Cooling Channel Redesign for SGT-A05 Second Stage Vane with Considerations for Additive Manufacturing

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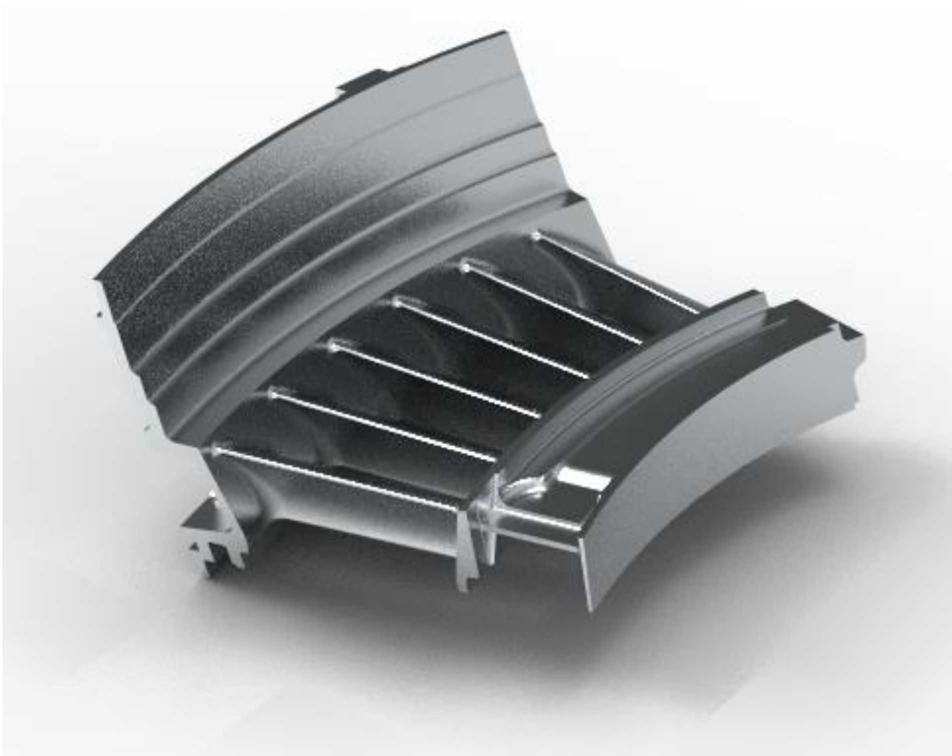

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Abstract

This report presents an updated design for the 2^{nd} Stage Vane in the aeroderivative SGT-A05 engine. Vane 2 is traditionally cast from Alloy 247CC, but recent efforts have been made to explore the feasibility of manufacturing the component with selective laser melting (SLM). The proposed geometry reduces blade temperatures and material costs by about 20% while still meeting equivalent stress requirements. By expanding cooling channels, the new design leverages additive manufacturing (AM) to increase convective heat transfer while removing redundant support material.

A comparative thermal-structural model is used to evaluate several design variables, including temperature, yield utilization, creep rupture, and creep strain. Boundary conditions were obtained from empirical, computational, and analytical sources. The analysis of existing designs provided insights about the nature of the thermal and pressure loads present in this application. Ultimately, these observations, along with Siemens' growing experience in AM, helped motivate the changes that were made to the cooling channel. This report begins by summarizing the design requirements and describing the existing approaches to establish baseline results and identify areas of potential improvement. Next, the technical details behind the FEA model and proposed design are introduced. After analyzing the results and comparing them to the baseline, recommendations are made for future efforts.

