DESIGN AND STRUCTURAL ANALYSIS OF A DUAL COMPRESSION ROTOR

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DESIGN AND STRUCTURAL ANALYSIS OF A DUAL COMPRESSION ROTOR

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ABSTRACT

DESIGN AND STRUCTURAL ANALYSIS OF A DUAL COMPRESSION ROTOR

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The Dual Compression Rotor (DCR) is a turbine engine component technology which enables the novel turbine engine concept titled the Revolutionary Innovative Turbine Engine (RITE). The DCR and RITE concept is an attempt to provide significant improvements over the traditional turbine engine design. The RITE concept, along with the DCR, represents a paradigm shift over the traditional turbine engine design. The design of the DCR features two compressor stages, one forward flow and one reversed flow, along with an outer turbine stage on a single rotor. The RITE concept offers the potential to decrease specific fuel consumption over the current state of the art, while maintaining thrust and decreasing turbine inlet temperature. The RITE concept will eliminate the need for cooling and improve performance during operation away from the design point. The DCR decreases engine axial length requirements, reducing weight, and features available turbine cooling flow inboard on the rotor. This thesis focuses on the development of a small scale demonstration of the DCR concept. An iterative design process was
performed on the DCR until an aerodynamic design of the compressor and turbine stages aligned with the structural performance of available materials. Finite element analysis was performed on the DCR geometry for each iteration. Following the establishment of a preliminary design, additional design work was performed on static structures, dynamic face seals, bearings, and test fixtures. Lead time for the fabrication of the DCR and static structures prohibited the inclusion of experimental results; however, suggested testing procedures and conclusions based on the design being fabricated are included.
ACKNOWLEDGEMENTS

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<th>Description</th>
</tr>
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<tbody>
<tr>
<td>DCR</td>
<td>Dual Compression Rotor</td>
</tr>
<tr>
<td>F/FR</td>
<td>Fractional Thrust</td>
</tr>
<tr>
<td>PR</td>
<td>Pressure Ratio</td>
</tr>
<tr>
<td>RITE</td>
<td>Revolutionary Innovative Turbine Engine</td>
</tr>
<tr>
<td>S</td>
<td>Fuel Consumption</td>
</tr>
<tr>
<td>SFC</td>
<td>Specific Fuel Consumption</td>
</tr>
<tr>
<td>STOVL</td>
<td>Short Takeoff and Vertical Landing</td>
</tr>
<tr>
<td>VTOL</td>
<td>Vertical Takeoff and Landing</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Specific Heat Ratio</td>
</tr>
<tr>
<td>$\eta_T$</td>
<td>Thermal Efficiency</td>
</tr>
<tr>
<td>$\eta_O$</td>
<td>Overall Efficiency</td>
</tr>
<tr>
<td>$\eta_P$</td>
<td>Propulsive Efficiency</td>
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CHAPTER I
INTRODUCTION

Continuing demands to cut life cycle costs and increase the performance of aircraft drive the need for the constant improvement over existing propulsion technology. Currently most aircraft utilize air-breathing propulsion systems, so improvements to this technology are of interest. General goals for the improvement of air breathing propulsion are increased overall efficiency, larger power output, larger power-to-engine weight, volume, and frontal area, greater service life, reduction of adverse environmental exhaust gas, and, reduced noise [1]. Current technology has been refined to the point that major improvements in efficiency and performance using traditional methods are difficult. Therefore new and innovative ideas must be investigated to significantly advance the technology. The research discussed in this thesis focuses on investigation into a novel turbine engine component, and corresponding cycle, which enables a new and unique operation of the traditional gas turbine engine.

Conventional Gas Turbine Engines

Over time the gas turbine engine has emerged as the propulsion standard for all but small recreational vehicles. The gas turbine is desirable in aircraft propulsion for its high power output and power-to-weight ratio, as well as its ability
to achieve high overall efficiencies at a variety of flight speeds. Depending upon the desired flight speed, different configurations of the gas turbine are utilized to provide a high propulsive efficiency. The propulsive efficiency of an exhaust jet is a function of the flight speed relative to the exhaust speed. At low flight speeds, the gas turbine is typically operated as a turboprop, where a gas turbine produces shaft power to spin a propeller and slow exhaust speeds are produced. At higher transonic speeds turbofans are used, where a large portion of the air ingested bypasses the core of the engine. Turbofans provide thrust at lower speeds than the core air but faster than propellers. Finally, to propel an aircraft at supersonic flight speeds, the traditional turbojet is employed which exhibits high exhaust velocities.

The gas turbine engine consists of three main components: a compressor, a turbine, and a combustor. The simplest configuration for aircraft propulsion is the single-shaft turbojet, shown in Figure 1. The basic single-shaft turbojet operates by ingesting atmospheric air into the compressor and compressing it according to the engine’s designed pressure ratio. After the compressor, heat is added in the combustor through the combustion of an air/fuel mixture. The hot, high pressure air is expanded through the turbine and work is extracted. For the single-shaft turbojet just enough work is extracted from the fluid to drive the compressor. The flow then travels through a nozzle, accelerating the air, and utilizing the remainder of the work as thrust. In a standard single-shaft turbojet, such as shown in Figure 1, the compressor and turbine are connected via a fixed shaft and must operate at the same rotational speed.
Figure 1: Single-Shaft Turbojet Block Diagram [2].

Thermodynamically, gas turbine engines can be considered to operate based on the Brayton cycle. The ideal Brayton cycle consists of the isentropic compression of air, heat addition, and isentropic expansion of air through a turbine until the pressure returns close to the original atmospheric pressure. The increase in the pressure of the air as it passes through the compressor is typically referred to as the pressure ratio, PR, of the cycle. The equation for the Brayton cycle thermal efficiency, $\eta_{th}$, is given as:

$$\eta_{th} = 1 - \left[ PR \right]^{\frac{1}{\gamma}}$$  \hspace{1cm} (1)

where $\gamma$ is the specific heat ratio. As shown in Equation 1, the thermal efficiency for the ideal Brayton cycle at a given specific heat ratio is dependent upon only the amount the pressure is increased through the isentropic compression of air in the cycle.

Figure 2 shows the thermal efficiency of an ideal Brayton cycle plotted versus PR for two different specific heat ratios. These plots are defined by the equation for the efficiency of the ideal Brayton cycle and are a function of PR and $\gamma$ only. It is obvious from the figure that a higher PR leads to a higher thermal efficiency. One of
the largest contributions to the overall efficiency of the turbojet is the cycle or thermal efficiency.

![Ideal Brayton Cycle Thermal Efficiency](image)

**Figure 2: Ideal Brayton Cycle Thermal Efficiency [1].**

To create higher PRs required for increased thermal efficiency, the compressor requires more power from the turbine. Therefore, to maintain desired engine power while increasing the PR, the engine's firing temperature must increase. The firing temperature is the temperature of the flow reached through combustion and is also called the turbine inlet temperature. For high performance and efficiency, extremely high turbine inlet temperatures are desirable. However, this temperature is typically limited by the melting point of the turbine blade materials. Current turbosjets incorporate elaborate air cooling techniques and
thermal barrier coatings enabling extremely high turbine inlet gas temperatures which in some cases, can even exceed material melting points [3].

