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Concept Study for Adaptive Gas Turbine Rotor Blade

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ABSTRACT

Articulating the pitch angle of a turbine blade can improve performance by maintaining optimum design incidence and thus reduce the probability of flow separation and thermal stresses developed due to aerothermal loads for variable speed gas turbine engine applications. Potential benefits to Army Aviation are highly efficient (aerodynamically) turbine blades, possible reduction of the need for active blade cooling and thermal barrier coatings, increased fuel efficiency, power density, and the ability to fly faster and longer. The goal of this effort is to assess the benefit and feasibility of an adaptable variable pitch turbine blade for maintaining attached flow and optimal thermal design for a gas turbine engine. A technology concept study has been conducted to enable a viable adaptable turbine rotor blade that can enhance the performance and efficiency of future aircraft gas turbine engines. A typical aircraft turbine blade is used for this technology concept study. An adaptable turbine rotor blade, if made feasible, can lead to a leap ahead technology innovation in improving part-load efficiency of gas turbine engines.

Keywords*– adaptable turbine blade, articulating blade, gas turbine rotor blade, highly efficient turbine blade*

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I. INTRODUCTION

The present study is part of an effort underway by the Army Research Laboratory (ARL) with the U.S. Army Aviation and Missile Research, Development and Engineering Center – Aviation Development Directorate (AMRDEC-ADD) to develop the underlying technologies of a physics informed articulating adaptive turbine blade optimized for aerodynamic performance and thermodynamics impact. The current study that is presented in this paper investigates the feasibility of an adaptive turbine blade without cooling.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, the flow through the turbine may need to be turned to a more optimum direction. One way to do this is to use variable turbine geometry, which has traditionally been used to change the angle of attack of non-rotating stator vanes to optimize the aerodynamic performance and efficiency of the turbine over a wide 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. This method however has the disadvantage of increased weight and complexity, and the operating range is limited since the vanes can only be turned a certain amount before severe flow angles begin to affect the rotating blades downstream.

Another 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 (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 is slowed down by as much as 51% during cruise flight compared to hover flight [2]. The potential high speed tilt rotorcraft that is the focus of the VSPT technology development effort is a large vertical take-off and landing (VTOL) transport capable of Mach 0.5 forward cruise at 28,000 ft with a range greater than 1,000 nautical miles. The notional vehicle would be powered by two 7500 SHP-class power turbines, one per nacelle and rotor. The main rotors would operate over a wide speed range from 100% at take-off to 54% at cruise.Significant design challenges exist for turbine blades operating over such speed ranges due to the turbine blades experiencing a wide range of incidence angles, high work factors at cruise, and low aft stage Reynolds numbers at 28,000 ft cruise flight

[3].Slowing down the power turbine will require higher work factors (flow turning) and will result in lower efficiencies than can be achieved in a turbine optimized for near constant high speed (100%) operation[2].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].

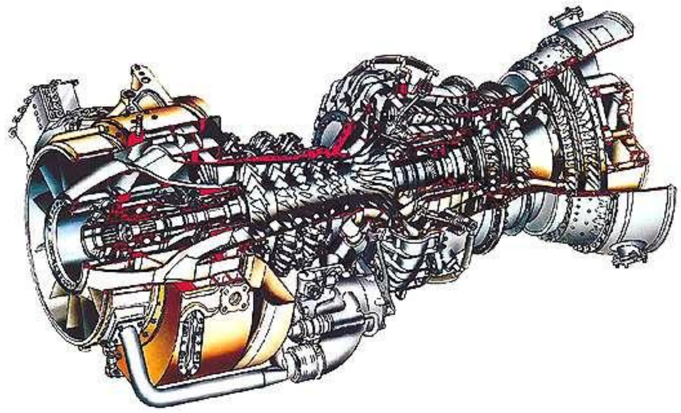

Figure 1. Cut away illustration of a typical rotorcraft engine

While variable geometry and incidence tolerant blading can increase the operating range of a turbine, further optimization and performance improvements could result by articulating the rotating blades of the turbine. The focus of this study is to explore an alternative to incidence tolerant blade design by articulating the pitch angle of a rotating uncooled gas turbine blade for variable speed applications to maintain an incidence angle 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 further discuss the concept of articulating high pressure turbine blades with the goal of possibly reducing the need for active air cooling and thermal barrier coating. Reducing the parasitic losses due to active bleed air cooling will also help to increase the engine performance.In essence it is postulated that the compressor blades, gas turbine stator and rotor blades and the power turbine blades, will benefit from the articulating blade technology 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