Contents

Introduction

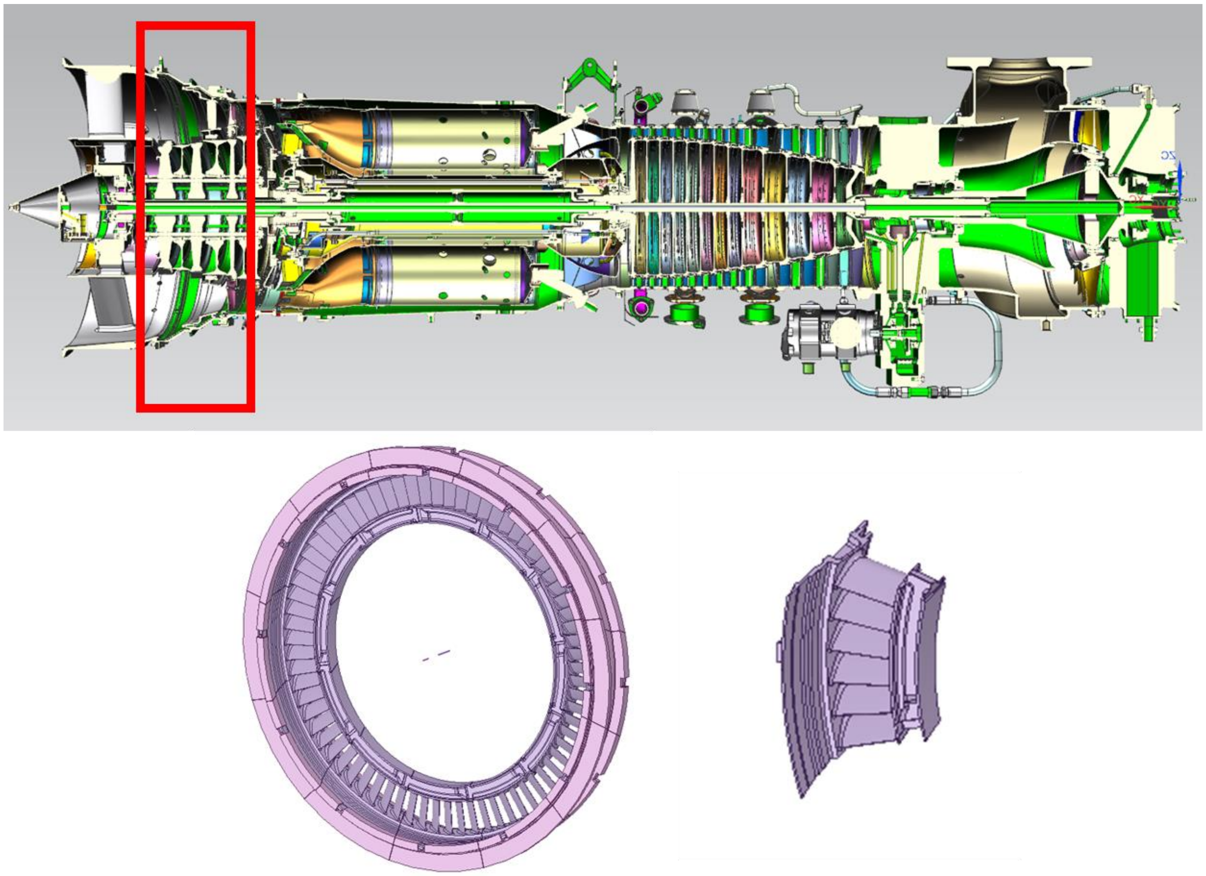

Figure 1. Longitudinal view of SGT-A05 Turbine and the 2nd Stage Vane, which is made of 12 identical interlocking segments. This stationary component is the focus of this design analysis.

Siemens' SGT-A05 (Industrial 501-K) is a lightweight gas turbine engine used in cogeneration, offshore, and emergency power applications (Fig. 1). An aeroderivative based on the engine in the Lockheed Martin C-130 Hercules, it has proven to be a reliable option for over 500 Siemens customers around the world [1]. The design includes many components that are viable candidates for additive manufacturing (AM), which increases geometric flexibility and decreased lead times relative to traditional casting methods. This report focuses on Vane 2, which has undergone multiple iterations to optimize heat transfer & structural properties by taking advantage of AM capabilities. The latest design meets the minimum requirements, but there are concerns about high temperatures at the leading edge of the vane blades causing premature corrosion. The intent of this proposed design is to introduce a new cooling channel geometry that increases convective heat transfer while still meeting the component's structural needs.

Internal vane cooling is an area of significant interest to industrial and academic researchers and has resulted in many novel features and insights over the past decades. Modern vanes are some of the most complex components in entire turbine, with networks of turbulence promoters, pin fins, and weaving channels. They are often the product of computationally intensive algorithms designed to optimize design life [2]. Perhaps the most exciting development in this area is the increased viability of selective laser melting (SLM), a transformative AM technology that is not only used for custom prototypes, but as the primary means of manufacturing. The new design intends to leverage these breakthroughs for a production-level component.

After establishing baseline results for the existing Vane 2 design, this report will introduce the cooling channel modifications and perform a comparative analysis based on the thermal and structural performance.

Existing Design Cases

To establish a baseline on which to assess the proposed design, two previous iterations will be analyzed under the same operating conditions. First is the unmodified geometry intended for casting of Alloy 247CC, with a 0.065mm bond coating and no internal cooling features, i.e. the current production-level component. An AM-focused design (to be printed in Inconel 718) with a 0.150mm coating and 1.2mm-diameter cooling channels (among other updates) is also considered. The cooling channels are of particular interest in this report, as they form the basis of the modifications in the proposed design.

Whereas complex internal features would present significant challenges in a traditional casting approach, AM allows for unique geometries that not only save material, but also take advantage of a radial pressure gradient through the vane blades. Cooling air is channeled from the OD to ID to pull heat from the leading edge of the blades. As discussed in the model description, the pressure loads on Vane 2 are low relative to the stresses caused by thermal expansion, so reducing internal temperatures can significantly increase its design life. More importantly, better cooling and an effective bond coating can decelerate corrosion on the blade surface. This section establishes the design requirements, model, and results for the existing cases.

Design Requirements

All designs must meet the requirements set forth for Strength, Low Cycle Fatigue, Creep, and Oxidation in Table 1. Both the original cast and new printed baseline designs meet these specifications, but there are significant thermal stresses in the AM part, especially when the platinum aluminide coating is suppressed. Therefore, the principal goal of the new design is to expand the cooling channels to reduce temperatures throughout the blades without sacrificing structural performance.

