OBSERVED FLOW CHARACTERISTICS OF ROTATING STALL INCEPTION AND ITS PREVENTION USING DISCRETE TIP INJECTION IN THE NASA STAGE 35 AXIAL COMPRESSOR WITH NEW ANALYSIS METHODS

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ABSTRACT

In order to further our understanding of the effects of tip injection in preventing rotating stall, a number of computational cases were run which modeled stall inception in the NASA compressor Stage 35. The flow solver TURBO, written and developed by Dr. Jen-Ping Chen, was used and new post-processing analysis methods were implemented in these cases. These include the investigation of three-dimensional disturbance (zero axial velocity) pockets, diffusion factor analyses, angle of attack analyses, and negative axial velocity volume measurements.

The utilization of these methods led to a number of observations. The first was that the three-dimensional disturbances were first formed in the mid-span of the rotor passages and then migrated to the tip region. Secondly, in both the stable and unstable cases, the disturbances travelled at 100% rotor speed around the annulus upon their inception. The third observation made was that, in stalling cases, the disturbances would eventually occupy the entire breadth of a rotor passage in the vicinity of the tip. Upon this occurrence, the disturbance would begin to propagate upstream of the leading edge of the rotor blade. It would then migrate around the rotor leading edge, merging with the disturbances in the adjacent passages while slowing to approximately 50% rotor speed.
The diffusion factor and angle of attack analyses proved less conclusive than had been hoped in providing a definitive, quantitative indication of the inevitability of stall. The original hope was that one or both of these parameters would prove to be a reliable, definitive indicator of the inevitable onset of stall at a given throttle. The diffusion factor analysis provided a means to indicate qualitative differences between different cases, i.e. indicating whether one case is more likely to stall than another. The angle of attack analysis, for the most part, seemed to accurately reflect the actual flow conditions - high angles of attack were recorded for blades which exhibited leading-edge flow separation.

Two cases were chosen to represent a stable and stalling case. The results of the stable case indicate that the tip injectors maintain stability in the compressor by preventing the formation of disturbances which occupy the full breadth of a given rotor passage. As the disturbances migrated toward the tip, the injectors would wash them away. To maintain stable operation, some disturbances required passage through the influence of only one injector, while in other cases passage through multiple injectors was required. The results of the unsteady case indicate that if the amount of injection is insufficient, the subsequent merging and growth of the disturbances blocks a significant portion of the rotor face and prevents sufficient mass flow from getting through, resulting in rotating stall.
Dedicated to my patient and loving wife.
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\[ DF = 1.0 - \frac{W_{\text{out}}}{W_{\text{in}}} + \frac{abs(R_{\text{in}} * W_{\text{1,in}} - R_{\text{out}} * W_{\text{1,out}})}{(R_{\text{in}} + R_{\text{out}}) * \sigma * W_{\text{in}}} \]  

(2.1), ........................................ 18

\[ \sigma = \frac{\text{chord}}{s} = \frac{\text{chord} * 2 * (\text{Number of blades})}{(R_{\text{in}} + R_{\text{out}}) * 2\pi} \]  

(2.2). ......................................... 18

\[ W_{\text{avg}} = (\rho u W)i(\rho u A)i \]  

(2.3), ........................................... 20

\[ R_{\text{in}}(\text{in, out}) = R_{\text{max}}(\text{in, out}) - R_{\text{min}}(\text{in, out}) \]  

(2.4). ...... 23
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CHAPTER 1

INTRODUCTION

1.1 PURPOSE OF STUDY

Rotating stall is a phenomenon that greatly limits the performance of both axial and centrifugal compressors. The susceptibility of a gas turbine engine to this phenomenon can be increased by erosion of the rotor blades caused by the ingestion of foreign objects/particles, blade tip-rub during hard landings, distorted intakes due to the implementation of stealth technology, and many other factors and situations faced on a regular basis. One approach used to combat the inception of rotating stall is to use high-energy flow tip injectors. These injectors collect fluid aft of the compressor and inject it from locations close to the casing upstream of the rotor blades. The effectiveness of this method has been proven numerous times both experimentally\(^1\), \(^2\) and computationally\(^3\), \(^4\), \(^5\), \(^6\). Despite the quantity of research devoted to this topic, there is still relatively little understanding of the physics governing the inception of rotating stall and its prevention using tip injection.
1.2 RECENT CFD STUDIES PERFORMED

In order to pursue this understanding, the use of CFD analysis becomes helpful for its ability to provide detailed knowledge and observation of phenomenon which may not be measured by current experimental techniques. TURBO, an unsteady turbomachinery flow solver written by Chen\(^7\), has been used recently to model full-annulus, time-accu-urate simulations of both axial and centrifugal compressors\(^3, 4\). Many cases were analyzed, some of which are used in the research now being presented.

1.3 STALL WARNING CRITERIA

Perhaps the most potentially useful outcome of any study regarding rotating stall would be the discovery of a criterion or criteria that would indicate, quantitatively, the eventual occurrence of stall. Two quantitative techniques have been proposed in previous studies. One such proposed criterion has been the diffusion factor in the rotor blade tip regions\(^6\). Another has been the angle of the rotor blade tip clearance vortex\(^3\). Each of these criteria has proven useful but incomplete in their ability to definitively predict the occurrence of rotating stall.