II. AERODYNAMIC PERFORMANCE

Historically, there have been many research attempts in aircraft design to have articulating wing designs to maximize aerodynamic performance at all operating conditions. One such innovative design is shown in Figure 2 for a short take-off and landing (STOL) aircraft by Zenith Aircraft Company [4]. This design uses leading edge slats and articulating trailing edge flaps to achieve high lift and low stall speeds. The leading slats allow high incidence at lower speeds by accelerating the air between the slat and the wing (venturi effect). The leading edge slats allow for steep climb angles of up to 30 degrees [4] (see Figure 3). The trailing edge flaps can be articulated to maximize the aerodynamic performance at different incidence angles. These flaps and slats however create extra drag over the wing and affect optimal performance. With new advanced materials and techniques such as shape memory alloys and compliant flexible morphing, slats and flaps can be eliminated, reducing drag and improving performance of the wing. These concepts can also be applied to the blades of a turbine engine to improve aerodynamic performance and efficiency.

As previously mentioned, variable turbine geometry has traditionally been used to change the angle of attack of non-rotating stator vanes to optimize the aerodynamic performance and efficiency of the turbine over a wide operating range. But variable geometry comes with increased weight and complexity, and the vanes can only be turned a certain amount before severe flow angles begin to affect the rotating blades downstream. This effect could be alleviated if the rotating blades were also able to be articulated to change their angle of attack together with the vanes, thus increasing the operating range and efficiency of a variable geometry turbine.

There are many articulating mechanisms currently studied that can be used in rotating applications. Traditional types of actuators such as mechanical, pneumatic, electro-mechanical, or hydraulic systems have been used successfully for many applications. Although they might be difficult to package in the disk of a rotating turbine blade, they will be considered for further study. Piezo-electric, hydraulic and electromechanical based actuators have been used for blade pitch actuation mechanisms in helicopter rotor blade and wind turbine applications. In large rotating turbine systems such as wind turbines, it is possible to house the articulating mechanisms in the hub attachment or the gear box housing of the turbine blade. A conceptual mechanically articulated wind turbine blade is shown in Figure 4 from reference [5]. The articulating blade involves an airfoil on a straight-blade vertical axis wind turbine that maintains its angle of attack regardless of the position to the hub or central shaft through a hinge allowing out-of-plane or in-plane motions. While in vertical axis wind turbines, the airfoil changes angle of attack as the rotor revolves. In other wind turbines, like Darrieus rotors, the blades have a constant pitch angle articulation. That case implies coordinated movement of a jointed assembly. Under any case, articulation enables maximization of lift [6]. Other types of actuation mechanisms that would be applicable to the current study include smart materials such as shape memory alloys (SMAs) and compliant morphing materials.The power turbine efficiency is impacted by the positioning of variable stators, but with careful design the drop in turbine efficiency can be offset by maintaining a higher turbine inlet temperature at part-load [7]. However, increasing the turbine inlet temperature adds additional design burden on material choice or cooling needs for turbine blades.

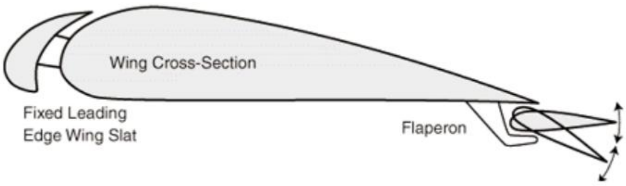

Figure 2. High-Lift wing design for a STOL aircraft (Courtesy: Zenith Aircraft Company, [4])