Table 1. Rolls-Royce requirements for Vane 2 Designs

Requirement	Value	Source
Strength	0.80*F_{ty} (yield strength) i.e. "Yield Utilization" < 80%	Rolls-Royce Engineering Design Spec 3526-CS
LCF	3000 desired 15000 for V2 per EDS	Rolls-Royce Engineering Design Spec 3526-CS
Creep Rupture	Stresses < Creep Rupture Strength for design life i.e. "Rupture Utilization" < 100%	Rolls-Royce Engineering Design Spec 3526-CS
Creep Strain	<1% circumferential creep strain for transverse direction (ballooning) for design life (60,000hrs)	Rolls-Royce Engineering Design Spec 3526-CS
Oxidation	Coating will be applied to minimize	Life'd per LGT design criteria (safePG)

Model Description

All designs were analyzed in ANSYS Workbench using both Steady-State Thermal and Static Structural models. Loads and boundary conditions for the thermal model were determined from a variety of sources, including empirical data, CFD simulations, and analytical solutions.

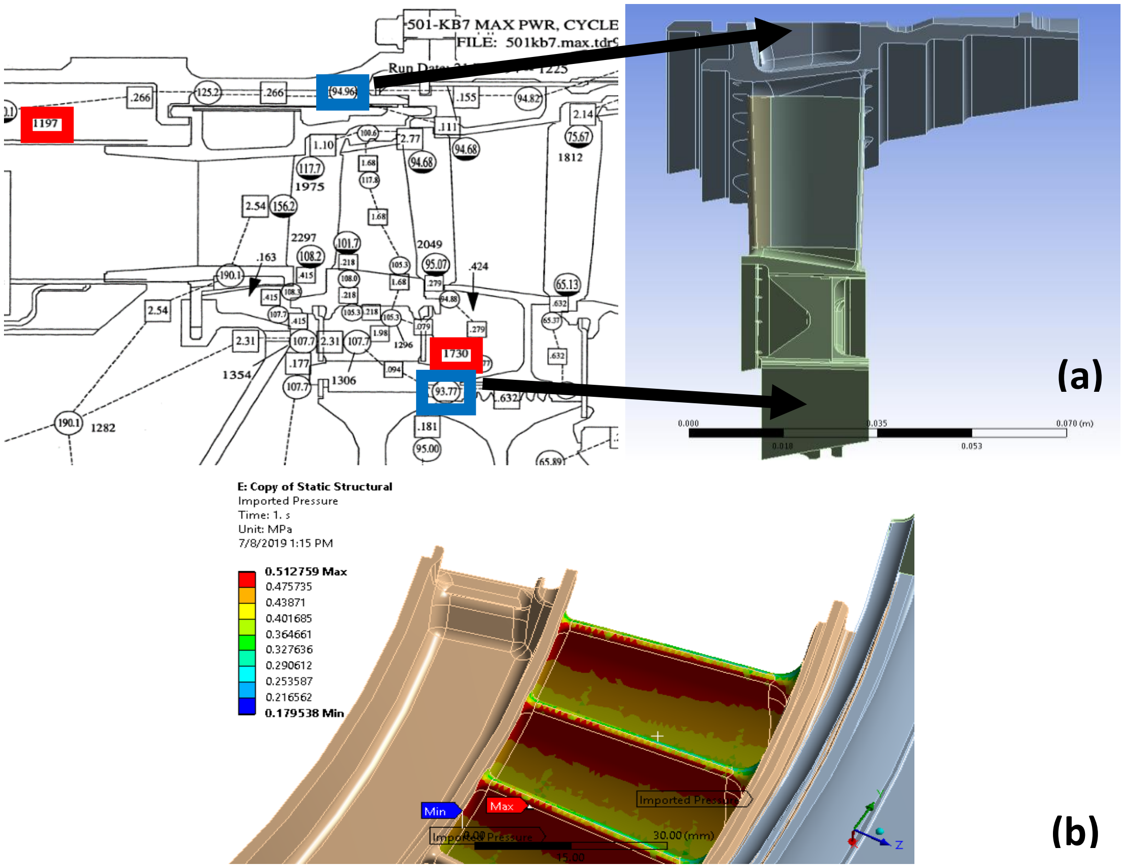

Figure 2. (a) Temperatures (red) and pressures (blue) from the OD and ID were taken from the 501-KB7 Max Power Flow Analysis displayed above. Units are in Rankine and pounds-force per square inch, respectively. (b) CFD-calculated pressures on the airfoils were imported from an external analysis and interpolated onto the structural mesh.

For instance, Figure 2a shows radially symmetric, steady-state measurements of pressure and temperature at the inner and outer diameters of Vane 2 during a study of SGT-A05. Pressures and heat transfer coefficients (HTC) on the surfaces of the airfoils were calculated via CFD analysis and imported onto the mesh for the appropriate study. The HTC throughout the cooling channels was derived from a conservative application of the Dittus-Boelter correlation for turbulent flow through a duct,

$$\mathrm{Nu} = 0.023\mathrm{Re}_D{}^{4/5}\mathrm{Pr}^{0.4}$$

where Re_D is the Reynolds number, Pr is the Prandtl number, and Nu is the Nusselt number. An important insight from the quantification of the various loads on Vane 2 is that the stresses resulting from pressure loads on the airfoils are appreciably less than those derived from the temperature gradient. This suggests that although cooling channels require the removal of load-bearing material from the blades, the heat transfer benefits of internal convection balance the cost of this structural

modification. Refer to the appendix for additional details about the sources of the loads and boundary conditions.

