Muthuvel Murugan[1]
Mem. ASME
Vehicle Technology Directorate,
U.S. Army Research Laboratory,
Aberdeen Proving Ground, MD 21005
e-mail: muthuvel.murugan.civ@mail.mil

Anindya Ghoshal
Vehicle Technology Directorate,
U.S. Army Research Laboratory,
Aberdeen Proving Ground, MD 21005
e-mail: anindya.ghoshal.civ@mail.mil

Fei Xu
Department of Mechanical Engineering,
Iowa State University,
Ames, IA 50011
e-mail: xufei12345@gmail.com

Ming-Chen Hsu
Department of Mechanical Engineering,
Iowa State University,
Ames, IA 50011
e-mail: jmchsu@gmail.com

Yuri Bazilevs
Department of Structural Engineering,
University of California,
San Diego, La Jolla, CA 92093
e-mail: jbazilevs@ucsd.edu

Luis Bravo
Vehicle Technology Directorate,
U.S. Army Research Laboratory,
Aberdeen Proving Ground, MD 21005
e-mail: luis.g.bravo2.civ@mail.mil

Kevin Kerner
U.S. Army Aviation and Missile Research,
Development and Engineering Center,
Aviation Development Directorate,
Building 401,
Fort Eustis, VA 23604
e-mail: kevin.a.kerner.civ@mail.mil

Analytical Study of Articulating Turbine Rotor Blade Concept for Improved Off-Design Performance of Gas Turbine Engines

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 geometry resulting in reduced off-design performance. Articulating the pitch angle of turbine blades in coordination with adjustable nozzle vanes can improve performance by maintaining flow incidence angles within the optimum range at all operating conditions of a gas turbine engine. 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 engine applications. U.S. Army Research Laboratory (ARL) 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 articulating turbine blade concept. The flow patterns are compared between the baseline fixed geometry blades and articulating conceptual blades. The computational fluid dynamics (CFD) studies were performed using a stabilized finite element method developed by the Iowa State University and University of California San Diego researchers. The results from the simulations together with viable smart material-based technologies for turbine blade actuations are presented in this paper. [DOI: 10.1115/1.4036359]

Introduction

The present research reported in this paper is part of an ongoing effort underway at the U.S. Army Research Laboratory (ARL) together with the U.S. Army Aviation and Missile Research, Development and Engineering Center—Aviation Development Directorate (AMRDEC-ADD) to develop the basic underlying technologies of a physics informed articulating adaptive turbine blade concept optimized for aerodynamic and thermodynamic performance impact. 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 may need to be guided to a more optimum direction. One smart way to accomplish this is to use variable turbine nozzle

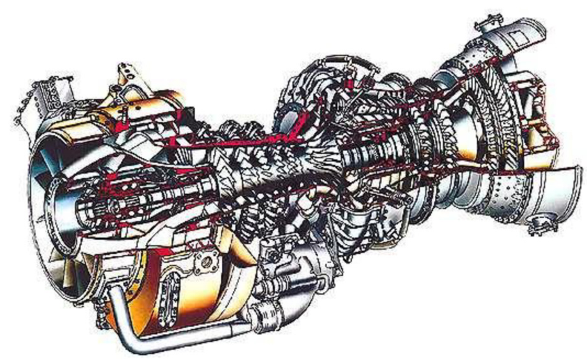

Fig. 1 Cut-away illustration of a typical rotorcraft engine

[1]Corresponding author.

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geometry, which has been traditionally used to change the angle of attack of nonrotating stator vanes to optimize the aerodynamic performance and efficiency of the turbine over a given operating range. By rotating the vanes, the incidence angle and the effective throat area can be reduced or increased to optimize the flow velocity for a range of varying flight operating conditions. However, this traditional method has some disadvantages, such as increased weight and complexity, and also limited operating range, since the nozzle vanes can only be turned to a certain amount before severe flow incidence angles begin to affect the rotating blades downstream.

