwall cases. A Paasche VL airbrush that was syphon fed was used for a conical application pattern. A gravity fed Iwata Kustom Highline TH airbrush was used for an elliptic application pattern. Isopropanol was used in select cases as a cutting agent to reduce the oil viscosity. Windex and isopropanol were used as cleaning agents between runs. And non-tinted mineral oil was used as a pre-application base in select cases.

Figure 2-3 presents results for both the L2F baseline and L2F-EF contour on the suction surface at a Reynolds’ number of 100,000. These cases show some interesting characteristics about the surface oil film technique in general and also about the flow field in question. For reference, the inlet is on the right of the figure and the exit is on the
left. For both contours the top left corner of the field of view can be seen to have very little oil coating and also almost no movement. The oil coating was purposefully left thin here after previous cases showed that this region moves slowly downstream and due to low surface shear is highly gravity dependent and often would corrupt the data below it. The bottom of the field of view for both cases is clearly wiped clean. This region is related to the passage vortex and has high shear on the suction surface. The coating on this region was left slightly thinner than elsewhere to avoid issues with puddling on the liftoff line. The flow direction here is very clear due to the long streaks left by the oil glow 44 dye. These streaks show the rotational direction of the passage vortex at different locations on the suction surface. Comparing the results for the L2F to those for the L2F-EF; we can note the significant reduction of passage vortex shear on the suction surface for the L2F-EF. One other key feature of note in these views is the separation bubble feature in the top right corner. The oil in the realm of a separation and reattachment quickly transitions from high shear to low shear and then back again.

Figure 2-4 depicts the L2F suction surface results for lower Reynolds’ numbers. One immediately notable change from results for Reynolds number 100,000 to Reynolds
number 50,000 is the large decrease in shear magnitude on the surface. The separation bubble is longer and weaker. The passage vortex is weaker and therefore has a very blurred separation line implying a more diffuse structure. Another difference is the near absence of the high shear region directly above the passage vortex in the bottom right corner of the field of view. In the top left corner we notice that the closer we get to the trailing edge of the blade the greater the influence of gravity on the results. The primary reason for this is that the slower fluid requires thicker oil to generate noticeable features and a longer run time to reach steady state. Sub-figure B depicts the results for Re_{Cx}=30,000. The high gravity dependence of the results at this flow speed rendered most results very difficult to interpret. Interestingly, there is a region of high shear and rotation in the bottom right corner that is not the passage vortex. The passage vortex can be seen but is very blurred and cannot be accurately depicted. The separation bubble as well is very difficult to see.

Figure 2-5 depicts the results obtained for the L2F baseline and L2F-EF glove on the endwall surface at a Reynolds’ number of 100,000. For both cases the flow enters from the bottom of the figure which is aligned with the leading edge of the blade and exits at the top of the figure which is aligned with the trailing edge. The notable features here are:
the inlet boundary layer separation with fluid entrainment towards the suction surface under it at the bottom of the figure, the passage vortex in the top left of the figure crossing the passage, the lift-off line of the passage vortex near the suction surface and the corner vortex between the passage vortex lift-off line and the suction surface. One particular difference between the contoured and baseline cases is the shift of the passage vortex upstream when the L2F-EF contour is used. The lower shear and blurring of features at lower Reynolds’ numbers seen on the suction surface is also the case on the endwall. No figure depicting this is presented in the interest of brevity.
3 TOTAL PRESSURE LOSS MEASUREMENTS

Prior studies have utilized total pressure loss measurements downstream of a turbine cascade to characterize the performance of blade profiles. Pitch-wise traces of data taken at the midspan of the blade profile are used to characterize the 2D performance of the blade. To characterize secondary losses 2D surveys of total pressure loss are necessary. These are referenced to the leading edge in the axial direction, the trailing edge in the pitch-wise direction and the endwall in the span-wise direction. An upstream pitot-static probe connected to a Druck differential pressure transducer (0 to 0.4 in H2O (0 to 100 Pa) range) was used to set the inlet tunnel speed. The total pressure port of the pitot along with a downstream Kiel probe (see Figure 3-1) were connected to a second Druck differential pressure transducer (-0.2 to +0.8 in H2O (-50 to 200 Pa) range) to measure the total pressure drop between the inlet freestream and the measurement location. The total pressure loss coefficient for a given location can then be determined according to the following equation:

Figure 3-1. Downstream view of the inline Kiel probe and connections.
\[
Y_t = \frac{P_{t,\text{in}} - P_{t,\text{out}}}{\frac{1}{2} \rho U_{\text{in}, \text{st}}^2}
\]  

(3.1)

For measurement planes downstream of the blade trailing edges data is taken across one pitch from the endwall up to 40% span where the loss profile is approximately equivalent to the midspan loss profile. To get the passage loss \(Y_{\text{ps}}\) the total pressure loss is then integrated across the full measurement plane area. For measurement planes within the passage, data is taken from the suction surface pitch-wise to near the pressure surface, as access allows, and from the endwall up to a point where the loss profile stops changing with span. For 150\% \(C_x\) this is at 40\% span, further upstream lower values are used. Figure 3-2 shows an example readout from LabView of \(Y_t\) at 150\% \(C_x\). This readout is used to monitor test results during operation and as a quick check that the results are reasonable.

Data at 150\% \(C_x\) has 30 points in each direction. All other planes used a data spacing of 5mm between each point in each direction and were bounded by the physical access of the Kiel probe. At each data point a 7 second settling time, to allow the pressure in the lines and transducers to stabilize, is used before acquiring data for 5 seconds at 1kHz.

Figure 3-2. Snapshot of the data acquisition readout in LabView.
In order to evaluate certain loss production mechanisms more thoroughly the local pressure gradient is also useful. The most valuable pressure gradient is in the streamwise direction, which requires out of plane derivatives to calculate. By taking closely spaced planes of total pressure loss the local pressure gradient coefficient can be calculated using a backward difference:

$$\frac{dP_t}{dx_s} = \frac{Y_{t,1} - Y_{t,2}}{x_{s,1} - x_{s,2}}$$  \hspace{1cm} (3.2)$$