The conventional turbojet or turbofan is typically designed for optimum performance at a single design point. Operation outside of this design point at off-design conditions (part throttle or part maximum thrust) can result in a decrease in overall efficiency or increase in fuel consumption. Overall efficiency, $\eta_o$, is a composition of all the other engine efficiencies; the individual component efficiencies, propulsive efficiencies, $\eta_p$, thermodynamic cycle efficiency, and many others. Some of these individual efficiencies have a less pronounced effect on the overall engine efficiency than others. Figure 3 shows thermal efficiency, propulsive efficiency, overall efficiency, and fuel consumption, $S$, as a function of fractional thrust, $F/F_R$. As shown in the figure, the overall efficiency is at a maximum and fuel consumption at a minimum for a fractional thrust around 0.35. The overall efficiency decreases and fuel consumption increases when the engine is operated at fractional thrusts significantly away from this value. If the thermal efficiency can be improved at this value of fractional thrust, then a large reduction in fuel consumption can be achieved.
In summary, the conventional turbojet configuration imposes a number of limitations towards the goal of increased engine performance and efficiency. Increasing cycle efficiency by increasing pressure ratio, results in increased engine complexity as additional compressor rows are needed. The increased pressure ratio drives up turbine inlet temperatures in order to maintain the engine’s desired power output. The higher temperatures require better cooling techniques and increased cooling flows from other parts of the engine. This further increases engine complexity and cost, and can reduce performance. Also, maintaining high efficiency during off design conditions in the conventional configuration is difficult. Once designed, control of the engine away from the design point is typically limited to combustor fuel flow and nozzle area.

**Unique Gas Turbine Rotor Designs**

To reduce the complexity and cost of turbojet engines, while maintaining efficiency and power, a variety of unique engine configurations have been proposed.
These configurations work to address the current turbine engine’s limitations, while at the same time consolidating the engine to reduce size, weight, and complexity. The configurations detailed in the following paragraphs focus on incorporating the compressor and turbine stages on a single rotor. Although a number of these configurations have been proposed, three specific variations will be discussed.

The first of these is the “Nested Core Gas Turbine Engine,” U.S. Patent No. 6988357. As shown in Figure 4, this design describes a turbojet engine where the compressor and turbine are contained on the same rotor. A combustor section is included in the center of the rotor. A turbine section surrounds the combustor section, with a compressor section radially outboard of the turbine section. The nested core engine rotor was proposed as a potential solution to alleviate problems associated with the use of gas turbines on a small scale. With its nested configuration, the design provides reduced engine size and weight compared to traditional configurations [4].

![Nested Core Engine Rotor](image)

**Figure 4: Nested Core Engine Rotor [4].**

A second configuration, similar to the previous, is the “Engine with Compressor and Turbine Passage in a Single Rotor Element,” U.S. Patent No.
This turbine engine design utilizes a rotor element consisting of an axial compressor stage and a radial turbine stage. Similar to the nested core engine, the goal of this design was to reduce axial length and engine weight. This configuration, however, also focused on providing cooling to the turbine stage using the compressor air, enabling higher turbine inlet temperatures without increased complexity from cooling flows. The goal of the reduced axial length of this design was to enable, at relatively low cost, significant improvements for short take off and vertical landing (STOVL), vertical takeoff and landing (VTOL), and conventional aircraft.

The third example is the “Single Rotor Turbine,” U.S. Patent No. 6807802, as shown in Figure 5. This turbine engine configuration utilizes a rotor element featuring a centrifugal compressor and axial turbine. As shown in the figure, the centrifugal compressor exits through the axial turbine blades providing cooling. Like the previous design, this enables higher turbine temperatures without the need for complex cooling circuits. This reduces engine size and enables turbine cooling on a small scale.
Although these concepts differ in their desired applications, as well as in the details of their design, all three accomplish improvements over the conventional gas turbine in a similar way. For this reason, all three have similar drawbacks. The three designs strive to reconfigure the conventional gas turbine to achieve significant gains in various aspects of performance. The designs accomplish this through the use of a single rotor element with two stages to provide equal or better engine performance, while greatly reducing length and weight. Collapsing compressor and turbine stages onto a single rotor allows for cooler temperatures without additional components or complexity. However, the changes these concepts make compared to the conventional gas turbine focus on the configuration of the flow path and therefore, their benefits are limited to improvement in engine size and weight. To make significant gains in performance, even more radical changes to the conventional gas turbine should be investigated. These should include changes not only to flow path geometry, but also to the way the cycle operates.
The RITE Cycle and DCR Concept

To continue increasing gas turbine performance and efficiency, the viability of unique and radically different engine configurations should be investigated. The Revolutionary Innovative Turbine Engine (RITE) cycle is one of these unique configurations. Figure 6 shows a possible configuration for the RITE cycle with the potential to significantly reduce axial length. Additional details on the RITE cycle are given below.

Figure 6: RITE Cycle Conceptual Assembly [6].

The RITE cycle is based around a component termed the Dual Compression Rotor (DCR). Similar to the previously discussed unique engine concepts, the DCR reduces engine size and weight by implementing compressor and turbine stages on a single rotor. However, the DCR features not one, but two, axial compressor stages on a single rotor. The single rotor includes one forward flow compressor, one reversed flow compressor, and a tip turbine. Figure 7 shows an example of one potential DCR concept.
The RITE cycle is made up of a single or multiple DCR elements coupled to a centrifugal compressor. Each turbine stage also has its own combustor. The diagram in Figure 8 is a basic configuration of the RITE cycle incorporating a single DCR. The airflow (1) enters through the first stage on the DCR in the forward direction (2). The flow is turned 90 degrees in a centrifugal compressor (3) and a turning duct (4) turns the flow an additional 90 degrees to the reversed flow direction. The flow then passes through the reversed flow compressor stage on the DCR (5). The flow next enters a combustor (6) which heats and reverses the flow. Now once again in the forward direction, the flow travels through the tip turbine of the DCR (7). Finally, the flow travels through a second combustor (8) and a turbine (9) to power the centrifugal compressor. The RITE cycle can be operated in this basic configuration, which is similar to a conventional turbojet, with the additional of a nozzle at the end of the cycle.
DCR elements enable reduced engine length while segmented combustor sections allow for increased engine control and decreased firing temperatures. Separate control of each of the independently supported rotors allows for optimizing performance for current flight conditions [6] and segmented combustors reduce peak engine temperatures. Heat can be added to power a set of compressor stages individually, rather than all at once in a conventional cycle with a single combustor. The DCR enables turbine blade cooling from inboard stages, eliminating the need for supplementary and complex cooling flows [6]. Turbine blade cooling flows can be easily added by the addition of passages between the reversed flow compression stage and the turbine. The DCR turbine bores are naturally cooled with compressor air, reducing thermal expansion and enabling reduced blade tip clearances [6]. With each DCR independent of one another and turbines on board, the need for long shafts are eliminated [6].
The DCR and RITE cycle can be configured to fit a number of different propulsion applications, similar to the conventional gas turbine. For a high speed application, similar to the turbojet discussed above, the RITE cycle would consist of one or multiple DCRs with a nozzle for thrust. Lower speed applications could include the standard RITE cycle, similar to that shown in Figure 10 but with the addition of a power turbine and corresponding combustor to drive a fan stage or propeller, depending upon the flight speed. This configuration is particularly appealing due to the RITE cycle’s high degree of engine control. At cruise conditions and other reduced power outputs, the RITE cycle core could still operate close to the design point. This would enable higher engine PRs at lower power requirements, increasing cycle efficiency. Engine core part lives may also be increased, as the core could run at a constant speed throughout the mission [6]. For STOVL/VTOL aircraft, the RITE cycle can improve vertical lift fan technology, as the reduction in axial length provided by the DCR could enable a low profile lift fan to fit in the fuselage of an aircraft [6].

