Articulating Axial-Flow Turbomachinery Rotor Blade For Enabling Variable Speed Gas Turbine Engine

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Abstract
Current technology gas turbine engines are generally optimized to operate at nearly a fixed speed with fixed blade geometries for the design operating condition. When the operating condition of the engine changes, the flow incidence angles may not be optimum with the blade geometries resulting in reduced off-design performance. But, if we have the capability of articulating the pitch angle of axial-flow compressor/turbine blades in coordination with adjustable stator vanes, it can improve performance by maintaining flow incidence angles within the optimum range for given blade geometries at all operating conditions. Maintaining flow incidence angles within the optimum range can prevent the likelihood of flow separation in the blade passage and also reduce the thermal stresses developed due to aerothermal loads for variable speed gas turbine applications. This paper discusses a recent invention of adaptable articulating axial-flow compressor or turbine rotor blade that can significantly impact developing a high efficiency variable speed gas turbine for rotorcraft or ground vehicles that may need to operate optimally at different torque/speed conditions during various maneuvers. U.S. Army Research Laboratory has partnered with University of California San Diego and Iowa State University Collaborators to conduct high fidelity stator-rotor interaction analysis for evaluating the aerodynamic efficiency benefits of an articulating axial flow turbine blade concept. In addition, a design study for articulating turbine or compressor rotor blade using smart material based actuators using Shape Memory Alloy (SMA) has been carried out. Highly coupled fluid-structure interaction computational study of articulating turbine rotor and stator blades, together with a design concept of articulating axial-flow turbomachinery rotor blade using a smart material such as SMA is presented.

Disciplines

Comments

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Current technology gas turbine engines are generally optimized to operate at nearly a fixed speed with fixed blade geometries for the design operating condition. When the operating condition of the engine changes, the flow incidence angles may not be optimum with the blade geometries resulting in reduced off-design performance. But, if we have the capability of articulating the pitch angle of axial-flow compressor/turbine blades in coordination with adjustable stator vanes, it can improve performance by maintaining flow incidence angles within the optimum range for given blade geometries at all operating conditions. Maintaining flow incidence angles within the optimum range can prevent the likelihood of flow separation in the blade passage and also reduce the thermal stresses developed due to aerothermal loads for variable speed gas turbine applications. This paper discusses a recent invention of adaptable articulating axial-flow compressor or turbine rotor blade that can significantly impact developing a high efficiency variable speed gas turbine for rotorcraft or ground vehicles that may need to operate optimally at different torque/speed conditions during various maneuvers. U.S. Army Research Laboratory has partnered with University of California San Diego and Iowa State University Collaborators to conduct high fidelity stator-rotor interaction analysis for evaluating the aerodynamic efficiency benefits of an articulating axial flow turbine blade concept. In addition, a design study for articulating turbine or compressor rotor blade using smart material based actuators using Shape Memory Alloy (SMA) has been carried out. Highly coupled fluid-structure interaction computational study of articulating turbine rotor and stator blades, together with a design concept of articulating axial-flow turbomachinery rotor blade using a smart material such as SMA is presented.

I. Nomenclature

\[ \alpha = \text{Absolute flow angle with respect to axial} \]
\[ \beta = \text{Relative flow angle with respect to axial} \]
\[ ARL = \text{U.S. Army Research Laboratory} \]
\[ C = \text{Absolute flow velocity} \]
\[ Ca = \text{Axial component flow velocity} \]
\[ CFD = \text{Computational fluid dynamics} \]
\[ FSI = \text{Fluid-Structure Interaction} \]
\[ I = \text{incidence angle} \]
\[ NiTi = \text{Nickel-Titanium shape memory alloy} \]
\[ p = \text{Pressure} \]
\[ Re = \text{Reynolds number} \]
\[ rpm = \text{rotations per minute} \]
\[ SHP = \text{Shaft horse power} \]