$Y_t$ can be used in equation 8.2 in place of $P_t$ because the inlet total pressure term cancels out. This allows the calculation of the total pressure gradient using only total pressure loss data. Total pressure loss measurements were acquired on 60, 70, 71, 80, 85, 90, 95, 96, 100, 125, 150, and 151% axial chord planes. The closely spaced planes at 70, 95 and 150% $C_x$ allow for calculation of the local pressure gradient. Figure 3-3 depicts a view of the cascade from downstream looking upstream. Part A is zoomed out to orient the reader to the viewing direction. Part B shows the region of interest with lines depicting the locations where the acquired planes of data intersect the endwall.
Figure 3-4. Downstream view of the $Y_t$ development on axial chord planes A) L2F B) L2F-EF.
Figure 3-4 uses the view depicted in Figure 3-3-B to present $Y_t$ contours as they develop through the passage for both the L2F baseline and the L2F-EF blade profiles. The data presented in this figure is non-dimensionalized by one half the inlet dynamic head but is otherwise uncorrected. The pitch-wise peaks present along the endwall are from the passage vortex as it crosses the passage and interacts with the suction surface. The large peaks that progress up the span as the flow propagates downstream are associated with the suction side corner separation vortex. It is clear that the suction side corner separation vortex is associated with higher local losses than the passage vortex. By 150% $C_x$ the total pressure loss region has widened out and dropped in peak magnitude by more than half. By that point the losses have mixed out enough for a clean comparison between cases.
4 STEREOSCOPIC PARTICLE IMAGE VELOCIMETRY

Stereoscopic Particle Image Velocimetry (SPIV) was used to capture the velocity field within and downstream of the blade row on closely spaced planes to enable calculation of out-of-plane derivatives. Measurements were made in axial chord planes at 69, 70, 71, 94, 95, 96, 149, 150 and 151% Cx (Figure 4-1). Velocity data was acquired for the L2F blade along with the L2F-EF profile contour. Comparisons with the L2F-EF2 and L2F-EB contours are briefly presented using SPIV data from a previous paper [47].

Two PCO 1600 cameras fitted with Scheimpflug adapters and 532nm band pass optical filters were positioned downstream of the blade row and focused onto a LaVision 106-10 two sided calibration plate placed at the measurement planes. Figure 4-2 shows one of the camera setups used, other similar setups were used depending on the plane of interest. For the 69, 70, 71, 94, 95 and 96% Cx planes an optical first surface mirror was placed in the tunnel downstream of the tailboard to allow a wider viewing angle.

The cameras were calibrated at the 70, 95 and 150% Cx planes using the camera pinhole calibration model in DaVis 8.3 and a 2 surface 106-10 LaVision calibration plate.
The fit residual error for the cameras was 0.2-0.3 and 0.35-0.45 pixels respectively. LaVision’s documentation recommends less than 1 pixel for a good calibration and less than 0.3 pixels for an excellent calibration. The fits acquired were all near or in the excellent calibration category despite the error induced by windows and mirrors. All planes were then self-calibrated using particle images according to the method described by Weineke [53] using 100 image captures, a 256 pixel window size and 50% overlap. The residual disparity was reduced to below $10^{-3}$ mm for all planes within 10 passes. The 1% $C_x$ distance between the original calibration plane and the sequential measurement planes used is well within the recommended bounds of the self-calibration.

A Concept Smoke ViCount oil smoke generator was used to seed the flow. The generator was operated with a supply pressure of 25 psig nitrogen for a period of one to two minutes. The output was directed toward the tunnel inlet to speed mixing. The seeding was allowed to disperse through the bay housing the wind tunnel for over a half hour to reach high seeding uniformity. The average particle duration was over three hours allowing more than two hours of data acquisition per session before the seeding had to be refreshed. A low repetition rate (15Hz) Quantel Evergreen double pulse laser was used to
illuminate the measurement volume. Sheet forming optics were employed to form a 1.5 mm thick laser sheet which was sufficient to reduce average particle movement to less than 30% of the sheet thickness between exposures allowing good resolution of the out-of-plane velocities. The laser was mounted on a Velmex BiSlide linear traverse which allowed the laser and sheet-forming optics to be moved accurately as a unit between each closely spaced plane without stopping the tunnel. This allowed each set of closely spaced planes to be acquired with identical run conditions and in rapid succession. All runs were progressed from zero velocity directly to the run condition to provide a consistent response and to avoid complications from hysteresis. Further details of the SPIV measurements are presented in Chapters 5, 6 and 7.
5 FLOW STRUCTURES IN A HIGH LIFT LOW PRESSURE TURBINE CASCADE

The turbine flow field has been historically well documented [13] [54] [55] [56]. Similar flow fields have also been documented such as a wing/fuselage junction flow which contains features such as a leading edge horseshoe vortex [57]. An analysis of the L2F and L2F-EF secondary flow fields and a brief comparison with the L2F-EF2 and L2F-EB flow fields is presented here based on earlier work by the author and others [38] [44] [47] [49] [48] to provide orientation for the subsequent loss production analysis. A common trend in turbine stage development over the past half of a century has been to progressively increase blade loading. The flow fields depicted in the literature have had to follow suit and update their flow field models and descriptions as the structures tend to change noticeably with loading magnitude. The following flow field description is applicable for turbine blades with a $Z_w \approx 1.55-1.6$ at $Re_{Cx}=100,000$. The flow fields for the contoured cases are more representative of designs with low stagger angle.

Equations presented are calculated from non-dimensional data. Spatial data is normalized by $C_x$ and velocities by $U_{in,st}$. Eq. 5-1 describes the rotation rate tensor of a velocity field. Eq. 5-2 likewise describes the strain rate tensor. The secondary coordinate system is aligned with the nominal blade exit angle as shown previously in Figure 4-1. The secondary vorticity coefficient is given in Eq. 5-3. Swirl strength coefficient is defined following Adrian and Westerweel [58]. The secondary swirl strength is given in Eq. 5-4.

$$ W_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right) $$

(5-1)
Figure 5-1. ILES Q=10 isosurfaces flooded by C_{\omega s}. The view is from downstream of the passage looking upstream.

\[ S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]  

(5-2)

\[ C_{\omega s} = \frac{dW}{dy_s} - \frac{dV_s}{dz} \]  

(5-3)

\[ C_{\lambda s} = \text{imag} \left\{ \left( \frac{dV_s}{dy_s} + \frac{dW}{dz} \right) + \sqrt{\left( \frac{dV_s}{dy_s} + \frac{dW}{dz} \right)^2 - 4 \left( \frac{dV_s}{dy_s} \frac{dW}{dz} - \frac{dV_s}{dz} \frac{dW}{dy_s} \right)} \right\} \]  

(5-4)

Q-Criterion is used to highlight regions of rotational flow. Positive values of Q represent regions dominated by rotation and negative values represent regions dominated by strain [59].

\[ Q = \frac{1}{2} \left[ W_{ij} W_{ij} - S_{ij} S_{ij} \right] \]  