The vane itself is one of twelve identical interlocking pieces that attach to the outer case, so the model assumes cyclic symmetry about a cylindrical axis. The part attaches to the steel case via frictionless contact to match the conditions outlined in Rolls-Royce report AR.0413-676 (2nd Stage analysis for T56 A15+ Upgrade).

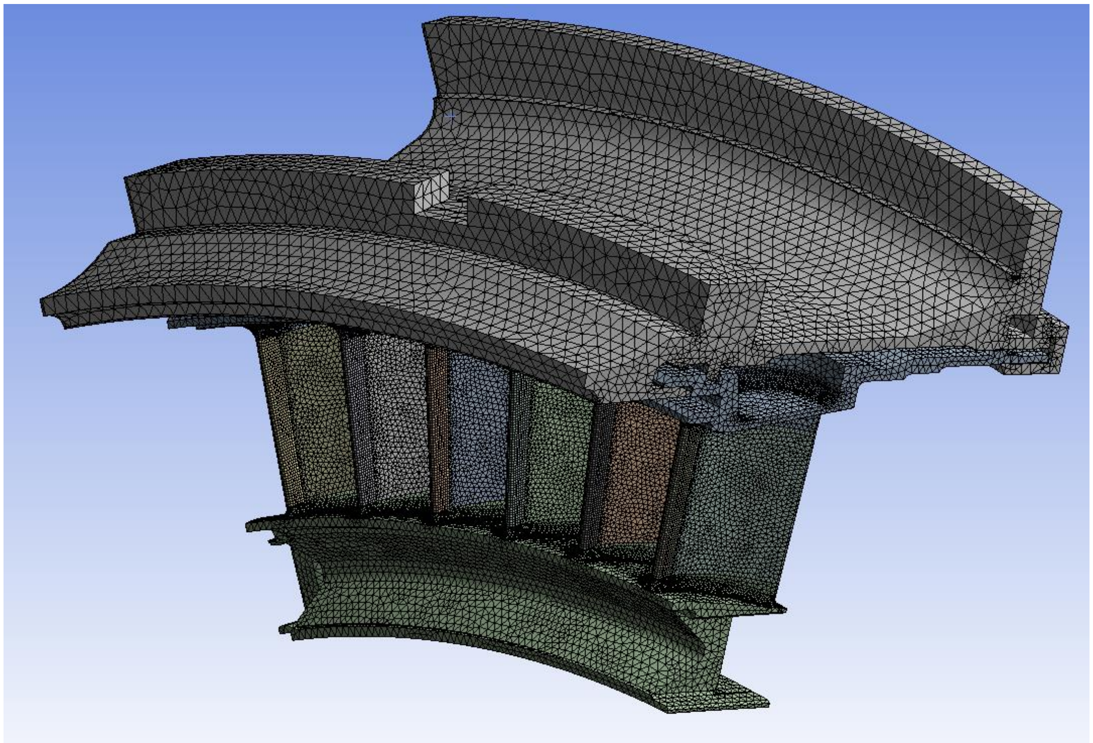

Figure 3. The mesh used in this model features approximately 1.2 million nodes and a combination of tetrahedral and brick elements.

Figure 3 shows the mesh used in this study, which features controls to capture areas of stress concentration, such as the interfaces between the airfoils and shrouds. It also displays the portion of the steel case that contains the vane segment. For the thermal studies of the AM designs, a 0.15mm thick surface body was attached to the airfoil segments to represent the coating's conductivity (see Appendix). After solving the thermal model for the body temperatures, these results were transferred to the static structural simulation to calculate the appropriate analyses of stress, deformation, and creep.

Baseline Results

Both the cast 247CC design and initial additively manufactured IN939 design meet the minimum strength, fatigue, and creep requirements. However, the baseline results show that there is potential to further leverage AM capabilities and increase part life by expanding the cooling channels. Stresses within the blades are very low, suggesting that some of this redundant material

can be removed without sacrificing the strength of the vane. These results are compared to those of the new design in the next section.