The diffusion factor analysis has proven insufficient in that, at this point, the consistency of its predictions has yet to be verified. Whenever a new geometry or flow solver is used, the diffusion factor analysis from previous cases would need to be redone and a new stall-indicating value produced. At the present time, this presents a problem in that it would require a great deal of computational time to
refine the analysis to the point that a definitive number could be attained for stall prediction.

The tip vortex angle analysis is incomplete for two reasons. First, the stall warning criterion should provide sufficient warning of stall without the requirement that the case be run all the way to near-stall conditions, which is the time-frame in which the tip vortex angle would indicate stall. Second, there is a lack of agreement among researchers as to the validity of the tip vortex angle analysis. Hoying et al.\(^{(8)}\), when performing a partial-annulus simulation of a low speed compressor near stall, prescribed that a central feature of stall inception is the movement of the tip clearance vortex forward of the leading edge of the following blade. Vo et al.\(^{(9)}\), after performing single-passage and partial annulus, time-accurate computational studies, made a slightly different conclusion. They have indicated that not only will the tip clearance vortex move forward of the leading edge, but also that “tip clearance backflow” will be created\(^{(9)}\). The conclusion drawn from this observation was that both phenomena are required for the onset of stall\(^{(9)}\). Hah et al.\(^{(10)}\) performed both single passage and full-annulus, time-accurate simulations and found that the most important phenomenon driving rotating stall is the interaction between the tip clearance vortex and the passage shock. They found that a low momentum area was created near the pressure side of the blade due to this phenomenon\(^{(10)}\).

The goal of this study was to further the understanding of rotating stall and its underpinnings. Specifically, new analysis methods were desired to make the study of this problem easier and more informative. Quantitative criteria were studied
(diffusion factor and angle of attack) which contributed a great deal of useful perspective and knowledge in this area. Other qualitative methods were developed and implemented as well.
CHAPTER 2

METHODS

2.1 PROBLEM SET-UP

2.1.1 TURBO DESCRIPTION AND SETTINGS

TURBO is a time-accurate, physics-based flow solver. It solves the unsteady Reynolds-averaged Navier-Stokes equations, implementing a decoupled k-ε turbulence model. The solution algorithm used is a Newton iterative implicit time-accurate scheme. More details regarding the solution algorithm and flow solver can be found in references (3, 4, 7, 11).

The temporal scheme was set up such that there were 3600 time steps per revolution, or 100 time steps per rotation of one rotor passage pitch. The validity of this scheme has been verified by Chen in previous work on the same geometry (3, 4). The tip clearance model used was prescribed by Kirtley (12) and maintains conservation of mass and momentum through the tip gap. This is done without requiring a tip clearance grid. More details of this approach can be found in reference (3).
No-slip boundary conditions were implemented at each solid surface. A time-accurate sliding interface was used at the injector-rotor interface and at the rotor-stator interface. This allowed for the unaltered passage of pressure waves in all directions between the injector, rotor, and stator. An isentropic inlet condition was applied\(^{(11)}\). This boundary condition can reflect outgoing pressure waves, which will be discussed later. The exit boundary condition implemented is a “choked” throttle model\(^{(3)}\) which specifies corrected mass flow at the exit of the system. This allows variation of exit static pressure to match the compressor exit mass flow which is specified by the corrected exit mass flow\(^{(3)}\). More boundary condition details can be found in references (3, 4, 11).

2.1.2 GRID CHARACTERISTICS

The compressor of interest in this study was the NASA compressor Stage 35. Stage 35 is a single-stage transonic compressor located at the NASA Glenn Research Center in Cleveland, OH. It produces a total pressure ratio of 1.8 at a mass flow rate of 20.2 kg/sec at a design speed of 17189 rpm\(^{(3)}\). Details of the compressor are outlined in Table 2.1 and Figure 2.1.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor RPM at 100% Speed</td>
<td>17188.7</td>
</tr>
<tr>
<td>Tip Speed (m/s)</td>
<td>454.456</td>
</tr>
<tr>
<td>Hub/Tip Radius</td>
<td>0.7</td>
</tr>
<tr>
<td>Rotor Aspect Ratio</td>
<td>1.19</td>
</tr>
<tr>
<td>Stator Aspect Ratio</td>
<td>1.26</td>
</tr>
<tr>
<td>Number of Rotor Blades</td>
<td>36</td>
</tr>
<tr>
<td>Number of Stator Blades</td>
<td>46</td>
</tr>
</tbody>
</table>

