Computational Finite Element Analysis of Adaptive Gas Turbine Stator-Rotor Flow Interactions for Future Vertical Lift Propulsion

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Abstract
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Disciplines
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Comments

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The objective of this work is to computationally investigate the impact of an incident-tolerant rotor blade concept on gas-turbine engine performance under off-design conditions. Currently, gas-turbine engines are designed to operate at a single condition with nearly fixed rotor speeds. Operation at off-design conditions, such as during hover flight or during takeoff, causes the turbine blade flow to excessively separate introducing performance degradations, excessive noise, and critical loss of operability. To address these issues, the benefits of using an incidence-tolerant rotor blade concept is explored based on a novel concept that articulates the rotating turbine blade synchronously with the stator nozzle vanes. This concept is investigated using a novel CFD/FSI framework based on finite element analysis. The model considers a complex single stage high-pressure turbine geometry with 24 stator and 34 rotor blades operating under combustor exit flow conditions. The rotor speeds investigated are 44,700 rpm, 33,525 rpm, and 22,350 rpm corresponding to the design point at 100% speed down to 51% speed during off-design flight mode. This study focuses on determining the optimal performance benefits possible by exploring the limits of rotor blade articulation angles, as well as reporting its impact over a broad range of rotor speeds at Army relevant conditions. The key variables of interest include moments on the blade suction surface, torque, power, and turbine stage adiabatic efficiency. Further, sensitivity analysis of the uncertainties in boundary conditions is conducted to determine its influence on turbine efficiency. The results show that it is possible to increase efficiency increases of up to 10% by articulating rotor blades at off-design conditions thereby providing critical leap ahead design capabilities for the US Army Future Vertical Lift (FVL) program.

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I. Nomenclature

\( \eta \) = adiabatic efficiency  \\
\( \theta \) = articulation angle  \\
\( \gamma \) = constant specific heat  \\
\( \mu \) = dynamic viscosity  \\
\( d \) = distance  \\
\( F \) = force  \\
\( P \) = pressure  \\
\( P_{Si} \) = total pressure stator inlet  \\
\( P_{Re} \) = total pressure rotor outlet  \\
\( S \) = operating speed  \\
\( T \) = torque  \\
\( T_{Si} \) = total temperature stator inlet  \\
\( T_{Re} \) = total temperature rotor outlet  \\
\( V \) = velocity  \\
ALE = Arbitrary Lagrangian Eulerian  \\
ARL = Army Research Laboratory  \\
CAD = Computer Aided Design  \\
CFD = Computational Fluid Dynamics  \\
FE = Finite Element  \\
FSI = Fluid Structure Interaction  \\
FVL = Future Vertical Lift  \\
HPC = High Performance Computing  \\
SUPG = Streamline-Upwind/Petrov Galerkin  \\
VSPT = Variable Speed Power Turbine

II. Introduction

Innovative engines are in high demand because of the ever-higher power and efficiency requirements needed to advance today’s propulsion systems [1–8]. Different engine modifications have been proposed to meet those requirements. Particularly, one promising design is the variable speed power turbine (VSPT). A VSPT would have the capability of operating at several different conditions without facing the substantial performance losses seen in traditional gas turbine engine [1, 2, 4–12]. This capability would enable VSPT to meet the requested power and efficiency levels. Specifically, the application of VSPT can be seen in the US Army Future Vertical Lift effort, where it would be utilized in rotorcrafts to overcome the challenges associated with off-design operation. These challenges include aerodynamic flow separation around the turbine blades that result in significant engine performance losses [5–7].

To enable VSPT, a novel turbine technology has been proposed by the Army Research Laboratory. This technology would synchronously articulate the turbine’s stator and rotor blades to maintain ideal flow patterns therefore, achieving optimal engine performance at all operating conditions [5–7].