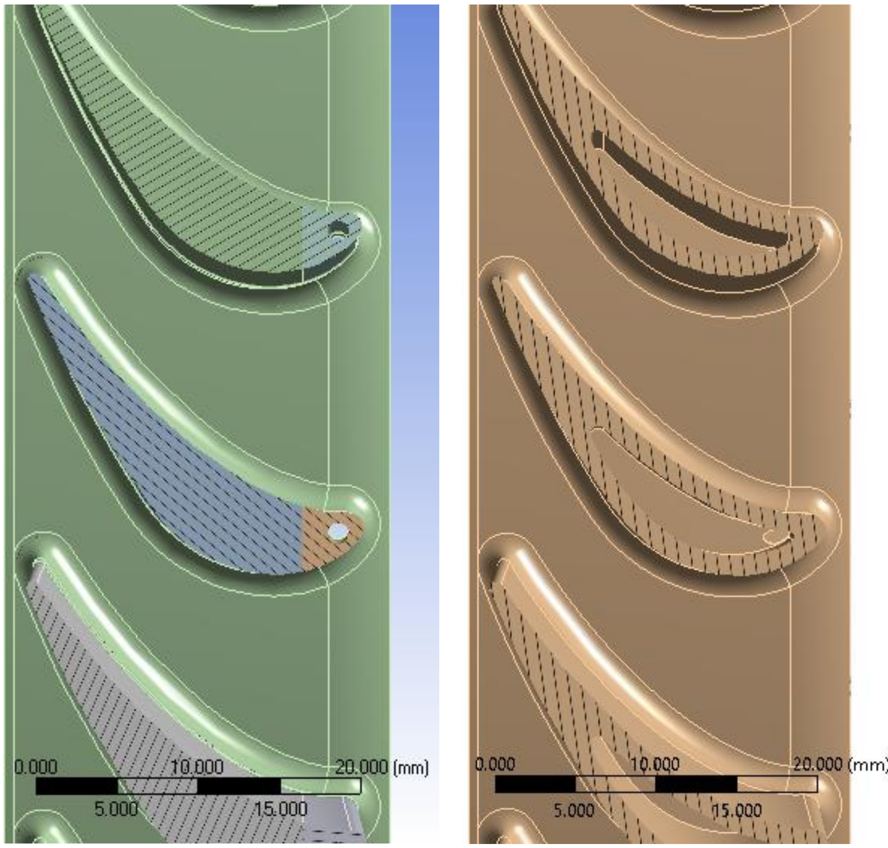

Figure 4. Side-by-side section views of the cylindrical channels in the existing AM design (left) and hollowed blade channels in the updated design (right).

Updated Design

The baseline AM design includes a 1.2mm-diameter cooling channel just inside the leading edge of each vane. The radial pressure gradient through the vane causes air to flow from OD to ID, drawing heat from regions of high thermal loading. The new design features hollow blades that significantly increase the channel surface area to promote convective cooling. These shelled geometries can be rapidly produced via SLM without the need for costly molds or post-build machining. In fact, self-supporting holes often naturally result in internal surface roughness, which can induce turbulent channel flow. The recirculating eddies accelerate the transfer of thermal energy, giving a higher overall HTC than a smooth duct [4]. As mentioned in the introduction, this is the reason that current state-of-the-art blade cooling channels have features like turbulators and pin fins.

Figure 5. Computer-generated rendering of the inlet holes located in the recesses of the shroud OD in the proposed design.

The inlet and outlet holes were made elliptical to match the profile of the channel's leading edge without removing too much load-bearing material from the shroud. Figure 4 compares section views of the baseline and expanded cooling channels. The minimum wall thickness in the proposed design is 1.2mm. A rendering of the elliptical inlets is displayed in figure 5. Like the baseline AM design, the channels gradually transition into the filleted corners of the self-supporting recesses in the shroud OD. Air is ejected through the shroud ID.

Analysis of Results

For the analysis of the proposed design, the boundary conditions in the cooling channel were updated to reflect the new geometry. The Dittus-Boelter correlation is no longer valid for the hollow blade channel, so a CFD model was used to evaluate the heat transfer coefficient on the inner walls. To limit computational effort, a simplified blade geometry and coarse mesh were used in this CFD analysis, which presents an opportunity for future refinement. This model gave an

average wall HTC that was approximately 30% lower than that of the cylindrical channel in the original design.