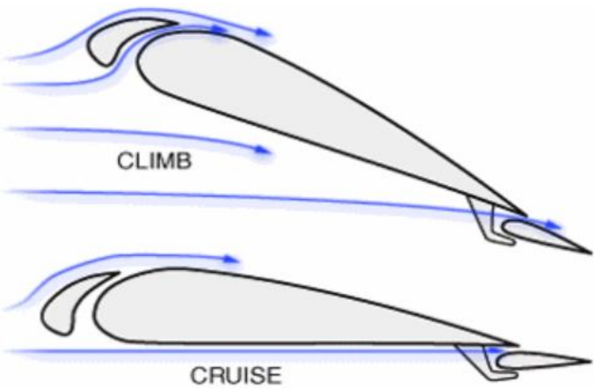

Figure 3. Leading-edge slats allowing high incidence angle (Courtesy: Zenith Aircraft Company, [4])

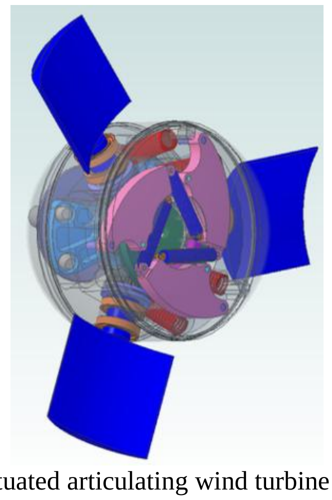

Figure 4a. Conceptual mechanically-actuated articulating wind turbine blade (Courtesy: Albert Questiaux, [5])

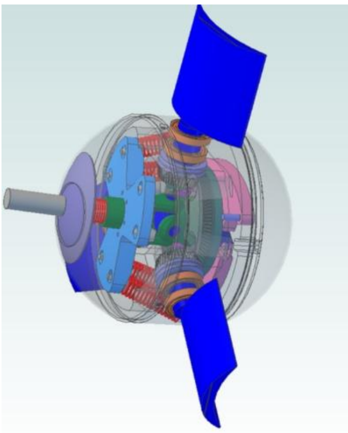

Figure 4b. Conceptual mechanically-actuated articulating wind turbine blade (Courtesy: Albert Questiaux, [5])

2.1. Benefits

Adaptable turbine blades that can change their incidence angles and/or shape may benefit power turbines by mitigating detrimental aerodynamic effects associated with low Re number and high work factor conditions.High altitude (28,000 ft) cruise requirements impose low Re number challenges for both fixed and variable speed power turbines. Low Re number operation often results in significant regions of laminar flow on the suction side of airfoils, which in turn makes them susceptible to laminar separations that may or may not reattach [8]. This transitional flow causes higher loss levels and reduced incidence capability compared to typical rotorcraft operation. The need for strong incidence tolerance exacerbates the low Re challenge. In addition, the increase in design-point loss due to Re lapse is larger in high lift airfoils than in low lift designs [8].

An adaptable blade design may mitigate this issue by maintaining an optimal incidence angle and not needing to rely on a thickened leading edge, incidence tolerant blade shape. Reducing low Re lapse and thus reducing performance loss associated with blade stall generally will require increasing the axial chord of VSPT turbine blading. This leads to increased engine length per stage and ultimately increased engine length and thus weight. An adaptable blade may avoid these issues through being able to adjust to an optimal angle and maintain efficient aerodynamic flow. For a given blade geometry the aerodynamic loading increases in proportion to the work factor. High work factors (flow turning) required at the lower power turbine speeds in VSPT applications will result in lower efficiencies than can be achieved in a turbine optimized for near constant high speed (100%) operation [3]. Retention of high turbine efficiency at the very high work factors and aero loading levels of cruise operation is one of the principal challenges for VSPT aerodynamic design efforts using incidence tolerant blades as incidence range decreases with increased loading [9]. An adaptable turbine blade, where the incidence angle can be varied to reduce work factor,will thus increase efficiency and may help to mitigate this issue.