![Fig. 1 Schematic of proposed concept for turbomachinery blade articulation.](image)

The articulation of the stator will be achieved by using exterior actuators as pictured in Figure 2a. This approach is similar to the methods used for compressor inlet vane articulation [13–15]. The novelty of this technology stems from the rotor articulation which, will be achieved by an intricate mechanism. This mechanism will be located within the turbine shaft and feature multiple actuators that will pitch the blades while maintaining a balanced disk. A concept of this mechanism has been applied for patent by the ARL and is depicted in Figure 2b.

Preceding beyond the conceptual phase of developing this novel turbine technology requires us to increase our understanding on the flow dynamics associated with blade articulation in the turbine stage. In detail, our lack of understanding regards the complex flow fields that exhibit unsteady flow separation. This flow separation is followed by the formation of dynamic-stall-like vortices whose evolution and interaction with surfaces generate inconstant forces along the airfoil blades and have a significant impact on performance [5–7, 16–19]. This impact includes degraded...
turbine power and efficiency as well as increased structure stress, noise, and frequency of engine stall as well as the occurrence of shocks \cite{5,8,19}. Previous works have focused on understanding the aerodynamic phenomena related to blade articulation within the compressor section of the gas turbine engine. Wang et al. \cite{20} conducted computational analysis to demonstrate the performance benefits possible by articulating stator blades on a marine gas turbine engine and reported improvements in efficiency and fuel consumption. Wirkowski \cite{21} completed an experimental study on a marine gas turbine engine with variable compressor stator blades also reporting improved engine performance. Similarly, Cyrus \cite{22} measured several flow parameters to create a detailed flow field and obtained performance data of the unsteady flow within an axial compressor stage featuring stator and rotor articulation. This study concluded that combined stator and rotor articulations are able to improve compressor off-design performance by reducing flow separation. However, previous works failed to report information on the influence of blade articulation within the turbine stage and provided limited information on rotor blade articulation. This study computationally investigated this novel blade articulation technology by examining the influence of rotor blade articulation on turbine performance to address this lack of understanding.

This paper is outlined as follows. In section 3, this study’s turbine stage geometry, computational modelling parameters and analysis variables are discussed. The salient theoretical and technical aspects of the computational tool and methods used for analysis are described in Section 4. Next, Section 5 presents and discusses the results of this study. This includes a parametric study completed on the modeling parameters to ensure an accurate simulation and an extensive investigation on the relationship between blade articulation within in the turbine stage and the turbine stage’s performance. Lastly, Section 6 and 7 describe a variety of conclusions on this study and the path forward.

III. Problem Setup

A. Turbine Stage Modeling Details

This study investigated the articulation of rotor blades within an Army-relevant single stage high pressure turbine. This annular turbine stage has a total length of 210mm, an inner shaft radius of 77.7 mm and a casing radius of 95.5 mm. It is composed of 24 stator and 34 rotor blades, whose geometries and baseline positions are illustrated in Figure 3. The articulation of the rotor blade is completed about the leading edge through a CAD software, where a positive angle corresponds to a counterclockwise rotation.

Fig. 3 Illustration of stator and rotor blade geometries and baseline positions.
This turbine stage was selected to operate at application specific conditions to meet FVL requirements [1, 2, 4–7, 9]. These conditions include two off-design operating speeds of 50% (22,350 RPM) and 75% (33,525 RPM) as well as a design speed of 100% (44,700 RPM). These operating speeds effectively replicate different engine conditions that are seen during cruise, takeoff, and hover [1, 2, 4–7, 9]. Furthermore, the computational model operates under theoretical gas-turbine combustor exit flow conditions. This includes a uniform axial inflow with velocity of 82.3 m/s, temperature of 1669.78 K and pressure of 2.02 MPa at the inlet boundary. On the opposite end, the outlet boundary has a fixed pressure of 0.971 MPa which is validated through a parametric study discussed in section 5. The stagnation temperature of the stator and rotor blades are specified to 1673.15K and 1423.15K. Also, the inner shaft and outer casing surfaces have a no-slip velocity and adiabatic heat flux condition. The reference viscosity of air in this model is $\mu = 5.551 \times 10^{-5}$ kg/(m s). The dimensions and parameters of this model are summarized in Figure 4.