Compared to the previously proposed multistage rotor concepts, the DCR and RITE cycle adds additional stages of compression, multiple combustion stages, and the capabilities for a diverse set of applications. Similar to the Heinkel HeS 3, the first jet engine to power an aircraft, the DCR and RITE cycle take advantage of the flow turning from the centrifugal compressor and reverse flow combustor to incorporate a number of stages of compression in a short axial space. The segmented combustors are unique to the concept and enable increased applicability.
For these reasons, further investigation into the design of the DCR and RITE cycle concept is desirable.

**The RITE Demonstration**

To demonstrate proof of concept, a plan for a low cost demonstration of the RITE cycle and DCR has been developed. The goal of this demonstration is to show a performance increase over an existing small scale turbojet, when the RITE cycle is incorporated. The planned demonstration will duct a DCR together with a JetCat P200 hobbyist turbojet, as shown in Figure 9. Figure 10 shows a schematic of the airflow through the JetCat coupled with the DCR. The centrifugal compressor, combustor, and turbine from the JetCat will take the place of (3), (8), and (9) in Figure 8.

![JetCat P200 Hobbyist Turbojet](image)

*Figure 9: JetCat P200 Hobbyist Turbojet [7].*
Figure 10: Airflow Schematic Of The JetCat Engine Coupled With The DCR.

The JetCat P200 turbojet is a small hobbyist turbojet which is roughly 6.0 inches in diameter with a mass flow rate of 1.0 lbm/sec. The JetCat features a centrifugal compressor and provides a PR of approximately 4.0. The engine has a maximum thrust of approximately 49 lbf. Table 1 shows the JetCat P200’s listed performance compared to a thermodynamic model created to match the turbojet. The model is a decent representation; however, some of the assumptions result in a lower estimated SFC. The table also lists the results of a thermodynamic analysis with the RITE cycle coupled to the JetCat. For equivalent engine temperatures and a DCR PR of 2.0, the SFC is reduced by 22% and thrust is increased by 45%.
Demonstrating the DCR on a small scale enables its complex geometry to be fabricated easily and cheaply through the direct metal laser sintering (DMLS) process. However, the complexity of testing a DCR at this scale drove the need to first develop a component demonstration testing the DCR individually. The remainder of this paper focuses on the design and analysis of a DCR component suitable for this initial demonstration. To accurately test the DCR component, three independent sets of supply air will be used to match conditions as if incorporated onto the JetCat. This allows for the initial testing of the DCR component in a controlled manner and at reduced temperatures, particularly in the turbine stage. Since the ultimate goal is to demonstrate the DCR component’s operation within the RITE cycle, when possible, design choices will be made with consideration to the final design coupled to the JetCat P200. Modifications of the design, which enable a component test but stray from what the RITE cycle demonstration would ultimately require, are noted as future design challenges.

Table 1: Thermodynamic Model Estimates for the RITE Demonstration.

<table>
<thead>
<tr>
<th></th>
<th>JetCat P200</th>
<th>JetCat P200 Model</th>
<th>RITE JetCat P200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Ratio</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Max Temp (F)</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
</tr>
<tr>
<td>Max EGT (F)</td>
<td>1382</td>
<td>1358</td>
<td>1186</td>
</tr>
<tr>
<td>TSFC (lb/lb/hr)</td>
<td>1.54</td>
<td>1.45</td>
<td>1.13 (-22%)</td>
</tr>
<tr>
<td>Airflow (lb/sec)</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Thrust (lbf)</td>
<td>49</td>
<td>49</td>
<td>71 (+45%)</td>
</tr>
</tbody>
</table>
CHAPTER II

STRUCTURAL DESIGN AND ANALYSIS

The major obstacle to successful demonstration of the RITE cycle is insuring adequate structural performance of the DCR. Typical turbomachinery rotors consist of a single set of blades at the tip of a solid disk. In standard applications, these compressor or turbine blades must only support their own mass under centrifugal and other loading. However, this is not the case with the DCR as the forward flow compressor blades, for example, must support the reversed flow compressor blades, turbine blades, and the shrouds between the blades. Blade thicknesses are kept small to reduce drag, but, as a result, there is a very limited amount of material area available to carry loads. Therefore, establishing a structurally feasible DCR configuration using traditional compressor design techniques presents unique challenges and requires analyses to be performed to verify the structural response. A number of design iterations, and corresponding structural analyses, have been performed to address the complexity of the DCR geometry and the potential for poor structural performance.
**Structural Design and Analysis Procedures**

As noted above, establishing an acceptable structural design of the DCR presents many challenges. This section discusses the structural design and analysis procedures used to evaluate candidate DCR designs. The first part of this section discusses the creation of solid models of the DCR geometry extracted from given flow path designs. Next, the material properties utilized for analyzing candidate designs are discussed. The last part of this section presents a brief overview of the loads and boundary conditions used to assess the structural performance.

**Solid Geometry**

Structural design of the DCR begins with specifying the desired flow path design. Engineers at the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (WPAFB) provided designs for the compressor flow path [8] and turbine flow path [9]. These flow paths were designed using a meanline flow analysis method. To mate with the JetCat, as shown previously in Figure 10, the mass flow rate and inlet conditions of each stage were matched accordingly. The designed mass flow rate matched the JetCat flow rate of 1 lbm/sec. The forward flow compressor was designed for ambient conditions with the reversed flow compressor designed to receive air leaving the JetCat centrifugal compressor, as illustrated in Figure 10. The turbine was designed following the compressor, to match DCR compressor power requirements and combustor outlet conditions.

The major factor affecting the structural performance of candidate DCR designs is the high rotational speed specified by the aerodynamic design of the
compressor. When the rotational speed is reduced, the compressor blade tip speeds are reduced, and the lower tip speeds reduce stage pressure ratios. Therefore, in order to maintain the desired pressure ratio with lower blade tip speeds, higher work coefficients are needed. Increasing work coefficients leads to higher drag and reduced stage efficiency. As discussed later in the design iterations section, a third compression stage was later added to help maintain the pressure ratio and efficiency at lower rotational speeds.

SolidWorks was utilized to create the solid geometry representations of the DCR. The discrete set of points representing a single blade was imported into SolidWorks, and used to form sets of curves. These blade profiles, such as those for the forward flow compressor blade as shown in Figure 11, were then used to create a solid representation of each blade. This process was repeated for a single blade on each stage of the DCR. Each of the single blades was then patterned about the central axis to create the number of blades specified by their aerodynamic design. A shroud was created between each set of blades by revolving the provided flow path profile about the central axis, creating a solid from the set of surfaces this formed. The axial length of each shroud was selected to reduce weight but to allow for complete fillet formation between the blades and shroud. The typical fillet size used for these blades was 0.02 inches. However, since the blades and flow paths were represented by discrete sets of points, fillets occasionally failed to generate between the blades and shrouds. When this occurred for different design iterations, the problem was alleviated by varying the fillet size between 0.01 inches and 0.04 inches until a fillet could be created. The stage axial location was chosen to optimize
structural performance. Stages were adjusted forward and aft until stresses were balanced between blade leading and trailing edges.