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SMA = Shape Memory Alloy  
T = Temperature  
U = Blade tangential velocity  
V = Resultant flow velocity

II. Introduction

Gas turbine blades of conventional rotorcraft turboshaft engines, as depicted in Fig. 1, are optimized to operate at nearly a fixed speed and a fixed incidence angle. If the operating condition of the engine changes, then the flow through the turbine or compressor may need to be guided to a more optimum direction using adjustable stator vanes to minimize the incidence angle. However, this traditional method has some disadvantages, such as, increased weight and complexity, and also limited operating range for optimization, since the nozzle vanes can only be turned to a certain amount before severe flow incidence angles begin to affect the rotating blades downstream.

Another approach to increase the operating range of turbine engines is to design a rotor blade that is also “incidence tolerant” of the incoming flow angles. Incidence tolerant blade research has been conducted by NASA Glenn Research Center (NASA-GRC) and ARL as a potential solution for maintaining turbine blade aerodynamic performance for a variable speed power turbine [1]. Variable speed power turbines (VSPT) are a potential enabling technology for high speed tilt rotorcraft, where the power turbine speed needs to be slowed down by as much as 51% during cruise flight compared to hover flight [2]. There are significant design challenges for turbine blades operating over such speed ranges due to the turbine blades experiencing a wide range of incidence angles and Reynolds numbers [3]. Slowing down the power turbine significantly will need higher work factors (flow turning) and will result in lower efficiencies as compared to a turbine optimized for nearly constant high speed (100%) operation [2]. While the previous approaches of incorporating variable stator nozzle vane geometry and incidence tolerant blading can increase the operating range of a turbine to some extent, further optimization and performance improvements could be achieved by articulating the rotor blades of the axial-flow turbine or compressor in coordination with stator vanes. This study explores an innovative approach to incidence tolerant blade design by articulating the pitch angle of rotating gas turbine blades and stator vanes synchronously for variable speed gas turbine engine applications to always maintain optimum incidence angles for maximum aerodynamic performance. This study will discuss stator-rotor interaction analysis conducted on articulating high pressure turbine blades and stator vanes synchronously with the goal of achieving improved aerodynamic efficiency over a wide range of off-design operating conditions. In addition, a design concept study has been conducted to package the actuators and mechanisms for achieving the articulation of rotor and stator blades together in a synchronous manner to maximize the performance. It is postulated that the axial-flow compressor and turbine blades (both stator/rotor blades) will benefit from the articulating blade technology concept in terms of optimized aerodynamic performance, reduced thermal stresses, widened engine stall margin, and higher energy conversion at a wide range of operating conditions.

III. Articulating Incident Tolerant Rotorcraft Concept

For illustration purposes, an example of typical stator and rotor blade flow passages for an axial flow turbine stage is shown in Fig. 2. The blade shapes shown are for reference only. In gas turbine engines the stator and rotor blade rows are close together; typically the gap is approximately 20% of the blade chord [4]. For the cascade shown in Figure 2, the corresponding flow velocity triangles are shown in Figure 3 for a conceptual design condition (100%
gas turbine rotor speed). For the chosen blade geometry, the flow at inlet to stator and at the exit of rotor has a slight tangential swirl as seen from the velocity triangles, shown in Fig. 3. In Fig. 3, \( C_1 \) corresponds to absolute flow velocity at inlet to the turbine stator or nozzle. The stator inlet blade angle is denoted as \( \alpha_1 \). \( C_{a1} \) is the axial component of flow velocity at inlet to the stator. \( U \) denotes the tangential velocity of the rotor blade. \( V_2 \) denotes the relative flow velocity at inlet to the blade passage. \( \beta_2 \) is the inlet rotor blade angle with respect to axial direction as shown in Fig. 3. \( C_2 \) is the absolute flow velocity at rotor blade inlet. \( \alpha_2 \) is the absolute flow angle with respect to axial direction at inlet to rotor blade passage. Similar notations apply to the flow velocity triangle at the rotor blade passage exit noted with suffix 3.