(5-5)
The flow structures that exist through and downstream of the LPT passage are presented in Figure 5-1 using the results of an Implicit Large Eddy Simulation (ILES) of the experimental arrangement. Details of the simulation are included in Ref. [48]. The view shown is from downstream of the passage looking upstream. Q=10 isosurfaces are plotted through the passage and flooded with $C_{\omega s}$ where blue regions represent clockwise rotation and red regions represent counterclockwise rotation. Four dominant vortical features are observed in the downstream half of the passage. The first is the passage vortex (PV) which forms as the pressure side leg of the leading edge horseshoe vortex. The inlet endwall boundary layer separates when it contacts the stagnation point on the leading edge of the blade. This separated boundary layer then rolls over forming the PV core. This rotation entrains fluid across most of the passage forming a large rotational region. The cross passage pressure gradient drives the PV across the passage until it interacts with flow features along the suction surface. Underneath the inlet boundary layer separation cross flow is observed generating smaller vortical structures. The PV was observed to lift off from the endwall as it nears the suction surface. The second feature is the corner vortex (CV) which forms as a counter rotation underneath the PV at the junction of the blade and endwall. The large rotational region penetrating up the suction surface is labeled the suction side corner separation vortex (SSCSV). It forms at the intersection of the suction surface and the endwall originating near the suction peak. This SSCSV travels downstream against the suction surface towards the trailing edge while moving away from the endwall. Near the trailing edge the SSCSV begins to separate from the suction surface and migrate out into the freestream. Directly above the SSCSV and the suction surface a region of high shear is formed. This high shear region
forms a counter rotation at the trailing edge resulting in a high shear high rotation shed vortex (SV). The L2F also has a short laminar separation bubble at the flow Reynolds number. The suction side leg of the horseshoe vortex dissipates by mid-chord and is not shown in the view of Figure 5-1.

The endwall flow features of the L2F and L2F-EF profiles are compared using Q-Criterion in Figure 5-2. Q-Criterion is plotted in a series of axial planes for both cases. The L2F PV is stronger and further away from the suction surface. The L2F-EF PV core is closer to the endwall and interacts with the suction surface farther upstream in the passage. This implies that the L2F-EF contour shifts the PV upstream. Recalling that the SSCSV originates from the region where the PV and the vortical structures under the inlet boundary layer impinge on the suction surface we can then recognize that the interactions of these features is strongly affected by the use of the L2F-EF contour. The L2F-EF SSCSV is stronger and further up the suction surface. At 150% C_x the L2F has two strong rotational peaks. The lower peak originates primarily from the PV but is influenced by the SSCSV as well. The upper peak is due to the SV. This feature
originates from the high shear region above the SSSCV and is strengthened by the negative spanwise flow from the pressure side of the trailing edge. The SV is significantly strengthened for the L2F-EF contour, however the lower peak generated by the PV and SSSCV is not visible. The contours are cut off at Q<5 implying a very low strength lower core.

A comparison between the L2F-EF2 and L2F-EB profiles using experimental Q-Criterion plots is presented in Figure 5-3. Q-Criterion is plotted for 50, 60, 70, 85, 92 and 99% C x for both cases. Data for these contours was not acquired for at 150% C x. For both contours the vortex paths through the passage almost exactly resemble the L2F-EF. The L2F-EF2 appears to have a slightly weaker PV and slightly stronger SSSCV than the L2F-EF. Recall from Figure 1-3 that the L2F-EF2 has a very similar loss reduction to the L2F-EF. It is concluded that for this Reynolds’ number the flow fields are, for all practical purposes, equivalent. The L2F-EB PV has a similar structure and intensity to the L2F-EF. Its SSSCV remains nearer to the endwall and to the suction surface than the L2F-EF. The L2F-EB performs best at lower Reynolds’ numbers and when the inlet

Figure 5-3. Experimental Q development through the passage A) L2F-EF2 B) L2F-EB
boundary layer thickness matches the bulb height. For the current conditions it is assumed that the benefit of the L2F-EB is diminished due to the tighter structure of the vortices. This follows trends seen by studies using boundary layer fences.

Total pressure loss ($Y_t$) development through and downstream of the passage are shown in Figure 5-4 for both the L2F and L2F-EF profiles. In the case of the L2F (Figure 5-4-A), total pressure loss ($Y_t$) cores develop in the region of the PV and SCSV. The SCSV also has a high loss region directly above it caused by the interaction of the endwall flow with suction surface boundary layer. From Figure 5-4-B we see that the upper loss core is compressed closer to the endwall for the L2F-EF.

A quantitative comparison between the L2F and L2F-EF passage total pressure loss becomes possible by integrating total pressure loss measurements across one pitch in the downstream plane. The integrate wake total pressure loss coefficients along the span are shown in Figure 5-5. Two key differences between the contoured and uncontoured cases can be seen. The addition of the L2F-EF contour reduces the spanwise extent of the upper loss core. The most important difference however is the significant reduction of the lower
loss core. This difference accounts for the majority of the improvement seen by using the L2F-EF [37].
6 LOSS PRODUCTION: TURBULENCE PRODUCTION

Historically turbulence has been regarded as a primary cause of pressure losses. While certain types of turbulent flow produce desirable effects such as reducing separation around a golf ball in flight there are many downsides to turbulence in practice that can be difficult to quantify. One early method of exploring turbulent flows and related losses is the use of Reynolds’ stresses. Reynolds’ stress shows up in the formulation for the Reynolds’ Averaged Navier-Stokes flow equations as each fluctuating velocity component multiplied by each other fluctuating velocity component. A velocity component times itself is referred to as a normal stress while a component times a different component is referred to as a shear stress. There are three normal stresses and six shear stresses of which three are duplicates. These Reynolds’ stresses can be used to evaluate the turbulence in various ways. Of particular interest in the current study is the secondary shear stress $vw$.

Figure 6-1 presents the secondary Reynolds’ shear stress for the L2F from ILES data (top), from experimental data (middle) and the L2F-EF from experimental data (bottom). This data is presented at 70, 95 and 150% $C_x$. This allows us to track the shear stress normal to the flow direction as it develops through and downstream of the passage. Figure 6-1-A, Figure 6-1-D and Figure 6-1-G present $vw$ at 70% $C_x$ for the L2F and L2F-EF. The L2F has a large negative peak that overlaps the PV with small positive regions just outside of it. The ILES predicts a slightly stronger and wider negative peak though the shape is the same. The L2F-EF has a massively reduced negative peak that has nearly disappeared completely. The positive peaks for the L2F-EF only exist on the suction and endwall sides of the PV rather than all around the negative region.
Figure 6-1-B, Figure 6-1-E and Figure 6-1-H present $v'w'$ at 95% $C_x$ for the L2F and L2F-EF. For the experimental data on this plane surface reflections corrupted the data near the suction surface. This region has been blanked and can be seen in the figure as the region to the left of the dashed red line. Tracking the features seen at 70% a few developments can be seen. The negative region associated with the passage vortex has diminished in size and intensity. The positive region between the PV and the suction
surface has grown in size and intensity and moved up the span signifying this feature is caused by the SSCSV. More detail on this feature can be seen from the ILES data. One interesting detail is the alignment of the edges of this positive peak with the $Y_t$ isolines. The positive region on the pressure side of the PV has expanded and is higher in strength. The L2F-EF trends appear to match the trends seen at 70% completely with all features showing up smaller and much weaker. Notably the positive region on the pressure side of the PV is once again absent.