![Blade Curves](image)

**Figure 11: Forward Flow Compressor Rotor Blade Curves In SolidWorks.**

**Material Selection and Data**

The direct metal laser sintering (DMLS) process was chosen to enable the fabrication of the small and complex geometry of the DCR. However, this process greatly reduced the number of available materials. Inconel 625 (IN625), a high-temperature nickel alloy, was selected for use during the preliminary iterations of the design. The RITE cycle demonstration requires a material capable of operating at turbine temperatures while still maintaining adequate strength. The IN625 material was chosen based on its ability to retain strength at high temperatures. Manufacturers claim that the DMLS materials have properties which are very similar to those of wrought metals. Mechanical property data for DMLS is still mostly proprietary, so properties for wrought IN625 from MIL-HDBK-5J were used as an initial estimate [10].
As mentioned, initial analyses were performed using IN625 material properties. These DCR designs far exceeded allowable stresses for all existing metals. As the design of the DCR was refined, so were the material options. Another high-temperature nickel alloy, Inconel 718 (IN718), was chosen as the final material since it has increased strength compared to IN625. Additional details relating to the selection of IN718 are discussed later in the chapter.

Material property data for wrought IN625 and IN718 was used to develop values for the DCR finite element analyses. The material properties for each analysis consisted of material property data at four different temperatures; 70°F, 500°F, 1000°F, and 1600°F. Linear interpolation was automatically performed by Abaqus for temperatures between data points. Isotropic material properties were assumed. However, the use of isotropic material properties for a DMLS material may cause inaccuracy in the model. It is anticipated that variations in mechanical properties may exist due to the build direction utilized during the DMLS process. Any anisotropy present cannot be quantified without mechanical testing; however, it is anticipated that post processing of the part after the laser sintering process will remove any significant anisotropy.

A simple elastic analysis requires data for the modulus of elasticity, Poisson’s ratio, and density of the material. The addition of thermal expansion effects required values for the thermal expansion coefficient. Material properties for IN625 and IN718 were taken directly from MIL-HDBK-5J. Elastic-plastic analyses were performed using a bi-linear stress strain curve which was derived from data in MIL-HDBK-5J. An example of this curve for IN625 at room temperature can be seen in
Figure 12. Due to the limited data provided in MIL-HDBK-5J the bi-linear curves were constructed based on the data provided. The yield strain was estimated based on the material’s modulus of elasticity and published yield stress. Similarly, another point in the bi-linear stress strain curve was estimated by assuming the materials ultimate stress and percent elongation occur at the same point on the strain-strain diagram.

![Bi-Linear Stress Strain Curve](image)

**Figure 12: Inconel 625 Bilinear Stress Strain Curve.**

**Finite Element Analysis**

Structural analyses were performed using the Abaqus/CAE software package. Static elastic and elastic-plastic analyses incorporating a variety of loading conditions were performed. The goal of each analysis was to determine the relative feasibility of the DCR under anticipated loading. Refinement of the structural
analysis was not a primary focus as only rough approximations for the structural response of the DCR were desired.

**Geometry and Mesh**

SolidWorks solid geometry files were exported to the ACIS (.sat) file format, to be used in Abaqus. The ACIS file type provided the best compatibility between these two programs. The DCR geometry was meshed using linear tetrahedral elements in Abaqus (C3D4 elements). The tetrahedral elements were used because of their ability to mesh the DCR's complex geometry. The use of linear elements reduced computational load and enabled quick results.

Generally, the DCR models included between two and four million elements. The variation in mesh size was a result of problems incurred during mesh generation. The fillet creation issues within SolidWorks sometimes resulted in small edge features which caused difficulties when meshing the geometry. This was alleviated by varying mesh resolution until a successful mesh was formed. As Figure 13 illustrates, the mesh resolution of the small features on the DCR was extremely coarse and may yield results with poor accuracy at these locations. However, since the goal of the FEA results was to determine the feasibility of the DCR, this rough accuracy was considered sufficient.
In later designs, sub-modeling was used to improve the mesh resolution at locations of interest. Typically these sub-models consisted of a small group of one to three blades. Since the sub-models consisted of a similar total number of elements, three to four million, but on a smaller section of the geometry, small features can be better represented without increasing computational demands. The sub-model shown in Figure 14 better captures the fillets than the coarse mesh of the global model. Although the sub-model resolution is better, error from the discretization of the geometry still exists and has not been quantified as a mesh convergence study was not performed. Linear tetrahedral elements also have been utilized to reduce computational demands, but likely introduce additional numerical error compared to quadratic elements. The numerical and geometric sources of error, in addition to the approximations used for the material properties, were considered allowable.
since the goal of this investigation again was only to provide an approximation for the DCR structural response.

![Forward Flow Compressor Sub-model Mesh Resolution.](image)

**Figure 14: Forward Flow Compressor Sub-model Mesh Resolution.**

**Boundary Conditions and Loads**

The objective for defining the boundary conditions and applied loads of the analyses was to generally mimic the anticipated loading without greatly increasing the complexity of the analysis. In operation, the DCR will be mounted to a shaft and spun at high rpm, resulting in loading and displacement that largely occurs in a radial direction. Loads on the geometry could result from centrifugal forces, differences in thermal expansion, and pressure forces on the blades.

Boundary conditions were applied with respect to a cylindrical coordinate system because of the purely rotational motion and circular geometry. To prevent rigid-body motion of the DCR, two degrees of freedom were held fixed on an edge of the rotor bore. Displacements were fixed in the axial and circumferential directions,
with radial displacements allowed. Results showed no significant stress concentrations near the boundary conditions. This confirmed that the boundary conditions did not significantly affect the results and the model represents the physics of the problem reasonably well.

For beginning design iterations, only centrifugal loading was used for the analyses. The final iteration incorporated loading due to thermal expansion using a rough estimate for the temperature profile through the DCR during operation. It was beyond the scope of this project to develop a computational fluid dynamics (CFD) simulation to establish an accurate temperature profile. Initial results showed that simulating the turbine stage during the DCR component test would not be structurally viable, so it was determined that the DCR component test should be simplified to demonstrate the design conditions of the compressor stages only. Therefore, the DCR temperature profiles in Figure 15 were estimated based on operating the turbine stage at the reversed flow compressor temperature of 550°F to reduce the magnitude of the thermal gradient through the rotor. A linear temperature gradient through the top quarter of the forward flow compressor blades, shroud, and bottom quarter of the reversed flow compressor blades was used to represent the demonstration. It is likely that this temperature profile is highly inaccurate and not representative of the final steady state temperature profile that would occur during the demonstration. However, since the purpose of defining the temperature profiles is to determine the relative significance of thermal expansion on the structural response of the DCR, this inaccuracy was considered acceptable.
Multiple design iterations were investigated as adjustments were made to the aerodynamic design. Generally, compromises in the compressor performance were made to benefit structural integrity. This was accomplished through the reduction of the rotor design speed. Four major design iterations were performed before a design with a realistic structural performance was established. The first three major design iterations incorporated a complete aerodynamic redesign of the compressor stages. The final major redesign incorporated an updated turbine stage matched to the compressor stage’s design speed and power requirements.