**Fig. 2** Stator and rotor blade passages in axial flow turbine stage.

**Fig. 3** Flow velocity triangles through stator and rotor blade passages for axial flow turbine stage (design condition).
One example of wide variation for engine speed/torque would be a power turbine for a tilt rotor aircraft. If the engine condition changes, say from take-off (100% power turbine speed) to cruise (50% power turbine speed) for a tilt-rotor vehicle, the incidence flow angles will change significantly. For a given off design condition, the resulting flow velocity triangles and blade angles for reduced gas turbine speed are shown conceptually in Fig. 4. In Fig. 4, the changed flow velocities and angles are shown through the stator and rotor blade passages. Since the vane and blade geometric angles always remain the same, the performance of the turbine would decrease due to high incidence angles and resulting flow separation losses. Figure 5 shows the typical aerodynamic loss (called as profile loss due to blade geometric profile) bucket curve increases rapidly as the incidence angle deviates away from zero [5]. For fixed axial-flow turbine blade geometry, Fig. 5 shows the variation of relative profile loss coefficient \( Y_{P}/Y_{P(i=0)} \) with respect to relative incidence \( (i/i_s) \) [5]. In Fig. 5, \( Y_{P} \) denotes profile loss at incidence \( i \), \( Y_{P(i=0)} \) denotes profile loss at incidence=0, \( i \) denotes incidence angle, \( i_s \) denotes stalling (flow separation causing) incidence angle. From this figure, it is evident that the allowable incidence variation is limited to have reduced profile loss in an axial-flow turbine cascade. Hence, if both stator vanes and rotor blades were able to articulate to change their respective flow incidence angles, as shown conceptually in Fig. 6, flow separations can be prevented; thus aerodynamic losses would be minimized; and turbine performance would remain optimum at all operating conditions.

Fig. 4 Flow velocity triangles through stator and rotor blade passages for axial flow turbine stage (off-design condition).

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IV. CFD Modeling Setup

The methodology proposed is to optimize the pitch angles of the stator and rotor blades synchronously and perform a series of simulations with different pitch angles. This requires a capability to change the blade-pitch angles parametrically. Following the idea of interactive geometry modeling platform by Hsu et al. [6], a parametric design tool was built based on Rhinoceros 3D [7] and Grasshopper [8]. The grasshopper tool is shown in Fig. 7(a). Note that we have two input parameters, “Rotor Pitching” and “Stator Pitching”. By changing the numbers in these two slider bars, we can directly change the pitching angle of the rotor and stator blades parametrically in our 3D model. The resulting geometric model is generated automatically and is ready for grid generation and analysis. The annular blade geometries with zero pitching and pitching by $15^\circ$ are shown in Fig. 7(b) and Fig. 7(c) respectively.

Fig. 5 Variation of profile loss with relative incidence angle [5]

Fig. 6 Coordinated articulation of stator and rotor blades for incident tolerance (conceptual).

Fig. 7(a) Parametric design tool in Grasshopper.
The Computational Fluid Dynamics (CFD) analysis was carried out on the full annulus region of a turbine stage using a finite-element based formulation to solve the 3-D compressible Navier-Stokes equations, developed by Iowa State University and University of California San Diego collaboration [9, 10]. The CFD mesh created with local refinement for stator section is shown in Fig. 8. In this work, we use SUPG [11] as the core technology to numerically solve the compressible Navier-Stokes equations. Novel stabilization techniques based on SUPG are developed, to both better stabilize the formulation and to model the turbulence. While the Eulerian frame of reference is commonly used for CFD applications, in order to describe the flow inside the turbine passage which includes the spinning rotor and stationary stator vanes, we employ the Arbitrary Lagrangian-Eulerian (ALE) formulation for compressible flow [12]. Furthermore, we partition the computational domain into the rotor and stator subdomains and couple them through the sliding interface [13], a formulation we extended to compressible flow in the present work. Finally, weakly enforced no-slip conditions [14, 15] are imposed on the blade surfaces in order to avoid excessive resolution of the turbulent boundary layers.