An alternative method to increase the operating range of turbine engines is to design a blade that is "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 (VSPT) [1]. VSPT are a potential enabling technology for high speed tilt rotorcraft, where the power turbine speed is 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]. For vertical lift air vehicles, maintaining high fuel efficiency is a challenge and a balance must be achieved with the fuel burn penalties associated with variable speed engine capability, and the gains achieved by slowing the main rotor speed substantially (to 51%) of take-off speed as required to maintain high propeller efficiencies at cruise flight speed [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 rotating blades of the turbine in coordination with stator nozzle vanes. The focus of this study is to explore an alternative to incidence tolerant blade design by articulating the pitch angle of rotating gas turbine blades and stator vanes for variable speed applications to always maintain incidence angles optimized for maximum aerodynamic performance. Future studies will include the possibility of morphing the blade shape in a high temperature/high pressure environment. 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 essence, it is postulated that the compressor blades, gas generator turbine stator and rotor blades, and the power turbine 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 reduction of flow losses, and higher energy conversion (power turbine) at a wide range of operating conditions.

Conceptual Blade Mechanisms Design

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 Fig. 2, the corresponding flow velocity triangles are shown in Fig. 3 for a conceptual design condition (100% gas turbine speed). For both rotor and stator rows, the flow is nearly tangential at outlet than at inlet. 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 α_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; β_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; and α_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. 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.

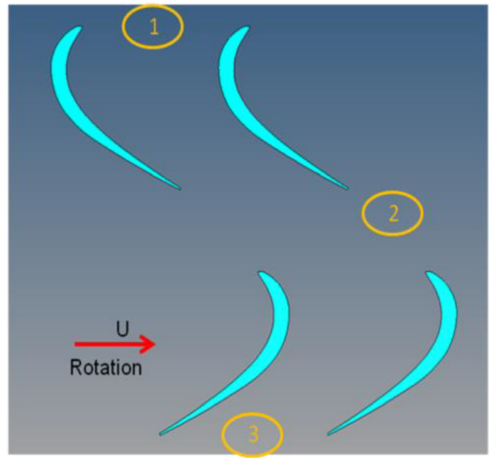


Fig. 2 Stator and rotor blade passages in axial flow turbine stage

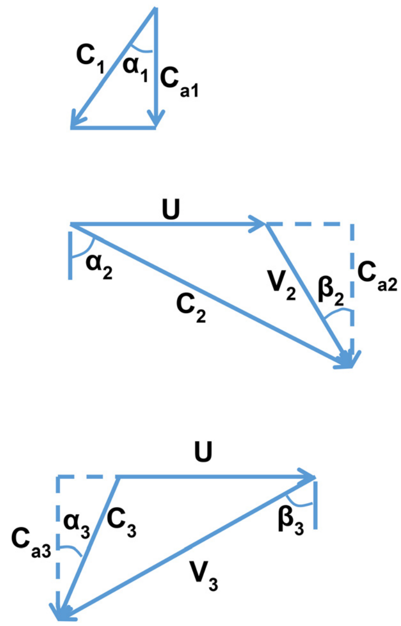


Fig. 3 Flow velocity triangles through stator and rotor blade passages for axial flow turbine stage (design condition)

For a chosen off-design condition, the resulting flow velocity triangles and blade angles for reduced gas turbine speed are shown in Fig. 4 conceptually. In Fig. 4, the changed flow velocities and angles are shown through the stator and rotor blade passages. Since the vane and blade angles remain the same in conventional design in current gas turbine engines, the performance of the turbine would decrease due to high incidence angles and resulting flow separation losses. But if both vanes and blades were allowed to articulate to change their respective pitch angles, as shown conceptually in Fig. 5, aerodynamic losses would be minimized, and