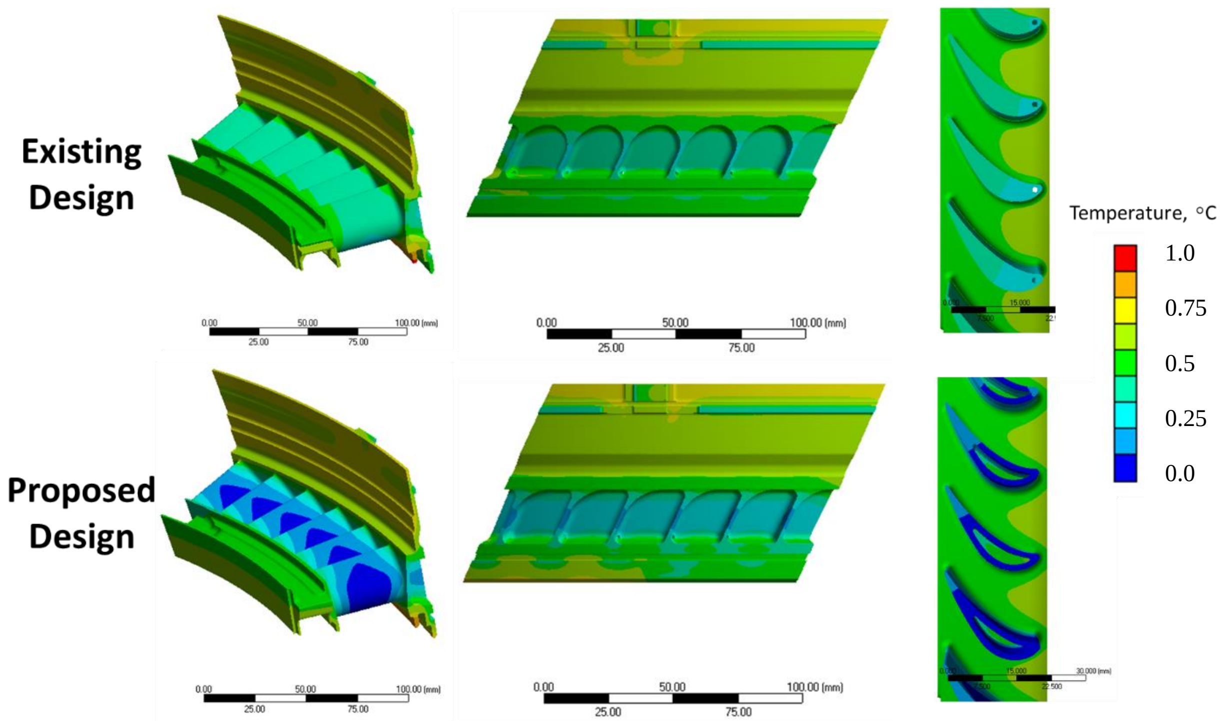

Figure 6. Temperature plots of the temperature profiles of both the existing AM design (top) and proposed design (bottom) with the expanded cooling channels (normalized to the maximum temperature in the existing design).

A comparison of the temperature profiles of the original AM design and the proposed design is displayed in figure 6. The expanded cooling channels decreased blade temperatures in the coated IN939 part by as much as 100°C, or 20%. This significantly reduces thermal distortion in the low-tolerance regions.

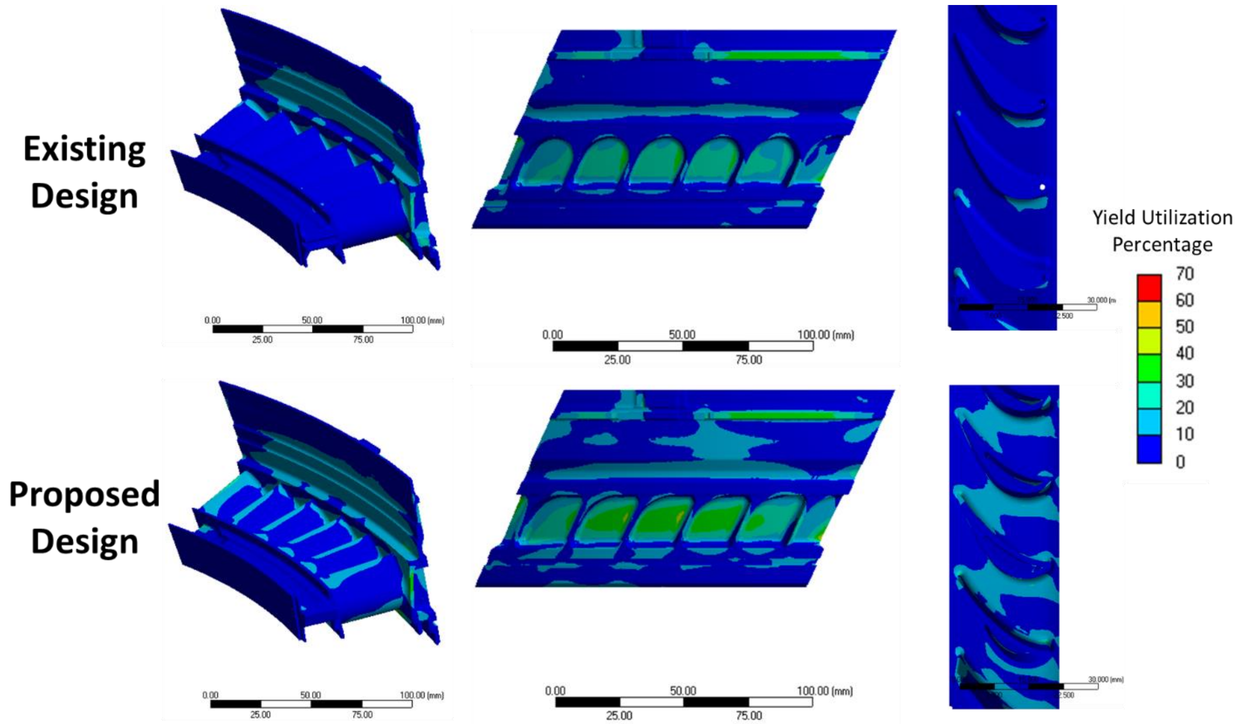

Figure 6. Plots of the utilization yield percentage of both the existing AM design (top) and proposed design (bottom) with the expanded cooling channels. A yield percentage greater than 100% signifies that the part will exhibit plastic deformation.

Even with a significant reduction in the blades' cross-sectional area (part mass was reduced by 22%), the equivalent stress in the new design remains at acceptable levels. Figure 7 plots the yield utilization percentage, which is the stress at each node divided by the yield stress of IN939. Both parts are well within the 80% threshold (maximum utilization even decreased slightly in the new part), and only localized areas on the shroud exceed 30% yield utilization. On average, utilization in the part is less than 8%. The new design also meets the rupture utilization (see appendix) and 1% creep strain requirements.