Additionally, in order to check the fidelity of the simulation using the newly developed method with finite-element based formulation as described above, a concurrent effort at ARL is also underway using the CONVERGE CFD multiphysics software [16] to simulate the flow field with articulating blade concept. CONVERGE is a finite-volume compressible Navier Stokes solver, based on a first order predictor-corrector (Pressure Implicit with Splitting of Operator (PISO) time integration scheme, and a choice of second or higher order finite volume schemes for spatial
discretization. The code uses various time-step controls to ensure that important flow parameters (e.g., CFL number, combustion rate, spray penetration) are kept below user-specified maximum values. This important feature is necessary to accurately resolve the different (and sometimes competing) physical phenomena involved [17]. To compute Fluid-Structure-Interactions (FSI), it computes external forces (e.g., aerodynamic and gravitational forces), and moments to model FSI. These forces are computed by a numerical integration of pressure and shear stress over the object’s surface [18]. It provides the option of increasing resolution through fixed-grid embedding and locally through Adaptive Mesh Refinement (AMR) methods. Further, it also provides a number of turbulence modeling options including contemporary forms of Large Eddy Simulation (LES) and Reynolds-averaged Navier-Stokes (RANS).

V. Computational Results and Discussion

A. Results from finite-element based FSI code

The reported turbine stage is designed to have an axial inflow velocity of 82.3 m/s. The tangential rotating speed at the tip of rotor blades is 447.23 m/s. The velocity triangle follows Figure 3, with $\beta_2$ matching the blade inlet angle of rotor blades. With the adaptive turbine blade we proposed earlier, we are able to pitch the rotor blades to change the blade inlet angle to match different stator exit flow angles. The 3-D flow field of flow inside the full annulus of the turbine stage is shown in Fig. 9.

![Figure 9](image)

**Fig. 9 Flow inside a gas turbine stage. Vorticity colored by velocity magnitude.**

Figure 10 shows the absolute velocity contour on a planar cut through the turbine stage. In Fig. 10(a), the inflow (stator exit flow) direction doesn’t match the blade inlet angle of the rotor, creating a large incidence angle. As a result, we pitch the rotor blades clockwise by 10° to better match the blade inlet angle to the flow inlet angle $\beta_2$. From Figs. 10(a) and 10(b), we can clearly see that after pitching, the flow exits the rotor passages with a smaller magnitude, meaning that after pitching more flow momentum is converted into rotor torque, therefore reducing the associated losses and improving the turbine design.

![Figure 10](image)

(a) Before pitching       (b) After pitching

**Fig. 10 Absolute flow velocity in a turbine stage.**
We show the relative velocity field inside the rotor passages in Fig. 11. Before pitching the rotor blades, since $\beta_2$ is smaller than the blade inlet angle, the flow is not fully attached on the pressure surface and the suction surface, which is not the optimal flow under these inlet conditions (see Fig. 11(a)). By pitching the rotor blade, we are able to recover a more optimal flow field associated to the turbine inlet condition. The flow is fully attached to the blades, on both the pressure and suction surfaces, as shown in Fig. 11(b).

![Streamlines of relative velocity in a rotor passage.](image)

(a) Before pitching  
(b) After pitching

**Fig. 11** Streamlines of relative velocity in a rotor passage.

### B. Results from CONVERGE FSI code

Figure 12 shows the 3-D flow field inside the turbine stage using the commercial CONVERGE software for the same flow conditions that were used in the newly developed finite-element based FSI code. In this study, the flow turbulence is modeled via a Reynolds Averaged Navier Stokes (RANS) approach and adaptive mesh refinement (AMR) that resolves the flow field in local intensity regions accurately and efficiently. The rotor is operating at 100% speed, 44,000 rpm, and is modeled via moving boundary approach and the rigid body fluid-structure-interaction approach. At the blade surface, a law of the wall model is utilized at a location of $y^+ = 50$ to avoid the excessive cost of resolving the viscous region. Further, a sinusoidal dynamic pitching blade motion is imposed at the rotor leading edge that extends from +20 to -20 degrees from the leading edge to come up with optimum blade angle orientation for the given flow conditions.