**Design Iteration #1:**

The initial aerodynamic design for the dual compression rotor was developed to achieve the highest pressure ratio and the largest improvement to the overall
efficiency of the DCR-JetCat system. This resulted in a design speed of 100,000 rpm and a PR of 2.0. Following a room temperature elastic stress analysis incorporating centrifugal loading only and IN625 material properties, it became obvious that the first iteration design was not feasible. Results indicated that von Mises stresses in most rotor areas exceeded the ultimate stress for almost all metals. The gray areas in Figure 16 exceed 60 ksi, which is the approximate yield stress for IN625. With the first design far exceeding the yield strength of IN625, it was decided that the rotational speeds must be greatly reduced in the subsequent design iterations.

![Figure 16: Design Iteration #1 Elastic Stress Analysis Results.](image)

**Design Iteration #2**

To reduce centrifugal loading, the compressor was redesigned to operate at a reduced rotational speed. A reduction from 100,000 to 70,000 rpm reduced the DCR’s overall pressure ratio from 2.0 to 1.5. An elastic analysis was again
performed with centrifugal loads only and IN625 material properties. Similar to Figure 16, the areas of gray in Figure 17 represent von Mises stresses which exceed yield strength for IN625. Although the DCR design in iteration #2 provided a huge improvement over iteration #1, the stresses were still far above allowable. A significant portion of the rotor in Figure 17 still exceeded the yield stress. An additional redesign of the compressor was necessary to further reduce the rotational speed.

**Figure 17: Design Iteration #2 Elastic Stress Analysis Results.**

A sensitivity study was performed on the second iteration to identify changes that could be made to improve the structural response. Based on this study, it was determined that thinner shrouds and thicker blades provided the best structural performance improvement beyond the reduction of rotational speed. However, these adjustments still provided a secondary effect compared to reducing rotational speed.
speed. Scaling up the DCR to a larger size was also investigated. To quickly identify if major gains through scaling were possible, the DCR size was increased and rotational speed decreased, maintaining blade tip speeds. This analysis, however, showed little to no change in the structural response, as it was determined that increasing radius to maintain tip speed, drove up the mass of the DCR enough to balance out the effect of the reduced rotational speed. The sensitivity study showed that the rotational speed of the DCR must be further reduced to achieve a sufficient reduction in stresses.

**Design Iteration #3:**

To further reduce rotational speed, a radical change to the compressor was required. To maintain a desirable pressure ratio and reasonable compressor efficiencies, it was necessary to add an additional compressor stage. Through the addition of a third compressor stage the basic DCR design was maintained, albeit with the addition of a compressor stage and a shaft forward of the original DCR. The forward flow direction now consisted of two stages, 2a and 2b in Figure 18. The third design iteration maintained the pressure ratio of 1.52 from the previous design; however, the rotational speed was reduced to 46,000 rpm. As expected, the greatly reduced rotational speed resulted in a significant decrease in centrifugal loading. The structural analysis for this iteration focused on the DCR only, as the upfront stage, labeled “2a” in Figure 18, was in a more traditional configuration where the blades only carry their own mass. For their modest tip-to-hub ratio and
lack of additional constraints, their structural response was not a concern and the new assembly shown in Figure 18 was limited by the structural response of the DCR.

Figure 18: Design Iteration #3 Component Diagram.

The structural analysis results in Figure 19 show that the third iteration DCR resulted in a feasible design. This design iteration consisted of only small areas with von Mises stresses at or above the yield strength of IN625. A sub-model of a forward flow compressor blade section was created in this iteration to refine the results in an area of high stress. Based on the overall results in Figure 19 and the sub-model results in Figure 20, this compressor design proved to be within structural limits and was selected for further refinement. The turbine now needed to be redesigned to match the lower rotational speed.
Figure 19: Design Iteration #3 Elastic Structural Analysis Results.

Figure 20: Elastic Stress Analysis Sub Model of a Fwd. Flow Compressor Blade.
**Design Iteration #4:**

The fourth design iteration incorporated a redesigned turbine stage with the prior DCR compressor design. The new turbine stage was updated from the initial design iteration to match the current design of the compressor. The significantly reduced rotational speed resulted in turbine blades that were much larger than those from the initial design iteration and presented a concern for the structural integrity of the DCR. An elastic structural analysis was performed on the fourth design iteration geometry with IN625 material properties and centrifugal loading only. The results in Figure 21 show an increase in von Mises stresses at the forward and reversed flow compressor blades due to the additional mass of the updated turbine design. The material selection was refined in the final design to provide increased material strength to mitigate the increased stresses from the modified turbine stage.

![Figure 21: Design Iteration #4 Elastic Structural Analysis Results.](image-url)
**Final DCR Design**

The fourth design iteration was identified as a feasible design for the DCR component test. To confirm the final design, the accuracy of the structural analysis was improved through the inclusion of additional behavior in the model. Elastic-plastic structural analyses were performed to model the effects of material plasticity in the DCR. With the final application being a controlled set of experimental testing, a small amount of yielding in areas of high stress concentration was permitted. As these areas yield, the load is redistributed and spread to other locations. However, these stress concentrations occur in small features which already have low mesh resolution and accuracy, therefore any yielding could potentially be exaggerated or underestimated.

The temperature was another added effect in the analysis of the final DCR design. Based on the multiple design iterations, it was determined that the DCR could not be feasibly tested at typical turbine temperatures. Without a more accurate temperature distribution through the turbine shroud and into the forward flow compressor blades, the operation of the DCR at the turbine design temperatures cannot be conservatively confirmed. However, the temperature profiles due to the compressor flows can be more comfortably accounted for without CFD since a smaller temperature gradient exists. By no longer testing at turbine temperatures, a change to IN718, a material with excellent strength up to 1200°F, was possible. The use of the stronger IN718 material benefited the highly loaded rotor.
An elastic-plastic structural analysis was performed on the final design using the IN718 material properties. Results from the room temperature elastic-plastic analysis showed no yielding under centrifugal loading. This result confirmed that a room temperature demonstration would have a high likelihood of success. In order to confirm a demonstration at the compressor design temperature, the DCR was analyzed with the previously described temperature profile. The first temperature effect added to the analysis was temperature-dependent material properties. The results from this analysis showed how the reduced yield strength of the material at elevated temperatures affected the structural response. The temperature-dependent material property results in Figure 22, as expected, show no discernible yielding. This was because the yield strength of IN718 stays relatively constant over a wide range of temperatures up to approximately 1200°F. At the demonstration temperature of 550°F, IN718 retains its room temperature strength.

![Figure 22: Final Design Temperature Dependent Material Property Results.](image-url)
The inclusion of thermal expansion had a much greater effect on the DCR, due to additional loading created within the model. The results from the structural analysis incorporating the effects of thermal expansion in Figure 23 showed an increase in yielding at high stress locations. Based on the conditions specified for the demonstration, the temperature of the turbine, reversed flow compressor, and shroud between them was 550°F; while the shroud between the reversed flow and forward flow compressor was at a lower temperature, between 550°F and 110°F. This variation in radial temperatures creates loads due to the difference in thermal expansion between locations. These loads are unavoidably positioned along the reversed flow compressor blades, a critical location. The increased yielding observed in Figure 23, as compared to previous results, was caused by thermal expansion effects but is within comfortable limits for this demonstration.