Conclusions & Future Work

Turbine vanes present a promising application for SLM approaches. In the extreme operating environment of a gas turbine engine, it is critical to limit corrosion in key components Complex internal cooling features can be produced via AM without the long lead times, high material costs, and geometric limitations of traditional casting and machining methodologies. This report presented an updated design for a 2nd Stage Vane that builds on a previous AM-optimized iteration to save material costs (and potentially, print times) by over 20% and decrease blade temperatures by nearly 100°C, while still meeting the strength and life requirements.

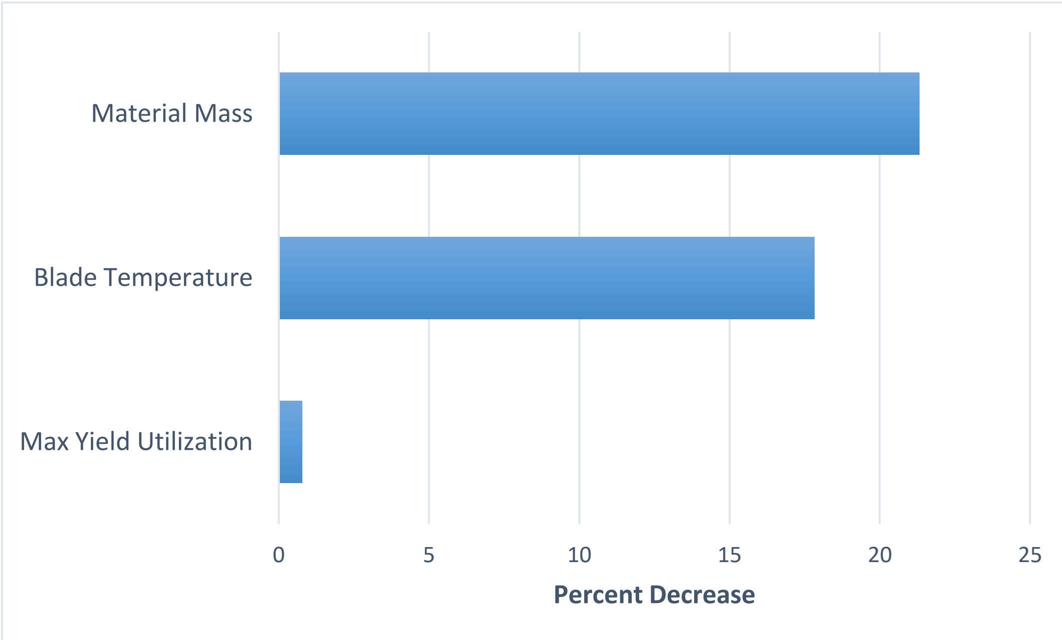

Figure 7. A summary of significant improvements made by the new design, which saves material (21%), lowers blade temperatures (17%), and slightly decreases maximum part stresses (0.7%) compared to the previous AM-optimized version.

Despite the promising improvements, there are still opportunities to refine the model. Many questions remain to be answered about the fluid dynamics through a channel like this, especially as they relate to print orientation, hole diameter, and surface roughness. Furthermore, research about the topic of vane cooling uncovered intriguing design possibilities regarding the geometry of the inlet and outlet holes. The elliptical holes used in the proposed design were intended to preserve support material in the vane shroud and allow for a relatively natural transition into the main channels. Depending on the nature of the circulating air at the inlet, it may be more effective to investigate the 777-shaped [4] or Nekomimi hole geometries to avoid choking airflow [5]. This analysis focused on an outlet at the ID, but it may be worth exploring the possibilities of ejecting air into the trailing edge of the airfoil, where there is a significantly steeper pressure gradient and thus greater airflow. However, this may disrupt the careful aerodynamics of the turbine system.