![Flow inside a gas turbine stage. Vorticity colored by velocity magnitude using CONVERGE CFD.](image)

**Fig. 12** Flow inside a gas turbine stage. Vorticity colored by velocity magnitude using CONVERGE CFD.

Figure 12 shows the 3-D flow field inside the turbine stage computed with the CONVERGE software using 256 processors and with a total count of 10 Million cells, highlighting the iso-surfaces of velocity. To better visualize the complex flow through the nozzle vanes a velocity iso-contours is extracted at 15 degrees during the rotor blade pitching, shown in Fig. 13. The current results demonstrate the ability of the high-fidelity commercial software to accurately model crucial features in stator-rotor interactions. It also provides a dynamic articulation framework and a stabilized solution. The developed tool will serve as the basis for future computational research as well as to cross-check the results from the newly developed FSI computational code through collaboration with University of San Diego and Iowa State University researchers.
Fig. 13  Absolute flow velocity in a turbine stage using CONVERGE CFD at 15 degrees.

C. Stage efficiency calculation
Gas turbine performance may be assessed by computing the adiabatic efficiency of the turbine stage. The adiabatic efficiency is defined as the ratio between the actual and isentropic (ideal) power output. With subscripts 1 and 3 denoting quantities at the stator inlet and rotor exit, respectively (as shown in Figs. 2 and 3), the adiabatic efficiency $\eta_{ad}$ is given by the equation as shown below [19].

\[
\eta_{ad} = 1 - \frac{T_3}{T_1} \left( \frac{P_3}{P_1} \right)^{\frac{\gamma-1}{\gamma}}
\]

where $\gamma$ is the specific heat capacity ratio of air, and T & P are total temperature and pressure at respective locations denoted by the subscripts. Using the above formula in the post-processing of our simulation results from the newly developed finite-element based FSI code, we find that we can obtain a 5% increase in stage efficiency between the baseline (before pitching) and after pitching (after 10° blade articulation) cases, shown in Fig. 11. This shows that turbine blade pitching can help improve gas turbine efficiency under off-design conditions significantly. In the actual design of adaptive blade technology gas turbine engines, it is envisaged that we can use an inlet flow velocity sensor (to provide flow direction & magnitude) to determine the in-flow incidence angle, and the blades can be articulated accordingly using a feedback control algorithm to set the blade at the optimum orientation for the best aerodynamic performance possible for each changing operating condition.

VI. Blade Articulation Mechanisms Design Study
In general, the blade actuation device can be built of hydro-mechanical mechanism or pneumatic-mechanical mechanism or electro-mechanical mechanism or MEMS (Microelectromechanical systems) based/piezo-electric material based mechanism or magnetic/electro-magnetic material based mechanism or Shape Memory Alloy (SMA) smart material based mechanism, as examples. The inner portion of the blade airfoil base mating with turbine rotor disk (turbine blisk) can be housed with suitable actuation device that is used to rotate or change the pitch angle of each individual rotor blade synchronously from its base. The blade rotation can be performed about a point close to the leading edge of the blade. This rotation changes the geometry of the blade angle with respect to the incoming flow incidence angle. By pitching the rotor blades in coordination with the adjustable stator nozzle vanes, the flow incidence angles can be maintained within the optimum range for improved aerodynamic performance. A typical turbine rotor blade with a fir tree base attachment is shown in Fig. 14. Figure 15 shows a typical turbine rotor blisk. Considerable design changes are needed to incorporate an articulating blade attached to a rotating turbine disk.
Figure 14 illustrates a blade articulation mechanism for a turbine rotor blade that is housed inside a hollow turbine disk. This picture shows SMA torque-tube actuator that is used to articulate or pitch the blade to reduce the incidence angle. The rotor blade can be any conventional design used for axial-flow turbine or compressor. The SMA torque tube drives an actuator-gear which in turn drives a blade pitch-gear (shown in Fig. 17). The circular disk shaped base of the turbine rotor blade is rotated as needed to change the incidence angle with the incoming gas flow. The inlet flow angle minus the blade geometric angle gives the incidence angle, i.e. The incidence angle is equal to 0 deg. for optimum performance with least aerodynamic profile loss coefficient [5].