![Figure 23: Final DCR Design Thermal Expansion Structural Analysis Results.](image)
Aerodynamic loading was also investigated in this final design, however, it had a less significant effect than the other loads included in the model. For a rough estimate, the pressure differential achieved in a stage was applied to one side of each blade. No discernable difference could be seen in the results, so aerodynamic loading was considered to be insignificant.

**DCR Structural Limitations**

The major structural limitation of the DCR design, besides the centrifugal loading, is the temperature gradient between stages and the resultant thermal expansion loads. A proof of concept incorporating a DCR with a turbojet and combustor, operating at high turbine temperatures, will suffer greatly from additional loading caused by turbine stage thermal expansion. In the future a solution to mitigate the turbine thermal expansion will be necessary, as the centrifugal loading on the rotor alone creates substantial radial loads on the compressor blades.

For the preliminary demonstration of the DCR component, the turbine stage will, at most, operate at the reversed flow compressor design temperatures. By maintaining the temperature in this way, the thermal expansion difference is spread between the forward and reversed flow compressor blades resulting in an allowable increase in loading. The choice to design the DCR while holding the turbine stage to the reversed flow compressor temperature inhibits the use of this DCR design in its final configuration as mated to the JetCat. Future design challenges will involve the redesign of the DCR to enable operation at typical turbine temperatures.
Due to the inaccuracies incurred during the development of the structural analysis model of the DCR, care should be taken during the testing of the component. The estimates used for the material properties of the DMLS material and the possibility of anisotropic material behavior may result in the model over-predicting the strength of the DCR. As a result, it is recommended that the DCR component initially be spin tested in a controlled and safe environment to monitor its response. The estimation of a temperature profile and the coarse mesh resolution could result in larger than simulated yielding to occur during testing above room temperature. It would be advantageous then, to perform room temperature testing to obtain data first, before increasing temperature.

Although several concerns exist, the design of the DCR should be sufficient for a test of the DCR compressor stages. The design of additional hardware is necessary to perform this testing. The following chapter discusses design considerations for most of the major components required.
CHAPTER III

DESIGN CONSIDERATIONS FOR MAJOR COMPONENTS

As discussed in the previous chapter, design and analysis of a functional DCR transitioned to focus on a component demonstration rather than an integrated demonstration with the JetCat turbine engine. The component demonstration will involve an air flow test of the DCR compressor stages only, with the turbine stage used to drive the DCR but using flows at the lower, reversed flow compressor temperature. To develop a complete component demonstration, design and selection of a number of additional components was necessary. This chapter discusses design considerations relating to the DCR casing, bearings, shaft, and seals.

Casing Design

During the design of the casing components to contain the rotor assembly, it was determined that the addition of a forward flow compressor stage presented a major mechanical challenge. An upfront compressor stage required a large number of separate casing pieces, and each additional piece created an undesirable amount of tolerance stack-up. With each separate casing piece used in the assembly, a tolerance must be added to enable the pieces to fit together. When using an end
supported shaft, the greater the number of parts, the more out of alignment the shaft and bearings could become. After investigating a number of possible configurations, it was determined that the experiment should be further simplified to involve the testing of the DCR only. The elimination of the upfront stage from the demonstration reduces costs associated with the fabrication of additional parts and enables a two piece casing design to reduce tolerance stack-up. The upfront forward flow compressor stage will be left as a future design challenge.

To design the casing components for the DCR component alone, the stator blades and flow paths from the compressor design were constructed in SolidWorks from discrete sets of points. To maintain accurate spacing between the rotor blades and their corresponding stators, a common coordinate system was used for both the DCR and casing parts. Aligning each model at the same origin results in an assembly aligned with the aerodynamic design specifications. The DCR’s three concentric flow path design required the addition of struts where stators did not already exist, to support the geometry. An overlapping flange at the joint between the two casings was added to locate the two halves so they were concentric. A set of bolt holes was added on the casing exterior to join the two pieces, with six bolts used to create an even clamping force. One side of each casing was designed to mate with the DCR and contains seal lands machined directly to the casing. The complex design of the casing components required the parts to be laser sintered. Therefore, to reduce costs, the axial length of each casing piece was kept as short as possible to reduce the volume of metal needed. The side opposite the seal lands was designed to mate with a machined adapter piece. This adapter piece, described later, consists of flow
paths that were tapered to generic diameters to enable a part constructed from smooth bore structural tubing to be welded onto it. The forward casing, shown in Figure 24, contains the stators for the reversed flow compressor and turbine. Since the forward flow stators are on the aft casing, struts were added to anchor the bearing block to the rest of the casing. To maintain a two piece assembly, the forward casing includes the turbine shroud and tip seal. The aft casing, shown in Figure 25, contains stators for only the forward flow compressor, so struts for both the reversed flow compressor and turbine stage flow paths were required.

Figure 24: DCR Forward Casing Design.
Figure 25: DCR Aft Casing.

**Bearing Selection**

The high rotational speed of the DCR was the major design concern affecting bearing selection. From a stability and rotordynamic standpoint, a large shaft radius was desirable; however, this reduced the allowable rotational speed of the bearings. A circulating oil bearing lubrication system, in combination with the concentric flow path design and size of the DCR, increased the design complexity beyond the scope of the demonstration. For these reasons, a bearing with both a high rotational speed and grease pack lubrication system was desired. The bearing system also had to allow for loads in both axial directions. Estimates of
aerodynamic axial loads resulted in a clear resultant force in the forward flow direction; however, during spin-up or spin-down the axial load direction and magnitude could change. To account for the bi-directional axial loads, angular contact bearings were selected to support the DCR. The high rotational speeds required the use of precision ABEC Class 7 bearings for an adequately high operating speed. A constant pressure preload, created through the use of a wave spring, allowed for bi-directional loading and flexibility of casing tolerances. The constant pressure preload allowed for the bearings to locate to tighter tolerances held on the shaft, avoiding potential problems caused by the larger tolerances allowed for the casing.

**Shaft Design**

Based on the bearing rotational speed limitations, a shaft diameter up to approximately 0.60 inch was considered allowable. Simplifying the DCR component test by eliminating the first forward flow compressor stage alleviated major concerns over shaft stability. Since no true rotordynamic analysis was performed on the rotor system, shaft design choices focused on increased stability. An end supported rotor was selected to provide the greatest stability. This rotating assembly design also allowed for a stepped shaft with increased diameter between the bearings. An Abaqus natural frequency analysis of a static representation of the rotor assembly was performed to provide a rough estimate of the rotordynamic behavior for the DCR component test. Rather than use fixed boundary conditions at the bearings, a more realistic elastic foundation boundary condition was applied. Based on a suggestion by an engineer at AFRL, a spring rate of 600,000 lb/in was
used to represent the bearings. The first non-rotational natural frequency occurred at approximately 2000 Hz. This translates to 120,000 rpm, which is 2.6 times higher than the operating speed of the DCR. Based on these results the shaft design should provide more than adequate stability as the DCR should operate significantly below the first natural frequency. Bearing spring rates higher than the estimated value will result in higher natural frequencies and are therefore not a concern. The chosen spring rate likely underestimated the true spring rate of the bearings used in the assembly, and also does not include any damping effects which would exist in the real system [11]. For these reasons, the operating speed of 46,000 rpm was considered to be well below any vibration modes of concern.