Figure 6-1-C, Figure 6-1-F and Figure 6-1-I present $vw$ at 150% $C_x$ for the L2F and L2F-EF. On this plane the edges of the data were corrupted due to lens barreling and are ignored as they should even out to the free stream values. The L2F has two distinct elongated peak regions. On the left is a negative peak and on the right is positive band. These peaks are within the $Y_t$ band but they do not align particularly well with peak $Y_t$ locations. The positive peak corresponds with the positive peak seen at 95% for the SSCSV. The PV negative peak has nearly completely disappeared but can still be faintly seen underneath the positive peak. The negative peak is related to the blade shed and possibly also the SV. The ILES predicts the shape and magnitude of the features better at 150% than the previous two planes. The L2F-EF peaks are lower in magnitude than the L2F following the same trend as seen before. Another interesting difference is that the positive peak has moved upwards following the lower $Y_t$ loss core. This could imply that $vw$ can predict the lower total pressure loss core but not the upper core.

Eq. 6-1 is the turbulent kinetic energy which is one half the sum of the normal stresses. Eq. 6-2 is the turbulence intensity derived from turbulent kinetic energy. Historically turbulent kinetic energy is used as a tool for loss analysis. This paper
presents values for turbulence intensity as it is often easier to read. It should be noted that conclusions made from turbulence intensity also apply to turbulent kinetic energy in a power law sense.

\[ k = \frac{1}{2} \langle u_i u_i \rangle \]  \hspace{1cm} (6-1)

\[ Tu = \sqrt{\frac{2}{3} k} \]  \hspace{1cm} (6-2)
Figure 6-2 presents the turbulence intensity for the L2F from ILES data (top), from experimental data (middle) and the L2F-EF from experimental data (bottom). This data is presented at 70, 95 and 150% C\textsubscript{x}. Note that the inlet FSTI for the experimental cases is 3% and 0% for the ILES case. This results in a higher FSTI on the planes of interest for the experiment than seen in the ILES. Figure 6-2-A, Figure 6-2-D and Figure 6-2-G present turbulence intensity at 70% C\textsubscript{x} for the L2F and L2F-EF. The L2F has a high turbulence intensity within the PV and along the suction surface. Immediately apparent is that the ILES predicts the turbulence intensity to be two or three times higher than the experiment at this plane. It is also clear that the turbulence intensity does not align with \( Y_t \) very well at all compared with \( \nu w \). The L2F-EF has a reduced PV turbulence intensity but has a similar magnitude along the suction surface.

Figure 6-2-B, Figure 6-2-E and Figure 6-2-H present turbulence intensity at 95% C\textsubscript{x} for the L2F and L2F-EF. The L2F has a turbulence intensity peak within the PV comparable to at 70%. Similar to at 70% the ILES predicts the correct shape but overpredicts the magnitude and the turbulence intensity peaks do not align well with \( Y_t \) peaks. This trend continues through 150% C\textsubscript{x} in Figure 6-2-C, Figure 6-2-F and Figure 6-2-I though the ILES predicts the magnitude correctly on this plane. The general conclusion from this is that turbulence intensity has peaks near \( Y_t \) peaks but does not predict them. This agrees with the findings of previous authors that total pressure losses are caused by shear stresses rather than normal stresses.

The RANS mean kinetic energy equation is given by [45] [60] in dimensional form:

\[
\rho \frac{\partial}{\partial t} \left( \frac{1}{2} U_i U_i \right) + \frac{\partial}{\partial x_j} U_j \left( P + \frac{1}{2} \rho U_i U_i \right) + \rho \frac{\partial}{\partial x_j} (u_i u_j) U_i - \frac{\partial}{\partial x_j} \mu U_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) = \\
\rho (u_i u_j) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} + \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j}.
\]

(6-3)
The terms beginning with the far left are described as [45]: change of mean kinetic energy with time, change in convective transport of total pressure with space, turbulent diffusion of mean kinetic energy rate, work of viscous stresses rate, work of turbulent deformation on the mean motion and viscous dissipation. The first right hand side term is of particular interest. Often referred to as turbulence production [61] [62] this work of turbulent deformation is specifically the rate of conversion from mean to turbulent kinetic energy. When turbulence production has a positive sign it represents conversion from turbulent kinetic energy to mean kinetic energy. Using non-dimensional variables the individual elements of the turbulence production can be written as:

$$\psi_{ij} = \langle u_i u_j \rangle \frac{\partial u_i}{\partial x_j}$$ (6-4)

MacIsaac et al. [46] plotted the entire turbulence production tensor downstream of a LPT cascade along with select traces of several individual components. Negative values of turbulence production have historically been associated with loss. The observation was made that positive values of turbulence production exist within the passage vortex implying a mean kinetic energy increase due to turbulent fluctuations. It was also observed that these regions overlapped with regions of high normal stress.

Sangston et al. [38] decomposed the turbulence production tensor using a combination of SPIV and CFD data. From this study it was concluded that shear components of deformation work dominate loss production. Initial work towards this thesis explored this further using closely spaced SPIV planes to validate the trends seen using CFD derivatives [47]. This study found that the conclusion of Sangston et al. that the components using out of plane derivatives contributed very little in terms of loss
generation was appropriate. It was also concluded that the dominant term in loss generation was the shear component normal to the bulk flow direction ($\Psi_{vw}$).

The secondary component of turbulence production ($\Psi_{vw}$) is plotted with isolines of total pressure loss ($Y_t$) in Figure 6-3. The ILES of the L2F blade (top) is compared with experimental measurements of the L2F (middle) and the L2F-EF (bottom) blades. The $\Psi_{vw}$ component has been shown to dominant loss production by previous authors [44].
Figure 6-3-A and Figure 6-3-D show $\Psi_{vw}$ on 70% $C_x$ for the L2F. There is a strong negative peak through the PV core at $z/H=0.02$ from $y/S=0.6$ through 0.9. There is a positive peak underneath it which is a region of shear. Figure 6-3-B and Figure 6-3-E show $\Psi_{vw}$ on 95% $C_x$ for the L2F. The negative core associated with the PV has migrated towards the suction surface. The SSCSV has both a negative peak and a positive peak around $z/H=0.07$ and $y/S=0.2$. The negative peak is closer to the endwall. Both of these peaks are similar in strength to the peak associated with the PV on this plane. Figure 6-3-C and Figure 6-3-F show $\Psi_{vw}$ on 150% $C_x$ for the L2F. Three peaks exist, two positive and one negative peak. The lower positive peak at $z/H=0.06$ and $y/S=0.5$ appears in the region we associate with the PV. The upper peaks at $z/H=0.1$ appear in the region we associate with the SSCSV.