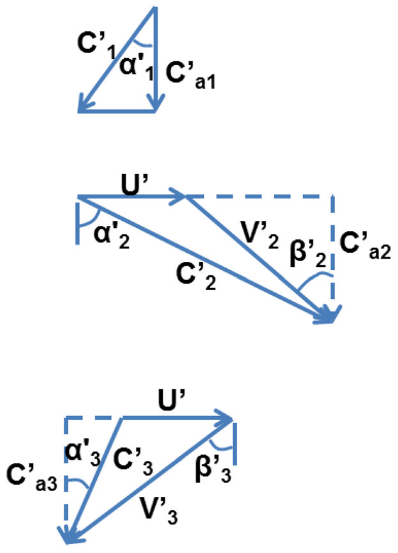


Fig. 4 Flow velocity triangles through stator and rotor blade passages for axial flow turbine stage (off-design condition)

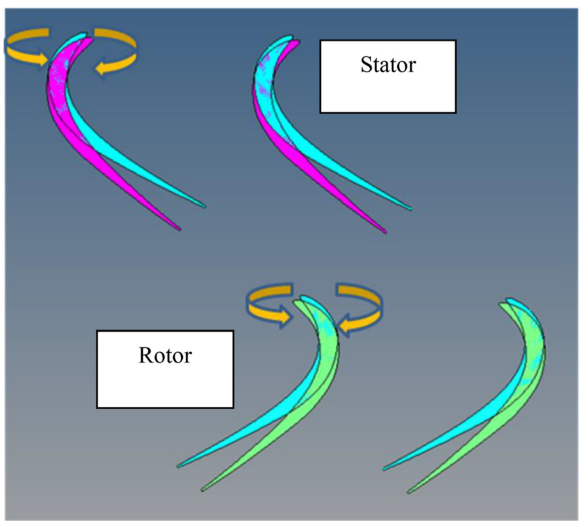


Fig. 5 Coordinated articulation of stator and rotor blades for efficient aerodynamic performance (conceptual)

turbine performance would remain optimum at all operating conditions.

By articulating both stator and rotor blades synchronously, we can establish optimal laminar flow to maximize aerodynamic performance at various stator and rotor flow angle variations under different operating conditions. Currently, the research team is studying candidate design concepts for blade articulation mechanisms. Promising candidate designs will then be down-selected for future efforts on this research. Figure 6 shows one of the possible articulation mechanism designs (blade pitch rotation) using shape memory alloy (SMA) smart material-based torque tube.

Smart Materials Based Actuation Systems. There exist several smart actuation mechanisms, such as piezoelectric, SMA, magnetic, and electrostatic, that have been used successfully in micro-electromechanical systems (MEMS), and may be applicable for microturbines. Pneumatic, hydraulic, electromechanical, magnetic, smart materials like SMAs, and piezoelectric materials should be considered when trying to determine the best mechanism for use in an articulating blade technology. However, the main disadvantage to all of the potential actuation mechanisms is that none can be used at high temperature and pressure, which is present in a gas turbine engine environment. The design constraint for the system needs to have minimal form factor and weight. The current design is to house the system at the hub or disk of the rotating blade. In order to determine the best mechanism that can be used in an articulating blade, several factors need to be considered, such as output power density, efficiency, actuation force density, and integration with the system. Reference [5] is a good reference comparing some of these actuator attributes.

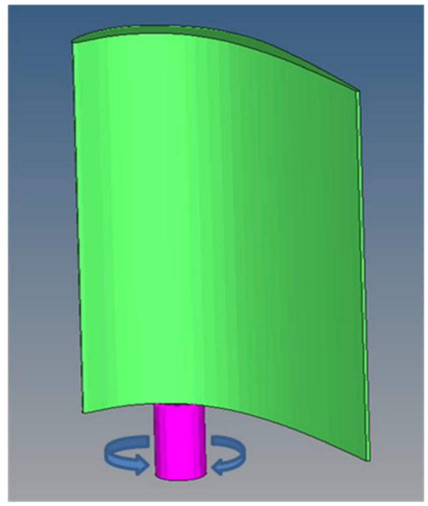


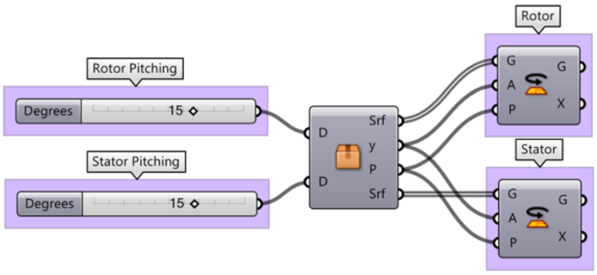
Fig. 6 Blade pitch articulation using a high-temperature capable SMA