![Diagram of turbine stage](image)

**Fig. 4** Parametric conditions of turbine stage.

### B. Model Analysis

To analyze the performance of the different rotor blade positions, the following were examined: turbine output power, turbine adiabatic efficiency, rotor blade pressure contours and streamline plots. Referencing several sources [1, 2, 4–7, 9, 23, 24, 25], power and efficiency are considered to be key variables in designing a turbine because these variables give insight on the capabilities of turbine. Furthermore, output power is calculated as follows:

$$P = F \times V$$

where $F$ is the total force produced by the rotor blades and $V$ is the velocity of the blades. This equation may be rewritten as:

$$P = \frac{n \times T}{d} \times V$$

where $n$ is the total number of rotor blades, $T$ is the torque produced by an individual rotor blade, $d$ is the distance from the rotor blade to the turbine’s drive shaft and $S$ is the operating speed.

Adiabatic efficiency is examined since our model features a zero-heat flux condition as discussed in the previous paragraph. Adiabatic efficiency is calculated with the following equation:

$$\eta = \frac{1 - \frac{T_{Ro}}{T_{Si}}}{\frac{1}{\gamma - 1}}$$

$$\frac{1 - \frac{P_{Ro}}{P_{Si}}}{\gamma}$$
where $T_{Ro}$ is the total temperature at the rotor blade outlet, $T_{Si}$ is the total temperature at the stator blade inlet, $P_{Ro}$ is the total pressure at the rotor blade outlet, $P_{si}$ is the total pressure at the stator blade inlet and $\gamma$ is the specific heat constant.

The rotor blade pressure contours and streamline plots are created in the post-processing phase through Tecplot 360ex. These illustrations allow us to locate and rate the magnitude of flow separation. Specifically, they help us to visually identify and analyze turbulence, recirculation zones and pressure disparity regions.

The calculation of these performance metrics is completed with time-averaged data. The model operates for 2.2 revolutions to develop the flow field. Afterwards, 3.3 revolutions are completed and averaged. The data is extracted with a validated spatially averaging technique.

IV. Computational Approach

A. CFD Methodology

To simulate the complex fluid dynamics associated with blade articulation in a turbine stage, a novel finite element (FE) fluid-structure interaction (FSI) code was utilized. Xu et al. [26] developed and extensively validated this application specific code. This code features a novel mathematical approach to compute the Navier–Stokes equations for compressible flows [26]. The approach is based on finite element analysis that couples the fluid and structure. This code is stabilized by the use of the SUPG method. Also, the formulation is written in the arbitrary Lagrangian-Eulerian (ALE) frame which, is an FE formulation where the mesh elements are not fixed in space or attached to a material. This frame has been proven to work in CFD applications that involve moving domains [27, 29]. The novelty of this code’s formulation originates from the use of weakly enforced boundary conditions and sliding interface formulations [26]. The weakly enforced boundary conditions are imposed on the stator/rotor blades and allow for the reduction of resolution in the boundary layer. In addition, the sliding interface formulations allow the code to separate and couple the computational domains into two subdomains that have relative motion. Specifically, the two subdomains are a stationary region consisting of the stator blades and a moving region consisting of the rotor blades.

The use of this novel code has been comprehensively validated among many subjects, where experimental data exists. Xu et al. [26] compared this code’s results to experimental values obtained for subsonic and supersonic flow around a NASA’s delta wing and turbulent flow around a sphere. All of these comparisons showed strong agreement and the code was then extended to modeling blade articulation within a turbine stage. Furthermore, this validation study [26] reported that the weakly enforced boundary conditions were more accurate than the strong boundary conditions for under-resolved engineering cases.