Table 2.1 Stage 35 Parameters<sup>(3)</sup>
Figure 2.1 Stage 35 Compressor$^{(3,4)}$
The NASA compressor Stage 35 was chosen mainly for two reasons. First, a great deal of experimentation has been conducted on this compressor, which provided direct comparisons for the TURBO data. Also, Stage 35 represents a state-of-the-art transonic compressor, allowing easier application of this research to other geometries currently under development. Stage 35 was modeled using a full-annulus grid. The grid was split into 328 blocks, representing the injector, rotor, and stator rows. The total number of grid points was 67 million. Each of the 36 rotor passages was comprised of 3 blocks, while each of the 46 stator passages were comprised of 4 blocks. Each of the 12 injectors was represented by 3 blocks, with a source term used to represent the actual inlet of the jets as seen in Figure 2.1. Each source term represents a uniform distribution of mass, momentum, and energy (3.6% design mass flow) at 5.5% span deep and 1.75 rotor chord upstream of the rotor\(^{(4)}\). The tangential width of the injector source terms is 10° and the injection is directed downstream with a 15° yaw angle against the direction of rotation of the rotor blades. Block segregation within each passage is in the axial direction only. The overall gridding scheme can be seen in Figure 2.2. The block segregation can be seen in both the short and extended inlet cases in Figure 2.3.
Figure 2.2 Grid for Stage 35 Compressor

\(^{(3)}\)
Figure 2.3 Grid Partitioning in the i (Axial) Direction for Both the Extended and Short Inlet Cases
The reference axes are visible in Figure 2.2. The i direction corresponds with axial, j with radial, and k with tangential. These are the coordinates referenced by TURBO while running solutions and are the coordinates used to number the cells within each block.

2.1.3 SPEEDLINE FOR STAGE 35 COMPRESSOR

A speedline was created for the Stage 35 compressor. The different values for the TURBO simulations were attained by varying the exit corrected mass flow boundary condition, which allows for variation in exit pressure\(^{(3)}\). After a particular case reaches a stable operating condition, a point on the speedline is produced and the exit corrected mass flow is then reduced. This process is repeated until the stall point is reached. Points a, b, and c in Figure 2.4 were created during the past year of research, while the other computational points were produced in previous research efforts\(^{(3, 4)}\) using the exact same grid and processing methods. Each of the points (a-c) utilized a steady, 3.6% design flow rate through the 12 injectors. The experimental data were taken from work conducted by Weigl\(^{(1)}\). It should be noted that point “c” on the speedline was previously studied with no tip injection which resulted in stall. A direct comparison between that case and the case run for this study was not possible due to the lack of full-annulus 3D data from the no injection case. This case will be reevaluated and compared with the injection case presented in this study so that baseline values can be recorded for this particular throttle point.
2.2 ANALYSIS METHODS

2.2.1 DISTURBANCE POCKET APPROACH

In previous numerical work performed on the Stage 35 rotor, much of the analysis on “reverse flow” was done using two-dimensional iso-surfaces in the i (axial) and j (radial) coordinate planes. These planes were studied in order to visualize both the span-wise depth and the tangential breadth of the reverse flow pockets. Upon closer analysis of these methods, it was discovered that, instead of...
using a two-dimensional plane, it is often more useful to construct three-dimensional representations of the reverse flow. This is accomplished by setting u-velocity (axial) as the iso-surface function in FieldVIEW. If the value of this function is set to a very small, negative value (-.0001 was used for this work), three-dimensional “pockets” are visualized, as seen in Figure 2.5. The leading edge (L.E.), trailing edge (T.E.), hub, and tip are all indicated in the figure.

Figure 2.5 Iso-Surface of Velocity = -.0001 on Suction Surface of Rotor Blade “a” for Speedline Point “b”
Each of these pockets is a closed volume composed entirely of reverse flow. This can be seen clearly in Figure 2.6 which shows the intersection of a j-plane iso-surface with a disturbance pocket. All of the pink-yellow on the j-plane represents flow with a negative axial velocity component. A complete collection of j-plane slices can be found in Appendix A.

![Figure 2.6 Intersection of Disturbance Pocket with j(radial)-plane Axial Velocity Iso-surface at ~65% span](image_url)
Figure 2.7 gives another view of the same intersection, showing the relative velocity vectors inside and outside the disturbance pocket. The color of the pocket was changed to teal for clarity.

In this view, it is clear to see that all of the velocity vectors contained within the disturbance pocket have a negative x-component. The direction of the velocity vectors is also verified in Figure 2.8, which is a relative velocity vector field along the suction side of the blade.
In addition to the negative x-velocity shown in Figure 2.7, this view shows that the relative velocity vectors have a positive radial component as well. This phenomenon will be discussed further in a later section. A great deal of circulation can be seen at the tip of the disturbance in Figure 2.8, which reflects the instability
(separation, swirling) in the flow surrounding the disturbance. The flow on the hub side of the disturbance exhibits non-uniformity as well in that the flow close to the disturbances has a much stronger radial component than that of the flow closer to the hub.

2.2.2 DIFFUSION FACTOR APPROACH

The diffusion factor is a parameter used to indicate the magnitude of the adverse pressure gradient for a given airfoil/flow situation, as well as the amount of turning induced on the flow as it passes over the airfoil. Both of these are evident in Equation 2.1. The diffusion factor values were calculated in much the same way that they were by Hathaway\(^{(13)}\) in previous work:

\[
DF = 1.0 - \frac{W_{out}}{W_{in}} + \frac{abs\left(R_{in} \cdot W_{t,in} - R_{out} \cdot W_{t,out}\right)}{(R_{in} + R_{out}) \cdot \sigma \cdot W_{in}} \tag{2.1}
\]

where \(W_{in}\) and \(W_{out}\) are the mass-averaged inlet and outlet relative velocity magnitudes, respectively, \(R\) is the radial location of the point of interest, \(W_{t,in}\) and \(W_{t,out}\) are the inlet and outlet mass-averaged tangential velocity values, and \(\sigma\) is the solidity of the compressor. The radial locations present in the third term are used to non-dimensionalize this analysis so that it can be applied to a 3-dimensional problem.