For the present research study, we propose to articulate the pitch angle of the stator and rotating turbine blades synchronously. One viable design would be to house the actuators inside the turbine disk for rotor blade and on the outer engine casing for stator vanes. Benefits from this design would be a radially lower placement of weight from the actuation mechanism and lower temperatures than if the mechanism were placed in the blade itself. SMAs or other potentially viable smart material-based actuators could be used for the blade pitch articulation application as shown in Fig. 6. For this proposed design, the smart material-based actuators can be 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.

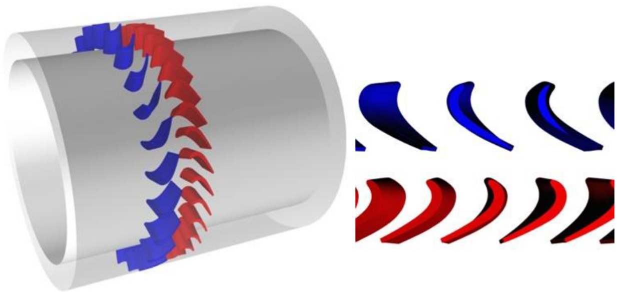
Currently, there has been continued interest in developing high temperature SMA for applications in aerospace, automotive, and process and energy industries. However, the present commercially available NiTi SMA alloys are limited in their high temperature durability and sustainability characteristics [6]. 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 [7]. Reference [8] reports 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. This research study will use high temperature capable NiTi alloys for developing a prototype articulating blade concept.

CFD Modeling of Stator–Rotor Interaction

Parametrical Geometry Generation. We propose to optimize the pitch angles of the stator and rotating blades synchronously



(*a*)



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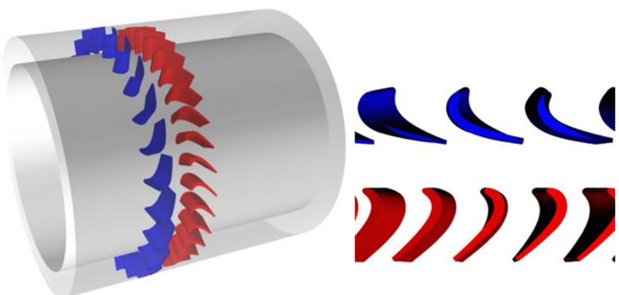


(*c*)

Fig. 7 The RHINOCEROS–GRASSHOPPER parametric design tool for adaptive turbine blades. (*a*) The parametric design tool in GRASSHOPPER, (*b*) pitching the rotor and stator blades both by 0 deg, and (*c*) pitching the rotor and stator blades both by 15 deg.

and perform a series of simulations with different pitch angles, which requires a capability to change the blade-pitch angles parametrically. Following the idea of interactive geometry modeling platform by Hsu et al. [9], we build a parametric design tool based on RHINOCEROS 3D [10] and GRASSHOPPER [11]. 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.

Figures 7(*b*) and 7(*c*) illustrate the results of pitching by changing the input parameters. From Figs. 7(*b*) and 7(*c*), we change the pitch angle of both rotor and stator blades by 15 deg. The resulting geometric model is generated automatically, and is ready for mesh generation and analysis.