Figure 6-4 presents $\Psi_{vw}=\pm 0.02$ isosurfaces accompanied by slices on 70, 95, and 150% $C_x$ from the ILES data [48] for comparison with the experimental data in Figure 6-3. Blue implies a negative value or conversion of mean kinetic energy to turbulent kinetic energy. Red implies a positive value or conversion of turbulent kinetic energy to mean kinetic energy. Previous studies have shown that both positive and negative production values can occur in stagnation flows [63] [64]. Additionally, they have shown that local increases in total pressure can occur under the same conditions. At 70% we see the dominant negative core of the PV along with a small positive core towards the suction side of the passage. This matches what we see in the experiment. At 95% we see the negative PV core has migrated closer to the suction surface and there are both positive and negative peaks overlapping with the SSCSV. At 150% there are two positive cores and two negative cores. The lower positive core is transported from the corner vortex
under the PV and into the wake. Next to this is a negative region that is much weaker in the experiment than the ILES data that originates on the pressure side of the trailing edge at the same spanwise location as the positive core. The upper positive core is generated by the SV. The negative region to the right of this is a remnant of the negative region from the SSCSV. This region is stronger in the experiment. Of these four regions none originate from the PV directly but are a result of mixing. The $\Psi_{vw}$ isosurfaces associated with the PV diminish quickly after exiting the passage. This implies the the PV generates loss primarily through the passage while the SSCSV and the SV continue to produce significant loss downstream of the passage as well.

In Figure 6-3-G at 70% $C_x$ the turbulence production for the L2F-EF is significantly

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Figure 6-4. ILES $\Psi_{vw}=\pm0.02$ isosurfaces with axial slices at 70, 95 and 150% $C_x$. 

39
reduced in the PV region and the negative region underneath the PV has grown in size. In Figure 6-3-H at 95% Cx the turbulence production near the PV is much lower. The positive region above the SSCSV is also significantly reduced in magnitude. In Figure 6-3-I we see that all four cores seen for the L2F have been reduced and also have moved away from the endwall. The reduced magnitude of the lower positive region implies the corner vortex under the PV has been reduced in strength resulting in less loss produced as it mixes out. The reduced strength of the upper two cores implies the loss associated with the SSCSV and trailing edge shed vortex have both been reduced. With all four cores close together however it makes sense that the upper loss core depicted in Figure 5-5 is not lower in magnitude.
7 LOSS PRODUCTION: TOTAL PRESSURE TRANSPORT

The incompressible RANS momentum equation is written as:

\[
\frac{\partial u_i}{\partial t} + U_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p_s}{\partial x_i} + v \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial (u_i u_j)}{\partial x_j} \tag{7-1}
\]

The equation can be rewritten in terms of the total pressure gradient following the procedure described by Lyall [37]. By assuming steady state conditions the time derivative is equal to zero. The second term can then be split into two parts with one part being the derivative of kinetic energy and the other twice the rotation rate tensor times the velocity. To cast the equation in terms of the total pressure gradient we recognize that the total pressure is the static pressure plus the kinetic energy. The resulting equation is written in Eq. 7-2.

\[
\frac{\partial p_t}{\partial x_i} = \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} - 2\rho U_j W_{ij} - \rho \frac{\partial (u_i u_j)}{\partial x_j} \tag{7-2}
\]

Eq. 7-2 can be written in non-dimensional form as Eq. 7-3, in which all of the terms can be resolved through velocity measurements.

\[
\frac{\partial p_t}{\partial x_i} = \left(\frac{1}{Re_{c,x}}\right) \frac{\partial^2 u_i}{\partial x_j \partial x_j} - 2 U_j W_{ij} - \rho \frac{\partial (u_i u_j)}{\partial x_j} \tag{7-3}
\]

We extend the analysis of Lyall [37] by using the substantial derivative of total pressure (Eq. 7-4). We again assume steady state to simplify Eq. 7-4. Combining Eq. 7-3 and Eq. 7-4 results in Eq. 7-5 which is the substantial derivative of total pressure in the local streamwise direction. In dimensional form this has units of Watts per cubic meter or power per unit volume.

\[
\frac{DP_t}{Dt} = \frac{\partial p_t}{\partial t} + U_i \frac{\partial p_t}{\partial x_i} \tag{7-4}
\]

\[
\frac{DP_t}{Dt} = \left(\frac{1}{Re_{c,x}}\right) U_i \frac{\partial^2 u_i}{\partial x_j \partial x_j} - 2 U_i U_j W_{ij} - U_i \frac{\partial (u_i u_j)}{\partial x_j} \tag{7-5}
\]
The right hand side terms of Eq. 7-5 are: (a) Laminar (Viscous) Total Pressure Diffusion, (b) a term that resembles a Coriolis acceleration term, and (c) Turbulent Total Pressure Diffusion. In turbulent flows (Re_{C_x} >> 1) the laminar terms become significantly smaller than the turbulent terms and can often be neglected. In the current study, we found the laminar terms to be more than four orders of magnitude smaller than the turbulent terms. Interestingly, when expanded, ‘b’ is algebraically zero disappearing from the equation. This leaves only term ‘c’ left in the equation. Physically this represents the average change of total pressure along a streamline. We will refer to this convective total pressure transport defined in Eq. 7-6 as \( \dot{P}_t \). This simplification also implies that for a turbulent flow the convective total pressure transport is approximately equal to the turbulent total pressure diffusion.

\[
\dot{P}_t \approx \frac{dP_t}{dt} \approx -U_i \frac{\partial u_i u_j}{\partial x_j}
\]  

(7-6)

To briefly explain the nomenclature used here I will use a generic nozzle as an example. Flow through a nozzle can have two types of acceleration, transient and convective. These are both captured using the substantial derivative of velocity. The transient acceleration, or the change in velocity with respect to time, is denoted by the time derivative of velocity. The convective acceleration, or the change in velocity with respect to space, is denoted by the velocity multiplied by the spatial derivative of velocity. The convective total pressure transport is analogous to the convective acceleration seen in a nozzle. \( \dot{P}_t \) therefore represents the rate of total pressure being transported in the streamwise direction in a volume through convective fluid motion. This implies that using \( \dot{P}_t \) the total pressure loss development can be tracked through the passage by tracking where total pressure losses have been convectively transported.
We can use the convective total pressure transport \( \dot{P}_t \) to further explore the total pressure loss development through the passage. With the current simplifications this is also the turbulent total pressure diffusion implying that higher values represent higher total pressure losses. Figure 7-1 presents the total pressure transport (\( \dot{P}_t \)), using ILES data for the L2F blade (top), experimental data for the L2F blade (middle) and experimental data for the L2F-EF (bottom), as it develops through and downstream of the blade row along with total pressure loss (\( Y_t \)) isolines. Figure 7-1 parts D, E, G and H are plotted neglecting the axial derivative terms. \( \dot{P}_t \) is sensitive to changes in Reynold’s stress and reflections off of the blade surface caused gradients in the axial Reynold’s stresses large enough to make the results difficult to interpret.