The solidity is expressed as:

\[
\sigma = \frac{chord}{s} = \frac{chord \cdot 2 \cdot (Number\_of\_blades)}{(R_{in} + R_{out}) \cdot 2\pi} \tag{2.2}
\]
The second term on the right hand side of Equation 2.1 reflects the outlet to inlet velocity ratio. The DF value goes up as this term gets smaller, indicating that the flow is experiencing more slow-down. This would also reflect a stronger adverse pressure gradient as the flow travels along the length of the blade, which would increase the likelihood of boundary layer separation. The last term in the equation reflects the change of angular momentum (turning) of the flow as it passes the airfoil. The more turning introduced, the more work added to the flow, and consequently the higher the DF value would be, again increasing the likelihood of boundary layer separation. Figure 2.9 indicates the frame of reference for the diffusion factor and angle of attack calculations made in this study.
The mass-averaging of each of the variables was performed using the following equation:

\[ W_{avg} = \frac{\sum (\rho u A W)_{i}}{\sum (\rho u A)_{i}} \]  

(2.3),

where \( \rho \) is density, \( A \) is the area associated with the given variable value, \( u \) is velocity perpendicular to the plane of the area \( A \), \( W \) is any given variable at the points of interest, and \( W_{avg} \) is the mass-averaged value for \( W \). Because Equation 2.3 requires that the velocity vector be perpendicular to the area measurement, the use of \( x \)-planes (shown in Figure 2.10) became the most convenient way to determine mass-averaged values due to the fact that axial velocity was a readily available flow variable. Also, because all the coordinates for each data point in FieldVIEW were known, it was an easy task to determine the area of each \( x \)-plane, while the velocity and other variable for each plane were taken as the arithmetic average of the four points comprising the plane. An abbreviated representation of the point distribution in FieldVIEW can be seen in Figure 2.10.
The summations shown in Equation 2.3 were taken at points with constant radial value from 50% passage pitch before and after each rotor blade. These data at these points, represented in red in Figure 2.10, were interpolated in FieldVIEW from the TURBO solution. This method is shown in Figure 2.11.
This approach resulted in the production of 19 span-wise mass-averaged values for each rotor blade, with each point representing a particular radial location.
The values for each of the variables (relative velocity magnitude, axial velocity, relative tangential velocity, density) used to produce the mass-averaged variables in Equation 2.1 were taken from 27360 (38x720) points around the annulus. These points were mapped to distribution that followed the shape of the leading and trailing edges of the blades in order to replicate the analysis performed by Hathaway\textsuperscript{13}. The radial distribution of the points, which can be seen in Figure 2.12, was as follows:

\[
R_{\text{inc}(\text{in, out})} = \frac{R_{\text{max}(\text{in, out})} - R_{\text{min}(\text{in, out})}}{20}
\]  

(2.4).

![Figure 2.12 Data Points Mapped to Leading and Trailing Edges of Rotor Blade](image)
The first point was mapped to have a grid k-value of 1 (corresponding to the blade leading edge) and a grid j value of ~4. This j value was chosen because it was far enough from the hub to have a distinct value other than 0 for the velocity (no slip boundary conditions were implemented on all solid surfaces). The next point had the same k and x values, but was incremented by the $R_{inc}$ value. These first two points form one edge of the lowest four-point plane in Figure 2.10. The third point was kept at the same radial value as the second, but had the same i and k values as the first point, attaching it to the blade leading edge. This procedure was continued from hub to tip, creating the edges of each of the planes in Figure 2.10.

This distribution of 38 points was then replicated 719 times around the annulus of 36 rotor blades, producing a grid which encompassed every rotor passage with 20 tangential segregations in each blade passage. Splitting the passages into 20 increments in both the tangential and span-wise directions was chosen for the fact that is similar to the distribution used by Hathaway\textsuperscript{(13)} and provides enough precision to produce detailed and unique distributions within each passage. It would be expected that the overall shape of the diffusion factor and angle of attack distribution would be the same if the number of radial locations were to be increased.

The x-planes mentioned previously can be seen in Figure 2.10. These four-point planes were created by replicating the leading edge point distribution in Figure 2.12 around the annulus. Each successive replication would create 19 radially distributed sets of 4 data points which each lay in the same x-plane. The mass-
averaged points were those that lay in the middle of each four-point x-plane around the annulus. This can be seen in Figure 2.13.

![Diagram of four-point x-plane used for Mass-Averaging](image)

Figure 2.13 Four-Point x-plane used for Mass-Averaging

Results of this approach are presented and discussed later in this study.