CFD Methodology. To perform the CFD analysis of the flow in the full annulus of the turbine stage, we use a finite element-based formulation to solve the 3D compressible Navier–Stokes equations

$$\mathbf{U}_{,t} + \mathbf{F}^{\mathrm{adv}}_{i,i} = \mathbf{F}^{\mathrm{diff}}_{i,i} + \mathbf{S} \qquad (1)$$

where $\mathbf{U}$ is vector of the conservation variables, $\mathbf{F}^{\mathrm{adv}}_i$ and $\mathbf{F}^{\mathrm{diff}}_i$ are the advective and diffusive flux, respectively, in ith direction, and $\mathbf{S}$ is the source term. Using the primitive variables; rather than conservation variable, it is possible to rewrite Eq. (1) into the quasi-linear form as

$$\mathbf{A}_0\mathbf{Y}_{,t} + \mathbf{A}_i\mathbf{Y}_{,i} = (\mathbf{K}_{ij}\mathbf{Y}_{,j})_{,i} + \mathbf{S} \qquad (2)$$

where $\mathbf{A}_0 = \mathbf{U}_{,\mathbf{Y}}, \mathbf{A}_i = \mathbf{F}^{\mathrm{adv}}_{i,\mathbf{Y}}$ is the ith Euler Jacobian matrix, $\mathbf{K}_{ij}$ is the diffusivity matrix such that $\mathbf{K}_{ij}\mathbf{Y}_{,j} = \mathbf{F}^{\mathrm{diff}}_i$, and the vector of primitive variables is $\mathbf{Y} = \{p, u_1, u_2, u_3, T\}^{\mathrm{T}}$.

In this work, we use streamline upwind/Petrov Galerkin (SUPG) [12] as the core technology to numerically solve the compressible Navier–Stokes equations (2). 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 [13]. Furthermore, we partition the computational domain into the rotor and stator subdomains and couple them through the sliding interface [14], a formulation we extended to compressible flow in the present work. Finally, weakly enforced no-slip conditions [15] are imposed on the blade surfaces in order to avoid excessive resolution of the turbulent boundary layers.

Simulation Results and Discussion

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 Fig. 3, with β_2 matching the blade inlet angle of rotor blades. With the

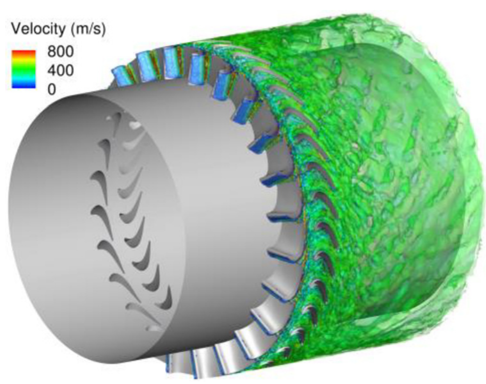
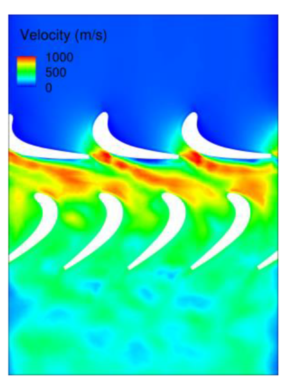
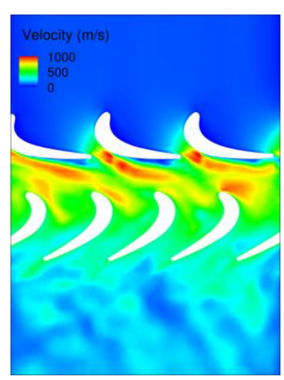


Fig. 8 Flow inside a gas turbine stage. Vorticity colored by velocity magnitude.



(*a*)



(*b*)

Fig. 9 Absolute flow velocity in a turbine stage: (*a*) Before pitching and (*b*) after pitching

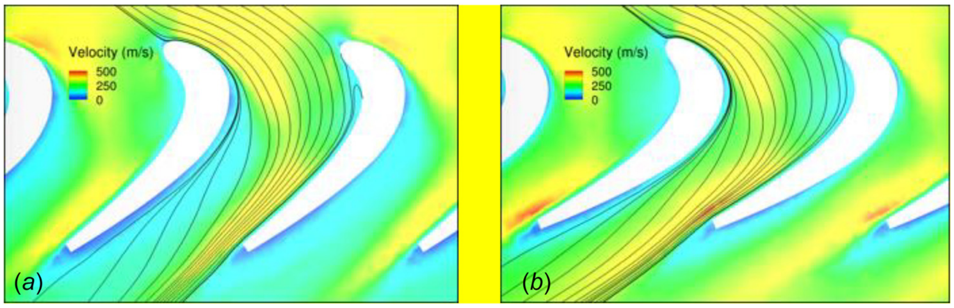


Fig. 10 Streamlines of relative velocity in a rotor passage: (*a*) Before pitching and (*b*) after pitching

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 3D flow field of flow inside the full annulus of the turbine stage is shown in Fig. 8.