B. CFD Mesh

As stated above, the advantage of using weakly enforced boundary conditions is they allow for the reduction of resolution in the boundary layer. This model features a coarse tetrahedral mesh with local refinement in section 2 of the turbine as shown in Figure 5. The mesh used in this study consists of roughly 11.7 million elements and has been suggested by Xu et al. [26].

![Fig. 5 Cross-section of gas turbine stage to illustrate mesh quality.](image_url)
V. Results and Discussion

A. Parametric Study

Prior to investigating the relationship between blade articulation and turbine performance, a parametric study evaluating the modeling parameters was completed. This study focused on ensuring the theoretically derived modeling conditions presented in section 2 are accurate and physically possible. Specifically, this study concentrated on the outflow boundary conditions as it is a challenging topic in CFD which requires special numerical treatment. This difficulty stems from the fact that most experiments do not report outflow conditions, causing model uncertainties. To reduce this uncertainty, a sweep of the outflow pressure as a key modeling parameter was conducted to reveal its impact on turbine performance.

An approximate outflow pressure of 1.21 MPa was derived from theory and swept by +/-20%. The parametric sweep results indicate that a pressure beyond 1.1 MPa yields unrealistic values of efficiency and should be disregarded. Referencing industry standards for single stage axial gas turbine engines [1, 4, 8, 30], an outflow pressure of 0.971 MPa is considered to be most accurate with an approximate efficiency of 85%.

B. Rotor Articulation Investigation

After ensuring the model’s parameters were accurate and realistic, an extensive study of rotor blade articulation was conducted at various turbine operating conditions. A total of 45 cases were simulated with the rotor blade articulated at angles between $-18^\circ < \theta < +66^\circ$ from the baseline position. A comprehensive data set was obtained on the aerodynamic fluid behavior at design and off design operating conditions. The results are presented and discussed for a primary study on the moderate range of blade articulation $-15^\circ < \theta < +15^\circ$ and subsequently, a secondary study on the extreme cases between $-18^\circ < \theta < +66^\circ$.

Murugan et al. [31] states that the proposed mechanism for blade articulation will have the capability to pitch the blades +/-15°. Therefore, the primary focus of this investigation was to explore this mechanism’s capabilities in this moderate articulation range. The results are shown in Figures 6 and 7 that illustrates rotor blade pressure contours and rotor blade streamlines for various positions that illustrate the influence of blade articulation on gas turbine performance.

Fig. 6 Selected cases of moderate rotor blade articulation. Rotor blade pressure contours.
These results indicate that a positive angle articulation results in flow separation initiating closer to the leading edge and an increase of the recirculation zone on the suction side and at the trailing edge. There is also a notable decrease in the recirculation zone at the leading edge of the pressure side and a reduction in pressure disparity on the blade. In summary, these results suggest that a positive articulation increases flow separation and turbulence intensity in the near field. Further, a decrease in operating speed, or in other words, operation at an off-design condition causes flow separation initiating closer to the leading edge and an increase in the recirculation magnitude but, a decrease in the area of recirculation. Similar to a positive articulation, operation at an off design condition results in increased flow separation and enhanced turbulence.

The extreme articulation range was to match previous blade articulation studies and further investigate blade articulation influence on turbine performance. Specifically, Suder et al. [32] investigated a pitching range of 80°s to explore the effect of blade articulation on the pressure loss coefficient and Ainley and Mathieson [33] investigated rotor stage losses while using a pitching range of 60°s. It is important to note that these extreme blade articulations include positions that contradict basic turbomachinery standards but, they do provide insight on the notable effect of wider range articulation angles. This includes significant changes to the flow dynamics within the rotor passage like point of separation, velocity surges, and turbulence behaviors. At each operating speed, a negative articulation reduces flow separation and increases the velocity in the wake region. This is due to the reduction in the throat area and local increase in the pressure fields. Conversely, positive articulation leads to enhanced flow separation and augmented re-circulation regions at the leading edge. There is also a significant reduction in flow velocity in the wake region at each operating
speed that is associated with the larger throat area and reduced pressure loses. The rotor flow results are summarized in streamline plots of Figure 9 and serve to interpret the analysis related to engine performance metrics. These common and consistent trends in the fluid’s behavior have a direct relationship to turbine performance.