For the proposed design (shown in Fig. 17), the smart material based actuators are housed inside the turbine disk from a packaging design consideration. However, the actuator will have to survive turbine disk temperatures that could reach 700°C and above. The advantage with this design packaging is that the temperature inside the turbine disk would be considerably lower than in the blade itself, allowing the possibility of using a NiTi SMA combined with Pd, Pt, Au, Hf, or Zr to sustain temperatures in the range of up to ~ 800°C. Currently, there has been continued interest in developing high temperature shape memory alloys (SMA) for applications in aerospace, automotive, and energy industries. However, the present commercially available NiTi SMA alloys are limited in their high temperature durability and sustainability characteristics. The addition of Pd, Pt, Au, Hf, and Zr to NiTi alloys have shown some potential to increase the high temperature sustainability of NiTi alloys up to ~800°C, but their mechanical strength characteristics at high temperatures have not been fully investigated. Active research is being conducted to overcome the practical temperature limitations for ternary TiNiPd and TiNiPt alloys and the ability of these alloys to undergo repeated thermal cycling under load without significant permanent deformation [20]. We plan to use high temperature capable NiTi alloys for developing a prototype articulating blade concept in our research. There are considerable materials challenges that include functional and structural fatigue under repeated actuations. Transmission electron microscopy studies show the development of plasticity when SMAs are heated and cooled, even in the absence of an external load. New high-temperature Ni-Ti-Hf alloys are able to suppress this phenomenon by engineering nanoscale precipitates that suppress plasticity and yet allow the phase transformation to progress seamlessly [20]. An understanding of these phenomena is critical to the design and application of new high temperature SMAs for blade articulation in gas turbine engine applications.
Fig. 16  Blade articulation design mechanism for a turbine rotor blade using SMA torque tube actuation

Fig. 17  Mechanism design concept for rotor blade (inside details)

Fig. 18  Sketch showing articulation mechanisms housed inside hollow turbine rotor disk
Figure 18 shows the arrangement of articulation mechanisms for all blades inside a hollow turbine or compressor rotor disk. For turbine, inside this hollow disk environment, where all articulation mechanisms are located, the temperature can be controlled (if needed for SMA torque tubes) by using bleed air from the compressor section of the engine. The temperature inside can be brought to about \(-450\) deg. C, so that the Hafnium doped NiTi SMA material (currently being researched for actuations under high temperature environment) can survive in this temperature environment. Figure 19 shows an embodiment of a design with four high torque capable SMA torque tubes and a set of linkage mechanisms to pitch all blades synchronously. This is similar to the embodiment shown in Fig. 18, except that this design arrangement shown in Fig. 19 uses less number of SMA torque tubes, which could result in a design option that may have less overall mass, less design complexity, and less packaging design space needed.

**Fig. 19** Sketch showing alternate mechanism design with few SMA tubes and linkages for articulation

Figure 20 shows a typical turbine stator nozzle vane doublet. Figure 21 shows a typical turbine nozzle ring. Figure 22 illustrates the turbine stator blade articulation mechanism embodiment that can be housed on the engine casing. This design concept is very similar to the rotor blade actuation mechanism shown in Fig. 16. It also uses SMA torque tube and a set of two gears. Since the stator vane is stationary, the vane with its articulation mechanism (Fig. 22) is housed on top of the engine casing. The stator blade in this case is articulated synchronously with the downstream rotor blade (shown in Fig. 16) to improve the off-design performance of the engine in the most optimum way.