**Seals Selection and Design**

The DCR required a unique and creative solution to seal between each of its three flow paths. For the DCR component test, a total of four flow path seals, in addition to a blade tip seal, were required. The extremely small scale of the DCR component test further increased the sealing challenges. To reduce the amount of centrifugal loading, the thickness of the shrouds between the flow paths was minimized. These weight reductions and the already small scale of the DCR component test resulted in a small amount of radial space to fit a seal. For example, Figure 26 shows the area available at two of the four required seal locations on the DCR. As shown in the figure, seals were needed between the forward flow compressor and the reversed flow compressor, as well as, between the reversed flow compressor and the turbine. With a pressure ratio of four between the forward flow path and reverse flow path, a small seal gap was important. Maintaining a
small amount of leakage through the seals was considered critical to the performance of the DCR. Since, the radial space available between the flow paths was only 0.060 inch, limited seal options were available.

Figure 26: DCR Seal Area (Aft Looking Forward View).

Many different styles and configurations of seals were initially investigated to find the best solution for the DCR demonstration. The high surface speeds at all the seal locations required the use of a non-contacting seal, such as finger seals, brush seals, or labyrinth seals. The limited radial space required that these seals act in an axially contacting manner. The manufacture of axially acting finger seals was not feasible and would require too much development time. A brush seal could be developed to seal axially and was readily available. However, these brush seals are typically made only as small as 0.125 inch thickness radially, so they will not fit on a DCR of this scale. Since brush seals provide good sealing performance it is recommended that brush seals be considered for future applications of the DCR,
especially those at larger scales. A labyrinth style seal was selected since it could be
easily developed and could fit in a small space radially. The flexibility of the
labyrinth seal design allowed it to be configured to act axially or radially. An axially
acting seal would be simpler and require less machining, but results in greater
leakage as it is more difficult to hold the rotor to small tolerances in the axial
direction. The radially acting labyrinth seal provided limited space for adequate
seal teeth but enabled a smaller gap between seal teeth and seal lands. The limited
space available for sealing is illustrated in Figure 27, where the gap between the top
of the seal teeth and the land is only 0.003 inch. This gap could expand or shrink
depending upon tolerance stack-up, thermal expansion, and expansion due to
centrifugal loading. To enable as small of a gap as possible, the seal land will consist
of a softer spray-on abradable metal. With the abradable metal, the designed seal
gap is set to allow for assembly. Expansion due to rotation or temperature could
cause the seal teeth to rub into the seal lands, reducing the gap between the two and
creating a better seal.
As noted previously, the mechanical complexity of an end supported rotor assembly in combination with the upfront compressor stage required simplification of planned experimental testing to include only the DCR component without the upfront compressor stage. Appropriate casing, bearing, shaft, and seal designs have been specified which, along with the final DCR design, enable such a demonstration. The following chapter discusses additional concerns relating directly to the experimental testing and provides recommendations regarding testing procedures.
CHAPTER IV
EXPERIMENTAL SET UP AND TESTING

At the time this thesis was written, the DCR and other components were in the fabrication phase. The fabrication lead time placed completion of the DCR experimental testing far outside the scope of this effort. However, consideration was given to the experimental setup and testing plans for the DCR components. This chapter discusses experimental testing concerns, including balancing and spin testing; test setup and fixturing; sensing and data acquisition; and, suggested testing procedures.

Balancing and Spin Testing

The high rotational speed of the DCR component and its method for fabrication created the need for balancing and a preliminary spin test prior to assembly. Additionally, the DMLS process is only accurate to within approximately 0.005 inch; therefore, it is imperative that the rotor be balanced before spinning up to design speeds. Following the balancing of the DCR rotor, a spin test will be performed to confirm the structural integrity of the rotor at room temperature.

The spin test and balancing will be performed with the DCR installed onto the shaft for a more accurately balanced final assembly. The spin test will be
monitored with high speed video to identify the onset of any undesirable rotordynamic vibrations. It is important the rotor be spun in a controlled and safe environment because of the uncertainty allowed during the structural analysis.

**Test Setup and Fixturing**

The DCR component demonstration requires the inlet and outlet conditions of each flow path be individually controlled to create the desired flow conditions. Laboratory facility air will be supplied to each flow direction at the desired mass flow rate, temperature, and pressure. Three separate streams of air must be ducted into the DCR. Each of these flow paths are concentric to one another, so fixtures forward and aft of the DCR were designed to mate with the casings.

In order to manufacture the air supply fixture from readily available materials, an adapter was designed to match the DCR casing flow paths to standard diameters of smooth bore structural tubing. The adapter piece will be machined to bolt to the DCR casing and permits the structural tubing, which makes up the air supply fixture, to be welded directly to the adapter piece. Each adapter piece, such as shown in Figure 28, will also contain the features necessary for the instrumentation of each flow path.
Figure 28: DCR Casing-Fixture Adapter.

The use of structural tubing for the air supply fixtures, such as shown in Figure 29, enables a long axial length for a fully developed velocity profile. Flow enters the DCR supply fixture at right angles to the final flow direction. Therefore, to allow for the fully developed velocity profile, a constant area section ten hydraulic diameters in length was necessary. Exhaust piping on air supply fixtures will require an adjustable valve to control the backpressure for each compressor stage. The back pressure will set the appropriate pressure upstream. RTV silicone will be used to seal leaks between each piece in the assembly.
Sensing and Data Acquisition

With each compressor and turbine stage fixed to the same rotor, the individual stage shaft power input/output cannot be directly measured. Due to the inability to quantify the shaft power of each stage, their complete characteristics cannot be determined. For this reason, as well as the temperature limitations placed on the component, experimental testing of the DCR will focus on the mechanical feasibility of the rotor. Focusing on mechanical feasibility still allows for the identification of shortfalls incurred throughout the design process, fabrication, and demonstration of the DCR component. Aerodynamic data will, however, still be taken as stage pressure rise, seal leakage, and stage adiabatic efficiencies can be derived through flow measurements.
The mass flow rate of each supply pipe will be set and calculated based on a pressure measurement upstream of a sonic nozzle, far upstream of the test section. Static pressure taps forward and aft of each compressor and turbine stage will used to quantify the change in pressure through the stages. A temperature probe will be inserted in the flow forward and aft of each stage to measure the stagnation temperature. With static pressure, stagnation temperature, mass flow rate, and the known flow path area in the test section, any additional parameters can be determined through calculations. A proximity sensor mounted to the inside of the forward casing will be used to measure rotational speed of the rotor shaft.

Temperature probes at each bearing will be used to monitor their temperature during operation to ensure they do not exceed their designed operating conditions. Accelerometers on the casings will be used to quantify vibrations and identify unforeseen and damaging vibrations.

**Suggested Testing Procedures**

For safe operation of the DCR during the initial demonstration, the reversed flow compressor and turbine should both be operated at the forward flow compressor temperature. Operating all three stages at the same temperature eliminates the additional loading in the compressor blades caused by thermal expansion. Demonstrating the reversed flow compressor at a reduced temperature results in a lower component efficiency because of the increased viscous losses as a result of the decreased Reynolds number [12]. For example, operating the reversed flow compressor stage at room temperature and pressure conditions results in a Reynolds number which is approximately one third that of the designed conditions.
Operation of the turbine at significantly lower temperatures will not only result in increased viscous losses similar to the reversed flow compressor, but could also require a mass flow rate greater than designed to extract adequate power to drive the compressor. Increased mass flow rates at lower temperatures result in higher Mach numbers and additional losses due to compressibility effects. However, as noted previously, the first forward flow compressor stage was eliminated from the design to reduce complexity. Eliminating the forward flow compressor stage reduces the amount of power that must be extracted in the turbine and benefits its operation at room temperature.