Figure 7-1-A and Figure 7-1-D show \( \dot{P}_t \) at 70% \( C_x \) for the L2F. From the ILES data a few details can easily be seen. In the corner where the suction surface and endwall meet there is a positive region. This is at \( z/H=0.02 \) and \( y/S=0.6 \). Moving away from the suction surface there is a negative region that is larger and lower in magnitude. This is at \( z/H=0.2 \) and \( y/S>0.7 \). Moving away from the endwall along the suction surface there is a positive band extending out from the suction surface with a negative band above it. These pitchwise bands are circled in Figure 7-1-B in red and labeled PB for clarity. This feature is in the same location as the SSCSV. Above \( z/H=0.07 \) the contour levels out to a constant positive band at the suction surface with a negative band just past it. From the experimental data we see these same features with some slight differences. The positive region in the corner is larger and weaker. The negative region to the right of it is smaller than in the ILES. And the positive bands traveling up the suction surface are lower in magnitude. The general agreement between the ILES and experiment despite the
experiment ignoring axial derivative terms on this plane suggests that \( \dot{P}_t \) is still relatively accurate without including every term.

Figure 7-1-B and Figure 7-1-E show \( \dot{P}_t \) at 95% \( C_x \) for the L2F. By comparing Figure 7-1 to Figure 7-1-A the features seen at 70% can be tracked as they travel through the passage. The positive and negative regions in the corner at the intersection of the suction surface and endwall have begun mixing and now have many smaller positive and
negative peaks. This region now clearly overlaps the passage vortex. The pitchwise bands (labeled PB in Figure 7-1-B) extending out from the suction surface are now longer and stronger as the SSCSV is strengthening towards the trailing edge. The positive and negative bands traveling up the span along the suction surface are now much wider and much weaker. Comparing with the experiment the same features are seen. One key difference on this plane is that the pitchwise bands are weaker. Further investigation has shown this is due to excluding the axial derivative associated with the axial normal stress. The spanwise bands are blanked out on this plane between the dashed red line and the suction surface due to reflection.

Figure 7-1-C and Figure 7-1-F show $\hat{P}_t$ at 150% Cx for the L2F. A comparison between the ILES and experiment shows nearly identical features and trends on this plane. In particular, as noted in a previous paper by the authors [39], the peak values of $\hat{P}_t$ fall entirely within the $Y_t$ region implying that $\hat{P}_t$ can be used to track loss development through the cascade. This is also true for the 70 and 95% Cx planes. The general shape of the 150% plane is banded. There exists a large spanwise positive band with negative spanwise bands on either side. The positive and negative bands associated with the SSCSV at 95% develop into the positive and right negative band at 150%. The left negative band forms from the pressure side of the trailing edge. The total pressure is transported downstream in the streamwise direction in positive regions and upstream in the streamwise direction in negative regions. This implies that negative regions will represent a local total pressure increase. This is shown to be reasonable in stagnation flows by Issa [64]. One note about the experimental data on this plane is that the large
negative peak on the right side of the wake is due to a local corruption of the axial reynold’s stress and should be ignored.

A more detailed evaluation of the $\dot{P}_t$ development through the L2F passage can be made using the ILES data. Figure 7-2 is isosurfaces of $\dot{P}_t=\pm0.25$ along with slices at 70, 95 and 150% $C_x$. The positive and negative regions seen in the experimental data along the endwall at 70% $C_x$ can also be seen in the ILES data originating at the leading edge and propagating downstream and across the passage along with the PV. The proximity of these regions to the endwall implies that the primary pressure transport of the PV occurs on the endwall side rather than within the PV core. The negative and positive regions adjacent to the suction surface in the experimental data are also present in the ILES data with one interesting difference, the positive region is almost completely enveloped by the
negative region all the way back to its origin at the suction surface endwall interface. This location also aligns with the origin of the SSCSV. This implies that the SSCSV begins as a bulk negative $\dot{P}_t$ region with a positive core and expands in the spanwise direction as it develops through the passage. This also implies the bulk total pressure transport occurs through the SSCSV rather than through the PV. This agrees with the conclusions from $\Psi_{vw}$. The spanwise bands along the suction surface are located at the same axial location as the spanwise separation bubble. This implies that the separation bubble transports total pressure.

Looking back at Figure 7-1-D and Figure 7-1-G the L2F total pressure transport can be compared with the L2F-EF at 70% $C_x$. Two significant differences are observed on this plane. First, the positive and negative peaks associated with the L2F PV region have been reduced for the L2F-EF and are low enough in magnitude to be indistinguishable from the noise floor. Second, the pitchwise bands extending out from the suction surface are not present for the L2F-EF implying that significantly less transport occurs within the L2F-EF SSCSV than the L2F.

Comparing Figure 7-1-E and Figure 7-1-H at 95% $C_x$ results in similar conclusions to at 70%. The positive and negative peaks associated with the L2F PV are once again diminished for the L2F-EF PV to the level of the noise floor. The pitchwise bands extending from the suction surface are reduced in magnitude but still exist on this plane. Another difference between the L2F and L2F-EF on this plane is the shape of these bands. The L2F-EF bands curve more towards the endwall than the L2F bands.

$\dot{P}_t$ can also be compared at 150% $C_x$ using Figure 7-1-F and Figure 7-1-I. The general banded structure is still the same implying that the correlation between the center positive
band and the right negative band with the SSCSV still holds. The corrupted region noted for the L2F is also present for the L2F-EF and should likewise be ignored. The L2F-EF $\hat{P}_t$ like the L2F overlaps the $Y_t$ peaks. From both $\hat{P}_t$ and $Y_t$ it can be seen that the lower loss core moves away from the endwall and is shortened and increased in strength. This agrees with the findings of $\Psi_{vw}$ that the remaining loss generation and transport is condensed to a smaller region further away from the endwall.
8 CONCLUSIONS

The secondary flow field in a high lift low pressure turbine cascade has been presented and evaluated using a variety of data types, methods and parameters. The use of profile contouring to reduce loss has been leveraged to compare similar flow fields and the loss associated with them in exploring various parameters associated with total pressure loss and its generation. The flow field in question has been thoroughly depicted and described. The loss development through this flow field has been depicted from multiple viewpoints and explained in detail.

The surface oil film technique was used to gain a general understanding of the secondary flow field present for the L2F blade along with multiple contours at multiple run conditions. The technique was uniquely developed for surfaces with multiple orientations and surface finishes. The development was described in detail to provide a reference for further development of low speed flow visualization in the future.

Total pressure loss measurements were acquired through and downstream of the low pressure turbine cascade. This total pressure loss data was then used to evaluate the development of total pressure loss for contoured and uncontoured cases at a Reynolds’ number of 100,000. This evaluation was later leveraged for further understanding of parameters calculated from velocity measurements.