2.2.3 ANGLE OF ATTACK APPROACH

The angle of attack of the inlet flow to the blade was computed using the same data point distribution implemented for the Diffusion Factor analysis. Mass-averaged values were found in the same manner, with the angle of attack value for each point calculated as the difference between the flow angle of a given mass-averaged point and the angle of the chord of the rotor blade at the same radial location. This localized evaluation of the angle of attack accounts for the twist in the blades by measuring the angle of both the flow and the blade at each radial location. The idea behind this particular study was that the angle of attack would be a good indicator of
the blade loading and thus the susceptibility of a given blade to boundary layer separation.

2.2.4 REVERSE FLOW VOLUME CALCULATIONS

An additional pattern monitored in later cases (extended inlet cases) was the reverse flow volume. This was monitored by putting a flag into the TURBO code that summed the total volume of all cells within each block that had negative axial velocity values. The block values were then summed into both rotor-passage totals and full-annulus totals. This approach was only recently implemented and thus will not be discussed in detail for this study due to the current lack of analysis.
CHAPTER 3

OBSERVED PHENOMENA

3.1 RADIAL MIGRATION OF THE DISTURBANCE POCKETS

As mentioned earlier, when investigating the direction of the velocity vectors within the disturbance pockets, it was found that the vectors on the suction surface of the blades tended to have a positive radial component. This observation makes good sense of the fact that the motion of the disturbances on the blades was, for the most part, downstream and radially outward. Figure 3.1 shows this phenomenon through a series of four, 40 iteration time steps which track the migration of the disturbance on the suction surface of one blade.
The disturbance pocket was initially quite small (T1), expanding as it moved toward the casing. This created a concentration of low-momentum flow on the casing (T4).

This radial motion is most likely attributed to the radial, centrifugal force exerted on the fluid in the rotor due to its rotational speed. This force is present for the fluid both inside and outside of the disturbance pockets. This is seen clearly in Figure 2.8 as the vast majority of the relative velocity vectors have a strong radially outward component. Because the fluid within the disturbance pockets would have a longer residence time in the passage than the majority of the flow, the centrifugal
force would have a longer period to act upon it, forcing it to migrate to the casing. The expansion of the disturbance pockets will be explained later in the study.

3.2 **B.C. REFLECTIVITY IN SHORT-INLET CASE**

It was discovered, upon close inspection, that the shock waves from the leading edges of the rotor blades were reflecting off of the inlet far-field boundary due to the reflective boundary condition used. The implications of this are discussed later. This phenomenon can be seen in Figure 3.2 below.

![Figure 3.2 Shock Reflectivity in Short Inlet for Point “b” (Axial Velocity Iso-Surface)](image)
After discovering this, the inlet far-field was extended significantly in order to avoid any shock reflections. The decay rate of pressure waves (with length $\lambda$) within the system, $e^{-x/\lambda}$, provided a guideline for the length of the extension. Long-length modal pressure waves within the machine can have length scales on the order of the annulus ($2\pi r$). The actual extension is approximately $0.68\pi r$. This extension is clearly seen in Figure 3.3 and has been implemented in all subsequent runs. Due to the fact that this phenomenon was only recently discovered, it has not been possible to redo the cases presented in this study.

![Extended Inlet (Axial Velocity Iso-Surface)](image)

Figure 3.3 Extended Inlet (Axial Velocity Iso-Surface)

This extension was found to be sufficient for this study because additional, numerical damping was added to the upstream grid, thereby completely dissipating the pressure waves before they propagated to the inlet boundary. The numerical
damping was accomplished by greatly increasing the size of the grid cells upstream of the rotor blades. Figure 2.3 indicates that the partitioning of the injector blocks was done in such a way that the block furthest upstream was also the longest block in the axial direction. This indicates a sizable increase of the volume of the cells within this partition due to the fact that the injector block was split evenly in the i (axial) direction between the three segregations before being extended, resulting in three partitions with similar dimensions in the i-direction (18, 18, and 17 for upstream, middle, and downstream partitions of the injector, respectively).

3.3 SPILLAGE – STALL CORRELATION (AROUND LEADING EDGE)

In each of the cases that stalled, it was found that the disturbances occupied the full breadth of the passages in the vicinity of the tip when the simulation began to stall. In addition, there was a great deal of spillage of the disturbances around the leading edge of the rotor blades. Figure 3.4 and Figure 3.5 show the spillage of the disturbances around the leading edge of the blades.
Figure 3.4 Three-Dimensional View of Reverse Flow Pockets Indicating Spillage of Disturbance

Figure 3.5 Streamline View of Disturbance Spillage from Upstream of Rotor Leading Edge
Figure 3.5 shows the streamlines of the flow in the vicinity of the tip along with a j-plane iso-surface showing the negative axial velocity at the blade tip. The streamlines were seeded along the tip of the suction side of blade “a”. This view indicates that a great deal of the flow is spilling around not only the leading edge of the adjacent passage (blade “b” in Figure 3.5), but also around the leading edge of the next passage (blade “c”). This spillage is instigated by the presence of the reverse flow pockets. As the flow spills over the tip of blade “a”, it is swept upstream by the reverse flow present in the passage, which causes it to migrate forward of the leading edge of blade “b”. This increases the angle of attack of the flow in the vicinity of the blade “b” and thus creates more disturbance. As it passes the leading edge of blade “b”, the reverse flow present in this passage once again pushes the flow upstream causing it to flow around the leading edge of blade “c”. This is continued until the flow enters a passage without a reverse flow pocket (that spans the entire pitch) and is allowed to continue downstream. Some of the flow is pulled downstream in the first passage but is then reverted back upstream. This spillage allowed the disturbances in the individual blade passages to merge, which led to a slow-down of the migration of the disturbance around the annulus.