Acknowledgments

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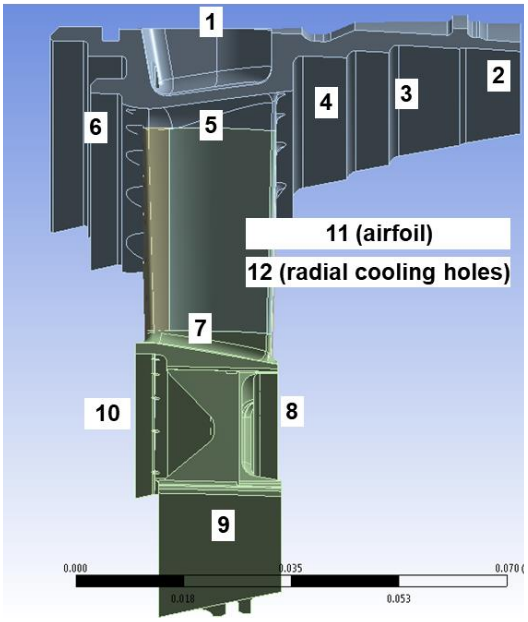
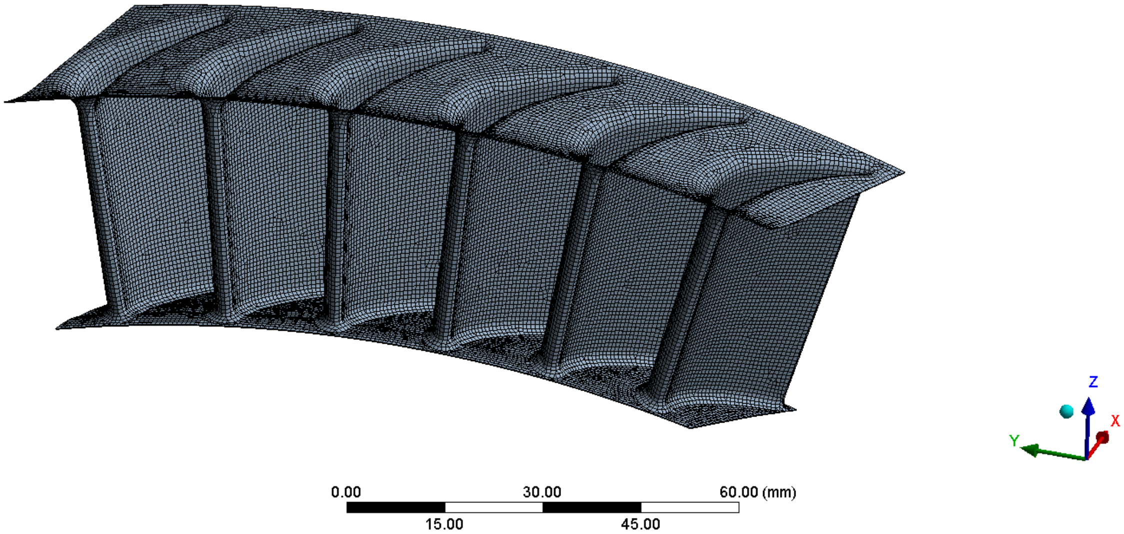
Appendix

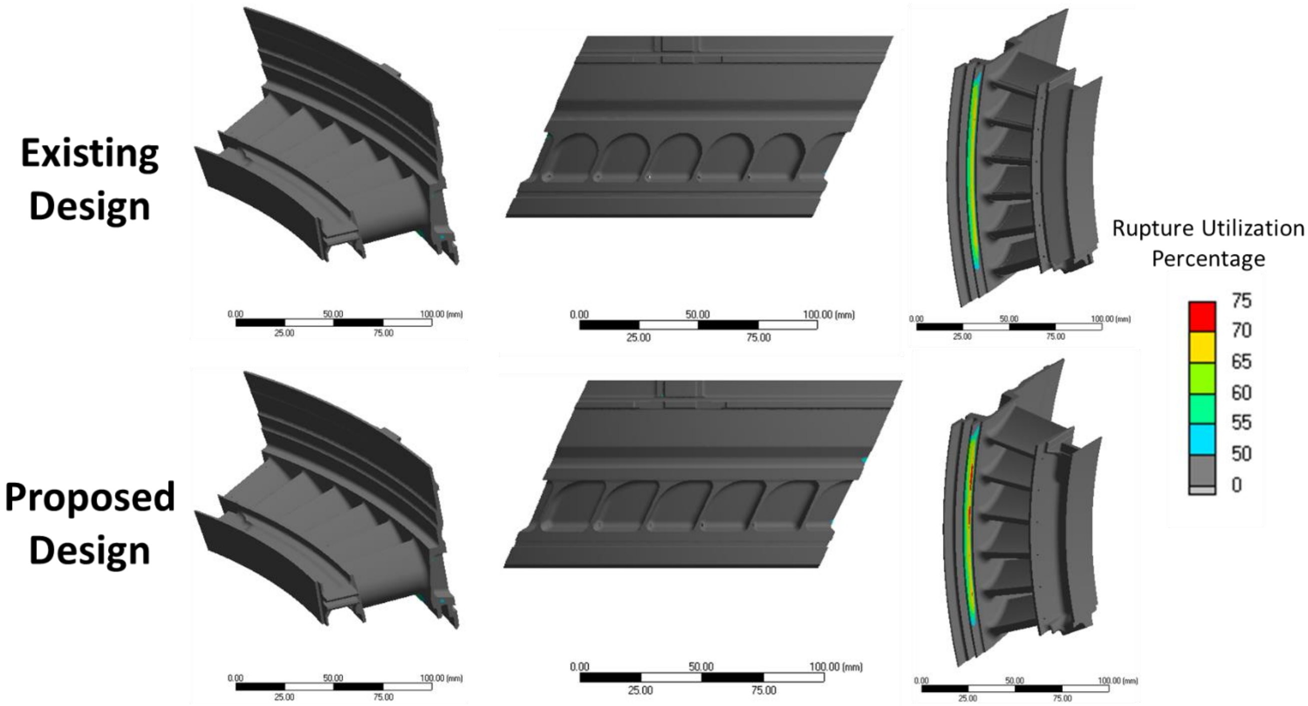
A.1 Locations of Loads and Boundary Conditions for Thermal Model



A.2 Thermal Shell used to Represent Bond Coating (suppressed for structural model)



A.3 Rupture Utilization Percentage Plots at 30,000 hours (100% = creep rupture occurs)



* Only Utilization Percentages greater than 50% are visible.

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