New SPIV measurements for the L2F and L2F-EF profiles have been presented through and downstream of a LPT cascade. The total pressure loss development through and downstream of a blade row was then described using parameters calculated using only velocity measurements such as Reynolds’ stress, turbulence intensity, turbulence production and total pressure transport.
The Reynolds’ shear stress normal to the bulk outflow direction (vw) was used to depict the shear through and downstream of the passage. While this stress had peaks that commonly overlapped with high total pressure loss it did not account for all of the total pressure loss peaks. When used to compare the L2F and L2F-EF cases it was observed that the stress was lower for the L2F-EF. This reduction of magnitude may imply a reduction of loss but does not account for all of the secondary loss produced or reduced. The turbulence intensity was similarly reduced for the L2F-EF over the L2F but aligned with the total pressure loss less than vw component of Reynolds stress.

The turbulence production normal to the bulk flow direction \( \Psi_{vw} \) was used to describe where features such as the passage vortex and the suction surface corner separation vortex produce loss through shear. More specifically it allows the production of turbulence to be tracked. Because positive values exist in the flow domain it is apparent that turbulence produced is not necessarily dissipated as loss. The findings from the present study support the hypothesis that out of plane derivatives are not necessary for sufficient tracking of turbulence production. It was found that the passage vortex generates loss through the passage but generates very little loss in the blade wake. The suction surface corner separation vortex generates loss through the passage and also downstream in the wake. The trailing edge shed vortex also generates loss in the wake.

The convective total pressure transport in the streamwise direction was used to describe how upstream losses propagate downstream and affect the total passage loss development. Through the passage the out of plane derivatives were ignored in the experimental data and still agreed with the ILES data. This implies that total pressure transport does not require out of plane derivatives for reasonable evaluation. Only small
amounts of total pressure loss are propagated through and downstream of the passage by the passage vortex. The suction surface corner separation vortex propagates large amounts of total pressure loss. It is associated with multiple of the total pressure transport peaks. The shed vortex only propagates total pressure losses downstream of the trailing edge and is associated with one of the total pressure transport peaks.

These findings support the use of both turbulence production and total pressure transport as tools for loss prediction and evaluation. Turbulence production evaluated normal to the flow direction appears to be dominant over other terms in loss reduction. Total pressure transport neglecting out of plane terms was seen to agree well with total pressure loss measurements as well as with the full tensor. Both of these details imply that streamwise derivatives are not needed to perform satisfactory loss analysis.
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APPENDIX A  SURFACE OIL FILM TECHNIQUE DEVELOPMENT

The initial surface oil film study utilized a simple mixture Kaydol heavy mineral oil tinted with Spectralite Oil-Glow 44. The oil was applied to the suction surface of the blade or to the endwall using an airbrush. The oil was illuminated using an ISSI high power blue LED light and photographed with a PCO 4000 scientific camera. The light and camera were set up downstream of the cascade for the suction surface cases (see Figure 2-2) and above the tunnel for the endwall cases. A Paasche VL airbrush that was syphon fed was used for a conical application pattern. A gravity fed Iwata Kustom Highline TH airbrush was used for an elliptic application pattern. Isopropanol was used in select cases as a cutting agent to reduce the oil viscosity. Windex and isopropanol were used as cleaning agents between runs. And non-tinted mineral oil was used as a pre-application base in select cases.

Development of the technique for each surface ran into a few obstacles. Use of the Paasche VL airbrush presented challenges with coating uniformity. The airbrush produced a conical application pattern that made application without peaks difficult. The airbrush also commonly spurted large drops of non-atomized oil onto the surface which often corrupted feature development or clarity. The Iwata Hi-Line TH airbrush was tried as a replacement. This airbrush had a flat application pattern and a feathering trigger which allowed greater control and solved the issue of large peaks. Other controls included air to oil proportion and maximum flow rate. Use of this airbrush provided higher consistency between applications as well.
In order to maximize coating uniformity with the Iwata Hi-Line TH, multiple tests were performed outside the tunnel by varying the supply air pressure, air to oil proportion setting, maximum flow setting and distance from surface. The results of these tests are depicted in Figure A-1. The final settings used were 15psig supplied, 2 turns from closed for both the air to oil proportion and maximum flow and 6 inch spray distance from the blade surface.

Figure A-2 depicts three of the common issues with application of the oil on the suction surface. Sub-figure A depicts the flow visualization when the surface was undercoated. Regions where the oil coating was too thin have high surface tension and do not move when flow passes over them. Sub-figure B depicts when the surface was overcoated. Large droplets coagulate and form drips which contaminate the data. Sub-figure C shows the gravity dependence of the oil on the suction surface. When left without turning on the tunnel for about half an hour, large amounts of oil would sheet off of the surface. Considering most runs would take between 15 and 25 minutes this illustrates the

![Figure A-1. Test Cases for Coating Pattern Optimization, A) Air Pressure, B) Needle Location, C) Surface Distance](image)

A) Air Pressure (15,20,25psig)  B) Needle Location (1-4turns)  C) Surface Distance (2,4,6in)
gravity dependence of the final results seen even with optimum coating. At higher Reynolds’ numbers this dependency was negligible but was problematic at lower speeds.

After tests on the suction surface were concluded the camera was moved to directly above the passage and focused on the endwall surface through the passage. The blue light was left in its downstream position for viewing the flow field during the run without affecting the flow field. Final images of the flow field at steady state were acquired with the tunnel off while using a supplementary black light. This plane presented new and different challenges than the suction surface due to differences in orientation and material.

The first obstacle encountered was that the oil thickness required for this surface was significantly different than for the suction surface. Attempts to vary the oil thickness appropriately led to the discovery of a new obstacle. Oil thicknesses thin enough to not produce beads and roll-off like seen in Figure A-2-B instead moved extremely slow or not at all like in Figure A-2-A. A remedy for this often seen in the literature is to mix a volatile substance into the oil/dye mixture before application. The desired outcome of this is that the oil would apply thinner, have a lower initial viscosity and then a short time into the test the volatile substance would evaporate into the air leaving a thin layer of higher
viscosity oil on the surface with an imprint of the flow features left in it. For our tests isopropanol was used for this purpose.

Isopropanol has the characteristic of flashing off quickly under the flow but came with additional obstacles of its own. The first and most prominent issue was that the isopropanol acted to split the dye into its color components. The yellows and greens in the dye were the smallest particulate and remained suspended in the isopropanol, the oil and red portions of the dye were denser and would settle at the bottom of the container. This was combatted by vigorously agitating the mixture immediately before application.

The next obstacle presented by isopropanol use was dispersion. The dyes would tend to drift away from any surface contaminations immediately after application. The first attempt to address this was to pre-coat the surface with clean oil. Examples of dispersion for both pre-coated and uncoated cases are depicted in Figure A-3. The solution to this problem turned out to be to clean the application surface with Windex immediately before oil application.