To operate each stage at the appropriate blade incidence angle the stage axial velocity must match the design point. Stage mass flow rates must be adjusted to achieve the design point axial velocity at the reduced temperatures. An incorrect axial velocity would result in the wrong blade incidence angle, causing significantly reduced stage performance and possibly rotor stall.

Following the initial battery of testing at room temperature it is suggested that the rotor be inspected for signs of wear or damage. After confirmation the DCR rotor is operating in a satisfactory manner, testing can continue. Next, data should be taken at various increased temperatures. To insure structural integrity of the DCR, testing should only be performed up to a temperature well below the reversed flow compressor design temperature. The goal of this testing is to establish how the adiabatic efficiency of the reversed flow compressor stage changes with increasing temperature. The adiabatic efficiency is expected to improve as the temperature increases. Viscous losses and compressibility effects will decrease with the
increased temperature up to the design temperature. Seal leakage rates are also likely to vary with changes in temperature. Some seal locations experience choked flow conditions where the speed of sound will vary with temperature and affect the leakage rate; also, all seal locations will experience increased density through the gap with the increased temperature. These effects will lead to a larger leakage mass flow rate.

A demonstration of the off-design performance of the DCR should also be considered. This would establish the performance of the rotor at reduced rotational speeds and various mass flow rates. One attractive feature of the DCR and RITE cycle was its controllability during operation. If experimental testing shows the opposite is true, the DCR could prove difficult to implement into an actual engine. The off-design testing should be performed by varying either corrected mass flow rate for each stage or the rotational speed of the rotor. The goal of the off-design testing should start by determining the range of blade incidence angles over which the stages can reasonably operate. This data would establish where significant decreases in stage efficiency and rotor blade stall occur. Following this testing and any additional testing that can be performed with a small thermal gradient, an attempt at the full compressor design conditions can be made. This scenario should be held for last, after adequate data has already been collected, since the risk of failure increases with increased reversed flow compressor temperature.

During experimentation it could prove useful to operate the DCR at elevated forward flow compressor temperatures to lessen the loads on the compressor blades from thermal expansion. Bearing temperatures should be monitored during
all testing and could become a problem with elevated temperatures in the forward
flow compressor section as heat transfer out of the bearings will be greatly reduced. Without circulating oil lubrication to aid bearing heat transfer, bearing performance will be dependent on the forward flow compressor flow path temperature. A balance between forward flow compressor temperatures and bearing temperatures could provide a way to mitigate risk associated with near design point testing of the reversed flow compressor stage.

Additionally, if an adequate estimate for the temperature profile in the DCR can be experimentally determined, then a more refined structural analysis can be performed. These results could show a less extreme thermal gradient then initial estimates, reducing the calculated risk of a realistic compressor design temperature test.

The previous chapters discussed the structural design and analysis of the DCR component, additional hardware required for assembly, and plans to experimentally demonstrate potential benefits of this unique concept. The demonstration of the DCR component can be considered successful depending on a number of both qualitative and quantitative results. The ease of assembly and lack of unforeseen complications will establish the mechanical design success of the DCR. The comparison of the compressor test results to the expected results specified by the aerodynamic design will determine the aerodynamic success. Seal leakage rates will be used to quantify their success. If the overall quality of the design is high based on these results, and vibrations of the assembly and bearing temperatures remain low, then the DCR component demonstration can be considered successful.
CHAPTER V

CONCLUSIONS

Based on the design and analysis efforts discussed in the previous chapters, a number of important conclusions can be made regarding the feasibility of the DCR component. Although fabrication and experimental testing remains to be completed, various recommendations and suggestions for future work with the DCR component, both with and beyond its use with the JetCat, are provided.

Future DCR Efforts Related To JetCat

Future work with the DCR and RITE cycle at the JetCat P200 scale is not recommended. The high rotational speeds required for acceptable performance at this scale have shown to be difficult for the DCR geometry. The structural performance at a larger scale presents a formidable obstacle. Although it was determined during the design iterations that a basic up-scale of the DCR does not result in any significant change in structural performance, a redesign of the compressor geometry for a larger sized application could prove otherwise.

The typical limitations of turbomachinery at small scales also hinder the performance of a DCR mated to a JetCat. The small flow path sizes required for a reasonable axial velocity increases the manufacturing constraints and tolerances. As the flow path size decreases, the gaps and tolerances in the assembly must also
decrease in size or performance will suffer. This results in machining tolerances which are extremely small.

The nature of the DCR design requires a two piece assembly to incorporate a shaft with end supported bearings. Allowing for disassembly creates nearly unacceptable tolerance stack-up for high speed bearings. Therefore, a DCR of this scale and configuration with high rotational speeds is exceptionally difficult. With the addition of a second forward flow compressor stage, as currently designed, three or more casing pieces must come together between the bearings. For future, single forward flow compressor, designs an alternative to the end supported shaft would be to mount bearings in the center of the rotor. A center supported rotor was not considered in this design due to rotordynamic concerns and the initially split forward flow compressor stages.

The small scale also results in limited space for seals. For the JetCat sized DCR, the space between flow paths is so small that it is nearly impossible to fit seals between them. However, with the concentric flow paths used in the DCR design, no alternatives exist to placing seals between flow paths. Seal performance could be increased by using a better seal technology, but the space between flow paths must be increased. Increasing the space between flow paths without increasing the scale of the rotor leads to an unnecessarily large amount of rotating mass and increased centrifugal loading. Therefore, the only viable option for improved seal technology is the development of a DCR on a larger scale.
DCR Potential Beyond the JetCat

Future work beyond the testing of the DCR component should start by determining if the DCR has merit at a larger scale. Tracking of the DCR centrifugal loading with increased mass flow rate should be established. This would involve analyzing a number of compressor structural designs at a fixed rotor pressure ratio and increasing mass flow rates until a trend for the structural response can be established. If results from this study are promising, a solution to mitigate the thermal expansion between each set of blade rows must be found. The thermal expansion caused by the reversed flow compressor stage temperature alone exceeds material strength. One possible solution could be sets of floating rotors that are fixed to spin together but can expand and contract individually. A thermal expansion solution will be required to develop a functional turbine stage. With the turbine at 1900°F and the forward flow compressor stage near room temperature, the rotor will likely yield without the addition of centrifugal loading. Provided a high performance DCR can be established on a larger scale and a solution can be identified for thermal expansion, a rough engine performance analysis should be performed on the design to ensure an estimate for a reasonable operating line can be established.

A more thorough compressor aerodynamic-rotor structural analysis study should be performed to identify a blade design with both good structural and aerodynamic performance. The initial study described in this thesis has established a moderately feasible rotor concept through the reduction of rotor axial length, to reduce weight, and the reduction of rotor rotational speed, to decrease centrifugal
loading. A future study quantifying the aerodynamic and structural performance of specific axial compressor design choices, such as blade chord length, axial velocity, flow turning angle, blade number, and blade thickness, should be performed to establish a higher performance future conceptual design. The current design of the DCR concept does not provide a large enough pressure rise for its mechanical complexity and poor structural performance.
WORKS CITED