The observed slow down could be due the following chain of events. As flow in the vicinity of the tip approaches the leading edge of blade “a” in Figure 3.5, it has two possible paths: one is to spill across the face of the adjacent passage while being pushed forward by the reverse flow pocket, the other is to continue travel down the pressure side of blade “a” without impedence. As the flow on the trailing edge of the
stall cell (blade “b”) spills to the adjacent passage, it merges with the already-existing reverse flow in the passage and the stall cell increases in size both down the span and in the axial direction up and down stream. Because the disturbance pocket represents flow that is separated from the main through-flow, the blades move through it as they would stagnant flow, causing the relative motion of the disturbance to be in the opposite direction of rotation, producing a slow-down in the absolute frame.

This slow-down phenomenon was found by Weigl\(^{(1)}\) in his experiments, though he recorded that the disturbance would slow to 40% rotor speed. The data in this study indicated a slow-down to approximately 50% rotor speed. This discrepancy will be discussed later.

3.4 CORRELATION BETWEEN DIFFUSION FACTOR, ANGLE OF ATTACK, AND DISTURBANCE POCKETS

OpenOffice Calc was used to calculate equations 2.1-2.4 using data interpolated by FieldVIEW. The results in Figure 3.6 –Figure 3.12 are separated into three groups, each corresponding to an identical position relative to the injectors. The passage numbers are identified in Figure 3.12.
Figure 3.6 Angle of Attack Values (point “b”) for Blades 1, 4, 7...
Figure 3.7 Angle of Attack Values (point “b”) for Blades 2, 5, 8 ...

Figure 3.8 Angle of Attack Values (point “b”) for Blades 3, 6, 9 ...

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Figure 3.9 Diffusion Factor Values (point “b”) for Blades 1, 4, 7 ...
Figure 3.11 Diffusion Factor Values (point “b”) for Blades 3, 6, 9 ...

Figure 3.12 Blade Number References for Diffusion Factor and Angle of Attack Figures (3.6-3.11)
The correlation between the angle of attack values and the disturbance evolution images holds pretty well for this particular case. The plots for each of the passages exhibited almost identical angle of attack values from the hub to approximately 20% span. It is also clear that each passage exhibits a drastic increase in angle of attack above 90% span. The major differences between passages could be found from 20% span to the tip. The passages are grouped in the figures so that each plot contains all of the blade passages that are at the same relative position to an injector. Upon inspection of Figure 3.12, it can be seen that blades 2, 20, and 24 exhibit a great deal of disturbance along the leading edge of the blades. This is reflected in the angle of attack values produced by the Calc analysis. It appears that if the angle of attack between mid-span and 90% span attains a value greater than approximately 13 degrees then leading edge separation will occur.

Correlation of the diffusion factor results with the presence of disturbances proved considerably more difficult than the angle of attack analysis. When looking at individual passages, there does not seem to be any significant correlation. The one useful characteristic that the diffusion factor distribution for the vast majority of blade rows provides is the indication of an increase in magnitude in the vicinity of the mid span. This lends evidence to the fact that the disturbances are generally formed in the mid span before migrating to the tip region. When looking at the average across the entire annulus, however, the diffusion factor analysis performed in this work is consistent with that performed by Hathaway\cite{hathaway}. This is as expected, considering Hathaway used the APNASA code, which is a steady-state solver that solves a
representative “annulus averaged” passage for each blade row. Unsteady fluctuations (i.e., deterministic and random (turbulent) fluctuations) are accounted for via their respective annulus averaged unsteady “stress” terms. TURBO is a time accurate solver that, for this case, solves the Unsteady Reynolds Averaged Navier-Stokes equations for the time dependent (relative motion of rotor and stator) solution of all passages of every blade row around the entire annulus. From analysis of the APNASA simulations results of the isolated NASA Rotor 35, Hathaway concluded that stall would occur when the diffusion factor value in the tip region reached 0.75. This was not intended to serve as a definitive, all-encompassing indicator of the inevitability of stall, but was instead the best estimate of the indicated stall threshold for the particular case being analyzed \(^{13, 14}\).

Figure 3.13 indicates that the stable cases for the TURBO simulations of the NASA Stage 35 compressor, (b) and (c) from Figure 2.4, had diffusion factor values which were lower in the tip region than that of the unstable, (a) case. The peak values for the unstable case, however, remained below 0.75. This discrepancy from the results presented by Hathaway may be explained by differences in the CFD modeling (unsteady TURBO simulation of NASA Stage 35 versus steady-state APNASA simulations of NASA Rotor 35) and post-processing procedures\(^ {14}\). Having considered these factors, the results of this study conclude that a diffusion factor value somewhere between .68 and .73 would indicate the appearance of rotating stall for the analysis of the NASA Stage 35 Compressor presented in this study.
The angle of attack measurements were also studied in an annulus-averaging fashion. The results of this study indicate that there is an increase in the overall angle of attack measurements as the corrected exit mass flow is reduced. Through analysis of Figure 3.14, it can be seen that the unstable, (a) case (from the speedline) has higher values for the angle of attack across almost the entire span. This phenomenon is present due to the fact that as the compressor is throttled down on a given speedline (constant rotor tangential velocity), the axial velocity of the incoming flow is reduced, which increases the angle of attack of the incoming flow with respect to the rotor.