**Fig. 20** Typical turbine stator nozzle vane.
A flow velocity & direction sensor together with a blade rotational displacement sensor can be used to have a feedback control algorithm for efficient control of blade articulation. Using the sensors and feedback control algorithm, the rotor/stator blades can be oriented and adjusted to remain at the optimum position dynamically during engine operation for the efficient performance of the engine at different operating conditions. Figure 23 depicts an example control system architecture which can be used to control the articulation of stator and rotor blades synchronously. It will be a feedback control system with the sensors (i.e., turbine rpm sensor, stator inlet flow velocity (with direction) sensor, blade angular position sensor, and blade geometric angle inputs (for a given design)) as shown in the flow chart (Fig. 23). Any suitable processor, micro-processor, or computing system may be used. The control section may be a proportional–integral–derivative controller (PID controller) which uses a control loop feedback, for instance.

While independent and separate control of the stator and rotor blades is possible, synchronous articulation control of both stator and rotor blades is preferable (in many instances) since this provides wider margin of control to effectively influence improved performance of each stage (Stage includes both stator & rotor) for all blade passages in the holistic annular flow field. For variable speed engine performance optimization, a turbine rpm sensor can be used. The rpm sensor types can be optical or Hall effect or brushless motor, for instance. The Hall effect or optical sensors can have good accuracy for use in a control system. The inlet flow velocity and angle sensors can be located at inlet to stator blade and at inlet to the rotor blade. Select sensors should be able to withstand the engine environment. Typically, the current applied to SMA torque-tube for actuation is proportional to the torque or twist of the SMA torque-tube. This relationship (whatever it may be) can be programmed into the controller logic within the desired range of operation.
VII. Conclusions and Planned Future Work

The paper provides a conceptual assessment of the benefit and feasibility of an adaptable variable pitch turbine blade for maintaining high aerodynamic performance and optimal thermal efficiency for gas turbine engines operating at part-load conditions. Three-dimensional CFD results of stator–rotor interaction in a turbine stage under off design condition were investigated. The results show that by articulating the rotor blades, we are able to recover a more optimal flow field under given off-design rotor inlet conditions. Through computations, it has been shown that the concept of articulating the turbine blades can potentially achieve high performance efficiency of gas turbine under off-design conditions.

Conceptual articulation mechanism ideas have been generated. Various smart materials have been reviewed for blade articulation application. The possibility of using high temperature capable NiTi SMAs has been reviewed. Existing challenges in using NiTi SMAs for high temperature application have been noted. Design studies of the conceptual articulation mechanisms for both stator and rotor blades using SMA torque tubes have been established.

Detailed aerodynamic experimental and computational investigations are planned in the future to determine the range of angular rotations and moments needed to articulate the blades with respect to the nominal design blade angle settings for axial-flow turbine and/or compressor stage. Simultaneously, promising high temperature capable SMAs and compact light-weight electric motor based smart actuators will be investigated in depth for blade articulation application. Additional future work will be needed to do more detailed computational modeling and analysis of the increased hub and/or shroud losses caused by the need to have clearance between the articulating blades/vanes and the hub/shroud, and design of geometries that minimize these clearance leakage effects (lessons learned from compressor variable guide vanes could be applied). This clearance effect will have to be quantified and assessed as to how much it counteracts the benefits of the articulated airfoils.

The expected payoffs post transition to a higher TRL (Technology Readiness Level) are:

2. Mitigate engine stall caused by flow separation, and expand engine stability margin in future Variable Speed Turbine technology for the Army’s Future Vertical Lift aircraft.

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