The final obstacle was oil wicking. Surface edges and scratches tended to wick oil to
them resulting in formation of droplets and also in a lack of sufficient oil for patterning in key areas. This issue was tested in a similar manner to dispersion and it was found that cleaning the surface with isopropanol and then allowing the surface to dry before application would correct it. The procedure used for the endwall surface was then to: clean off residual oil from the previous test, clean the surface with Windex, wipe the surface with isopropanol, agitate the isopropanol/oil/dye mixture while surface dries and then immediately apply the coating to the surface.
APPENDIX B A BRIEF LOOK AT MEASURED LOCAL TOTAL PRESSURE GRADIENT AND ITS APPLICATION

Figure B-1-A and Figure B-1-B compare hotwire measurements from Lyall [37] at one spanwise location 0.6C_x from the endwall (14.4% span) with SPIV measurements from the current study. ITD and RTD in Figure B-1-A are the irreversible and reversible components of turbulent total pressure diffusion respectively. The ITD is the derivative of the anisotropy tensor and the RTD is a term involving the derivative of turbulent kinetic energy. The right of the plot compares the total pressure gradient (Eq. 3-2) in the average streamwise direction (obtained directly from the experiment by taking measurements in two planes and computing the x_s-derivative) with the local convective total pressure transport (Eq. 7-6). The current results from SPIV in Figure B-1-B show good agreement with the hotwire data shown in Figure B-1-A. Additionally, the convective total pressure transport shows good spatial agreement with the local total pressure gradient. The local total pressure gradient was calculated in the average

Figure B-1. L2F loss decomposition A) Lyall B) Current Study
streamwise direction whereas the convective pressure transport was calculated in the local streamwise direction causing differences in peak location. The general alignment of convective total pressure transport with the sign of the local total pressure gradient implies that the total pressure transport could be used as a predictor of the direction of pressure change in the streamwise direction.

Previous work [39] also compared the local pressure gradient with the turbulence intensity and turbulence production with some notable conclusions. In particular, that neither parameter aligned with it at all either in location or magnitude. This indicates that the correlation between the local pressure gradient and turbulence intensity or turbulence production is most likely very weak.

Further exploration was not done after this due to the amplified noisiness of the out of plane pressure derivatives. This noise is most likely due to inaccuracies in each measurement plane’s datum measurement in both the pitchwise and axial directions. If a more thorough study of the out of plane pressure derivatives is to be undertaken it should be noted that a setup allowing traversal in all three directions without turning off the tunnel would be ideal.
APPENDIX C  UNCERTAINTY IN EXPERIMENTAL DATA

Uncertainty calculation in experimental measurements is a well-documented practice. The total pressure loss measurements detailed in this thesis were briefly analyzed using a root-mean-square uncertainty method. As also seen by McQuilling [1] for this setup the instrument and calibration uncertainties for the pressure transducers are many orders of magnitude smaller than the measurement values of interest. This implies that the uncertainty of the measurement is nearly exclusively tied to random error and repeatability errors. The 150% Cx data was taken with the same setup about half a dozen times across a few days and both the individual data points as well as the integrated losses were within 1% variation across the measurement runs. Additional data points were taken later with a faster acquisition system and were also shown to match.

PIV uncertainty has been a recent topic of discussion due to the many possible sources of error. Methods for approximating the vector uncertainty have been developed which take into account things like camera angle or correlation peak value [65] [66] [67] [68]. The current work assumes the uncertainty calculation in DaVis based on calibration parameters and standard deviation is sufficient for the current work.

Two PCO 1600 cameras fitted with Scheimpflug adapters and 532nm band pass optical filters were positioned downstream of the blade row and focused onto a LaVision 106-10 two sided calibration plate placed at the measurement planes. Figure C-1 shows one of the camera setups used, other similar setups were used depending on the plane of interest. For the 69, 70, 71, 94, 95 and 96% Cx planes an optical first surface mirror was placed in the tunnel downstream of the tailboard to allow a wider viewing angle. The camera angles used for the 69, 70 and 71% Cx measurement planes were -30° and -8°
normal to the measurement plane providing a 22° camera separation. This is much less than the optimum separation angle of approximately 78°. The lower separation angle was used because it allowed a wider field of view between the opaque blades. The deviation from optimum provides higher accuracy with respect to the in plane components but lower accuracy with respect to the out of plane component. For the 94, 95, and 96% $C_x$ measurement planes the camera angles were -39° and -13° providing a 26° camera separation. The angles used for the 149, 150 and 151% $C_x$ planes were -20° and 15° providing a 35° separation. For all cases, the three adjacent measurement planes remained in focus without adjustment.

The cameras were calibrated at the 70, 95 and 150% $C_x$ planes using the camera pinhole calibration model in DaVis 8.3 and a 2 surface 106-10 LaVision calibration plate (see Figure 4-3). The fit residual error for the cameras was 0.2-0.3 and 0.35-0.45 pixels respectively. LaVision’s documentation recommends less than 1 pixel for a good calibration and less than 0.3 pixels for an excellent calibration. The fits acquired were all near or in the excellent calibration category despite the error induced by windows and mirrors. All planes were then self-calibrated using particle images according to the method described by Weineke [53] using 100 image captures, a 256 pixel window size.
and 50% overlap. The residual disparity was reduced to below $10^{-3}$ mm for all planes within 10 passes. The 1% $C_x$ distance between the original calibration plane and the sequential measurement planes used is well within the recommended bounds of the self-calibration.

Each test case included 2000 images to provided statistical independence. These images were processed using 64x64 pixel interrogation windows followed by 32x32 pixel windows using the adaptive window shape and size technique described by Weineke and Pfeiffer [69]. While the use of 16x16 pixel windows was feasible it was found that the number of spurious vectors increased to unreasonable levels, sometimes going over 50% spurious. A 3x3 vector smoothing filter was applied between passes and vectors with a peak value less than $Q=1.3$ (where $Q$ is a parameter used by LaVision based on peak value) are removed and filled with the average of their neighboring vector values. After vector calculation was complete the data was filtered with maximum limits and 3 passes of the 3x3 vector smoothing filter. This was followed by removing and replacing vectors with a $Q<1.3$ or that were not within 1.5 times the RMS of the neighboring values. The final vector spacing was approximately 0.94% $C_x$.

All planes had a maximum calculated mean vector uncertainty of less than $\pm 1\% \ U_{in,st}$ at a 95% confidence interval with the bulk flow falling under $\pm 0.1\% \ U_{in,st}$ (see Figure C-2).
C-2). Note that the peak uncertainty values all lie at the endwall and suction surfaces where laser reflections exist interfering with data reduction. The Velmex traverse on which the laser and sheet optics was mounted has a positional uncertainty of $\pm 0.0033\% C_x$. All of these uncertainty values were deemed reasonable for the current study. These could be improved further by increasing camera view separation.