Figure 8 presents a summary of each of the performance metrics versus rotor blade articulation angle. When flow separation increases there is a significant loss in gas turbine efficiency. This relationship is evident from the positive articulation results showing the decrease in efficiency, and this is also supported by streamline flow analysis shown in Figure 9.

However, the results show that there is a notable penalty in turbine power as shown also in Figure 8. This penalty is seen for any articulation angle below the baseline and down to -18°. There is also a notable plateau region in turbine power past +10° articulation. This suggests that only engine efficiency and flow turbulence is influenced in this region, and it can be used to design control methods to further optimize the engine efficiency parameters.

![Fig. 8 Gasturbine engine performance metrics dependencies on rotor blade articulation angle during operation. (Top) shaft power, (Bottom) adiabatic efficiency.](image_url)
Fig. 9  Selected cases of extreme rotor blade articulation. Rotor blade streamlines on relative velocity contour.
VI. Conclusion

In this work, a novel FE FSI computational model was utilized to study the effects of rotor articulation on the aerodynamic flow characteristics within a turbine and the turbine’s performance. A systematic approach was implemented to study the model’s sensitivity to the pressure outflow boundary condition and to ensure an accurate and realistic simulation. Afterwards, the impact of rotor articulation on turbine performance and flow dynamics at design and off-design operating conditions were examined. This investigation had a primary focus on the moderate articulation range that was suggested by the rotor articulation mechanism patent and a secondary focus on matching previous studies pitch ranges. The comprehensive goal of this investigation was to obtain an extensive understanding of the flow dynamics associated with blade articulation at various operating conditions.

The results showed a prominent effect from a wide range of articulation angles on the rotor passage flow dynamics including point of separation, surge in velocity, and enhanced turbulence behavior. At each operating speed, negative articulation reduces flow separation and increases the velocity in the wake region. This is due to the reduction in throat area and local increase in the pressure fields. Conversely, positive articulation leads enhanced flow separation, more re-circulation zone regions at the leading edge. There is also a significant reduction in flow velocity in the wake region at each operating speed that is associated with the larger throat area and reduced pressure loses. The flow separation and pressure losses lead to a significant degradation in gas turbine efficiency. This relationship is evident from the positive articulation results showing the decrease in efficiency as well as the streamline flow and pressure surface analysis results in this range. Further, it was also shown that there is a notable penalty in turbine power at the same conditions. This penalty is seen for articulation angles below the baseline and down to -18°. There is also a notable plateau region in turbine power past +10 degrees articulation. This suggests that only the turbine efficiency and turbulence is influenced in this region, and it can be used to design control methods to further optimize the turbine stage’s performance.

In summary, this study provided much needed information on the aerodynamic and thermal turbulent flow characteristics in the rotor passage under a wide range of blade incidence angles. It determined the possible limits on articulation and expected performance benefits that can serve to influence the Army gas turbine engine development programs.

VII. Future Work

This study will be continued to further explore and understand the relationship between blade articulation and gas turbine engine performance by investigating stator articulations and synchronous vs non-synchronous stator/rotor articulation. Furthermore, this study only simulated rotor blades articulated at a fixed angle. Future simulations could simulate dynamic articulation movement in the simulation that would then show the transient effects of the blades from original position to their final position.

The results from this study and future studies will help in the design of a variable speed gas engine turbine. This turbine could change the blade angles according to operating conditions thus leading to a more efficient and more powerful engine across all operating conditions, including off design conditions which would hinder traditional turbine engine performance. One method to achieve this variable speed gas engine turbine is to use blade articulation mechanisms. A proposed rotor articulation mechanism has been filed for patent by the US Army Research Laboratory [31].

VIII. Acknowledgments

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References