Figure 9 shows the absolute velocity contour on a planar cut through the turbine stage. In Fig. 9(*a*), the inflow (stator exit flow) direction does not match the blade inlet angle of the rotor, creating a large incidence angle. As a result, we pitch the rotor blades clockwise by 10 deg to better match the blade inlet angle to the flow inlet angle β_2. We can clearly see that after pitching (Fig. 9(*b*)), the flow exits the rotor passages with a smaller magnitude, meaning that after pitching more flow momentum is converted into the rotor torque, therefore reducing the associated losses and improving the turbine design.

We show the relative velocity field inside the rotor passages in Fig. 10. Before pitching the rotor blades, since β_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. 10(*a*)). By pitching the rotor, 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. 10(*b*).

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, the adiabatic efficiency η_{ad} is given by Eq. (3) from Ref. [16]

$$\eta_{ad} = \frac{1 - \dfrac{T_3}{T_1}}{1 - \left(\dfrac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}}} \tag{3}$$

where γ is the specific heat capacity ratio of air. Using the above formula in the postprocessing of our simulation results, we find that before pitching $\eta_{ad} = 0.468$, while after pitching $\eta_{ad} = 0.494$, which presents a 5% increase in stage efficiency. This shows that turbine blade pitching can help improve gas turbine efficiency under off-design conditions significantly. In the actual design of adaptive technology gas turbine engines, it is envisaged to use an inlet flow velocity sensor (flow direction and magnitude) to determine the inflow incidence angle and the blades will be articulated accordingly using a feedback control algorithm to set the blade at the optimum position for the best aerodynamic performance possible for each changing operating condition.

Concluding Remarks

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 design for gas turbine engines operating at part-load 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 as well. Existing challenges in using NiTi SMAs for high temperature application have been noted.

Analytical investigations with 3D CFD results of stator–rotor interaction in a turbine stage under off-design condition are provided. The results show that by articulating the rotor blades, we are able to recover a more optimal flow field under certain rotor inlet conditions. The concept of articulating the turbine blades can potentially achieve high performance of gas-turbine under off-design conditions.

Future Work

Detailed aerodynamic experimental and computational investigations are planned to be carried out to determine the range of angular rotations needed to articulate the blades with respect to the nominal design blade angle settings for a turbine stage. Simultaneously, promising high temperature capable SMAs and piezo-electric-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 shroud losses caused by the clearance between the articulated blades/vanes and the hub/shroud and design of geometries that minimize these clearance 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 technology readiness level (TRL) are

(1) adaptive gas turbine blade technology insertion for optimized engine performance.
(2) mitigate engine stall and flow separation in candidate future variable speed turbine for future vertical lift aircraft.
(3) more efficient power generation (power turbine for a turboshaft engine).

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The views and conclusions contained in this paper are those of the authors and should not be interpreted as representing the official policies or positions, either expressed or implied, of the U.S. Army Research Laboratory, the U.S. Army Aviation and Missile

Research, Development and Engineering Center or of the U.S. Government.

Nomenclature

C = absolute flow velocity
C_a = axial component flow velocity
CFD = computational fluid dynamics
NiTi = nickel–titanium shape memory alloy
p = pressure
Re = Reynolds number
SHP = shaft horse power
SMA = shape memory alloy
T = temperature
U = blade tangential velocity
V = resultant flow velocity
α = absolute flow angle with respect to axial direction
β = relative flow angle with respect to axial direction

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