Figure 3.13 Annulus-Averaged Diffusion Factor Distributions for Three Cases
blades.

The data in Figure 3.14 would lend itself to the speculation that either an annulus-averaged angle of attack value greater than 9 degrees from mid span to 90% span or an angle of attack value greater than 14 degrees at the tip or both would indicate the inevitability of stall. The mid-span, 9 degrees indicator would assume that the production of disturbance flow which is prevalent in the mid-span is the primary driver of rotating stall. The primary reason for an overall increase of angle of attack values in the tip region, besides the existence of reverse flow pockets, is that the boundary layer flow on the casing creates an axial velocity deficit in the tip region, thereby reducing the axial component of the relative flow angle – increasing the angle of attack.

This increase in angle of attack also helps explain the expansion of the disturbance pockets as they migrate toward the tip – higher angle of attack moves the boundary layer separation point on the suction surface forward, increasing the magnitude of the disturbance pocket that is already present by creating more separated/swirling flow.
Figure 3.14 Annulus-Averaged Angle of Attack Distribution for Three Cases

Additional angle of attack and diffusion factor analyses can be found in Appendix B.
CHAPTER 4

CASE ANALYSES

4.1 STABLE CASE (POINT “b”)

A number of different cases were run for the study, some of which stalled, and some of which were stable (as indicated on the speedline in Figure 2.4). Point “b” on the speedline was chosen as a stable case due to the fact that it has run for 27 revolutions without stall. A number of characteristics were gleaned from this stable case that have shown to hold true for other cases as well.

First, the migration of the disturbances mentioned earlier lends a great deal of insight into the functioning of the tip injection cases. As the low momentum flow migrates to and congregates in the tip region of the blade passages, the tip injectors provide high-axial-momentum flow which alleviates the momentum deficit. This phenomenon is easily observed in the movie file created for point “b”. A few snapshots are given in Figure 4.1 below, each representing the passing of 80 time step iterations.
The tip injectors are represented by the blue and green streaks present in the tip region in Figure 4.1. As blade “a” in the figure passes through the injector, the stall cell at mid-span is almost completely washed away, as can be seen by the difference between T3 and T4. The disturbance on blade “b”, however, does not get washed away after passage through only one injector. Its growth can be seen after it passes through one injector from T1 to T2. It then grows from T2 to T3 and is then reduced somewhat as it enters the next injector at T4. Some larger (by volume) disturbances, as seen on blade “b” could pass through multiple injectors before being washed away.
A collection of full-annulus views can be found in Appendix C which outline the creation/destruction of disturbances as they move around the annulus. The washing-away of the disturbance is accomplished by the addition of high-energy flow into the tip region. This injection of high-energy flow contributes axial momentum to the tip region, thereby reducing the amount of fluid within the disturbances (increasing the axial momentum of the flow within the disturbances). More will be mentioned on this topic when discussing the unstable case.

A second characteristic, which correlates with the first, is the rise and fall of disturbances which travel at full rotor speed. This behavior is shown by the time variation of eight numerical entropy probes located upstream of the rotor blades. Chen et al used this approach in previous works\(^3\),\(^4\). The probes are located 44% chord upstream of the rotor leading edge at 98% span. The circumferential locations are 10, 70, 100, 160, 190, 250, 280, and 340 degrees. Figure 4.2 shows the recordings of these probes and the indicated rise and fall of the disturbances.
One such rise and fall is indicated by the redline (the second segment of the line is extended in order to show the speed of the disturbance). This particular disturbance migrates at rotor speed and lasts for approximately one revolution. It should be noted that this case was run with the short inlet, which led to a great deal of disturbance inception due to the reflection of the pressure waves from the leading edge shocks off of the inlet far-field. Upon close inspection, the far field reflections in Figure 3.2 connect the major disturbances. In other words, as one disturbance creates a stronger shock and associated pressure wave, this pressure wave is reflected off of the far field and creates another disturbance upon its return to the blade row.
Though this causes concern when analyzing the formation of disturbances, the effect of the tip injectors in their eradication of existing disturbances remains the same.

4.2 UNSTABLE CASE (POINT “a”)

Point “a” from Figure 2.4 was chosen as the unstable case for this study. This case ran for just under 14 revolutions before stalling. As with the stable case, disturbance pockets were formed in the midspan of the rotor blades which then migrated to the tip region of the rotor. Unlike the stable case, the disturbances in this case do not get washed away by the tip injectors. Instead, they continue to propagate for approximately 5 revolutions. Figure 4.3 uses the same probes previously mentioned for Figure 4.2, only this time the measurement taken is normalized static pressure instead of entropy.
The data from ~1.8 - ~3 revolutions was lost due to corruption of the file, making it difficult to determine the point of origin of the mapped disturbance in Figure 4.3. Normalized pressure is used here to indicate the disturbances because entropy had not yet been introduced as a probed variable in this case (case “a” was conducted before most of case “b”). It is clear that the major disturbance mapped by the red line travels at 100% rotor speed. A more dramatic disturbance is initiated during the ninth revolution and is mapped by the green line. This disturbance travels at approximately 50% rotor speed. This slow down is similar to the experimental results found by Weigl\(^6\) and is consistent with the characteristics described by
Cumpsty\textsuperscript{(15)}. Weigl found that the disturbances, when first formed, travel at 100% rotor speed. As the machine approaches stall, however, the measured disturbances exhibit a significant slow-down to approximately 40% rotor speed. Cumpsty states that part-span cells, as those seen in “a” (see Appendix C), travel close to 50% rotor speed around the annulus, whereas full-span cells travel at 20-40% rotor speed. Part-span cells are defined as those that occupy only a small portion of the compressor, often a single blade row\textsuperscript{(15)}.

The main reason for the discrepancy between the slow-down found in this study and the slow-down exhibited in Weigl’s experiment is that the computational model used in this study does not incorporate the upstream and downstream volumes of the experiment which can be seen in Figure 2.1. The volume effects associated with the upstream geometry add modal instabilities to the compressor that are not present in the computational analysis presented here. Thus, because the overriding, 40% rotor speed disturbance recorded by Weigl is associated with modal instability, the comparison between his work and that done in this study may not be appropriate at this level. The discrepancy could also be due to the fact that the analyses used to determine these speeds were very different. Weigl performed an FFT analysis on the pressure probe data recorded in his experiment (using the same probe locations used in this study) and determined the speed of the dominant disturbance wave to be 40% rotor speed. In this study, the entire disturbance wave was analyzed by viewing the overall data in Figure 4.3. This data represents the sum of all component waves of the disturbance, not only the most dominant. Also, the disturbance slow-down is a
dynamic process, while the analysis presented in this study approximates the speed of the stall cell using only straight line approximations from Figure 4.3.

The slow down of the disturbance seems to be directly related to the point at which it begins to occupy the entire breadth of a particular rotor passage. Upon this occurrence, the disturbance propagates upstream beyond the leading edge of the rotors. This allows it to migrate to the adjacent, following passage, merging with any existing disturbance already present. This process is continued until the volumetric magnitude of the disturbance grows to such a size that the compressor can no longer support the required mass flow.
CHAPTER 5

CONCLUSIONS

5.1 NEW METHODS OF ANALYSIS

Perhaps the most significant achievement accomplished was the implementation of new analysis methods for studying the flow structure of the Stage 35 compressor. The three-dimensional disturbance pocket approach proved very useful in furthering the understanding of the nature of the disturbances within the compressor. This analysis could be easily applied to any CFD application with the use of a 3-D post-processor.

The diffusion factor and angle of attack analyses could be adapted to any turbomachinery application, though a bit more work would be required in order to adapt the Calc spreadsheet and FieldVIEW data points to a new geometry. Both of these methods provided insight into the characteristics of the flow through the Stage 35 compressor. They were also valuable in that they provided quantifiable measures that could be associated with the flow, making the task of determining numerical stall indicators a bit more attainable.
5.2 OBSERVED BEHAVIOR OF DISTURBANCE POCKETS

The data in this study indicated that the disturbance pockets are first developed in the mid-span region of the rotor suction surfaces, which is most likely due to the increased diffusion factor value for this region. After inception, the cells migrate toward the tip region while moving downstream. As they migrate, the volume of the cells increases due to the increased angle of attack in the tip region. In the stable (sufficient injection) case, the cells would be washed away by the injectors. Some disturbances were cleaned up after passing through only one injector while others passed through multiple injectors before being washed away.

In the unstable (insufficient injection) case, the migration of the disturbances to the tip region caused a buildup of reverse flow to the point that the entire tangential breadth of the passage would be covered in the tip region. When this occurred, the disturbance would begin to spill around the leading edge of the following rotor blade and into the adjacent passage. This would increase the overall size of the cell in both the span-wise and axial directions. The cell would then continue this migration around the annulus, absorbing the disturbance pockets as it traveled. This migration was reflected in a slow-down of the disturbance in the absolute frame.

5.3 DIFFUSION FACTOR AND ANGLE OF ATTACK AS INDICATORS OF STALL

One of the primary goals of this study was to determine a quantitative measure that could be used to determine the susceptibility of given compressor to rotating
stall. Though this task was not accomplished in a definitive manner, the diffusion factor and angle of attack studies did produce valuable indicators of the potential for stall. It was found that if the diffusion factor attained a value between .68 and .73 in the tip region that this would indicate that it is either close to or at the stalling throttle. In addition, an annulus-averaged study of the angle of attack values for the rotor blades indicates that one or both of two parameters may indicate the inevitability of rotating stall: an angle of attack value greater than 9 degrees from mid span to 90% span and/or an angle of attack value greater than 13 degrees at the tip.
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