Adaptable turbine blades that can change their shape through morphing technology can allow the blade to transform so that it is shaped optimally for each mission design point such as for the 2,000 ft take-off/hover and 28,000 ft Mach 0.5 cruise points for the VSPT application (100% N (speed) and 54% N (speed) for main rotor and VSPT). The power turbine blade thus would not need to be incidence tolerant in shape and could change to one that avoids or reduces the adverse pressure gradient that will likely cause pressure side separation predicted at the strong negative incidence associated with the VSPT take off/hover operation condition[1]. It would then be able to change shape to one that has better performance at high loading and be more resistant to suction side separation at low Re numbers present at the VSPT cruise operation condition.

III. CONCEPTUAL MECHANISMS DESIGN

An example of typical stator and rotor blade flow passages for an axial flow turbine stage is shown in Fig. 5; the blade shapes are for reference only. In gas turbine engines the stator and rotor rows are close together, the gap is approximately 20% of the blade chord [10]. The corresponding flow velocity triangles are shown in Fig. 6 for conceptual design condition (100% turbine speed). For both rotor and stator rows the flow is nearly tangential at outlet than at inlet. In Fig. 6, 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. 6. C_2 is the absolute flow velocity at rotor blade inlet. 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 would be of 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.
For off design condition, the resulting flow velocity triangles and blade angles for reduced gas turbine speed are shown in Figure 7 conceptually. In Fig. 7, 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 Figure 8, aerodynamic losses would be minimized, and turbine performance would remain optimum at all operating conditions. Articulating both stator and rotor blades would allow for optimal laminar flow to maximize aerodynamic performance at various stator and rotor flow angle variations under different operating conditions. Candidate concept blade articulation design mechanisms for blade articulation are being studied. Selected promising candidate designs will then be down-selected for future efforts on this research. One of the possible articulation mechanism designs (blade pitch rotation) that is being studied is shown in Fig. 9.

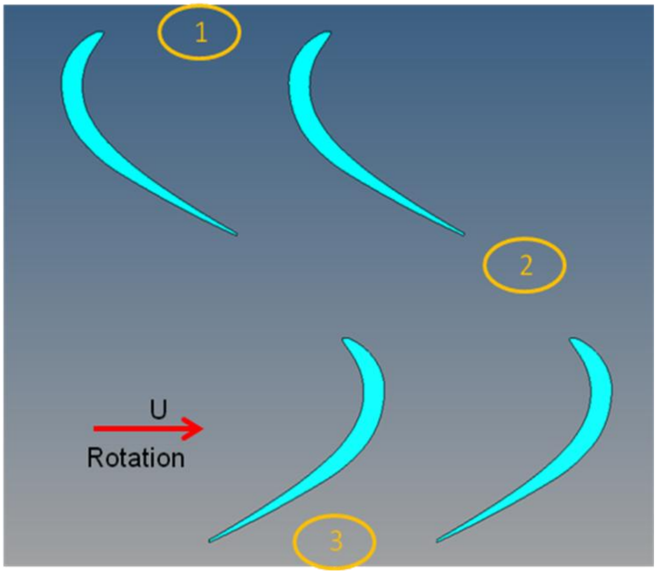

Figure 5. Stator and rotor blade passages in axial flow turbine stage

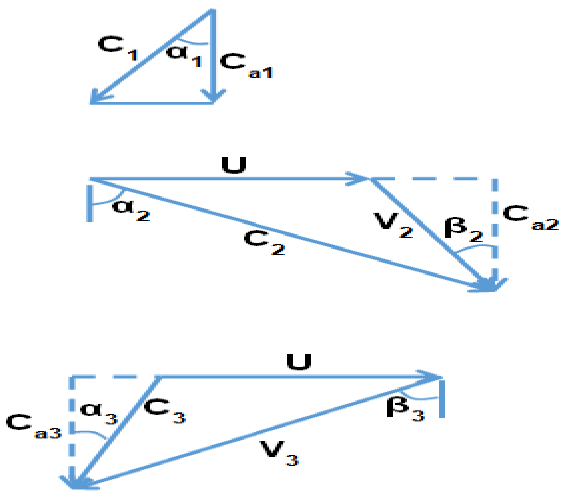

Figure 6. Flow velocity triangles through stator and rotor blade passages for axial flow turbine stage (design condition)

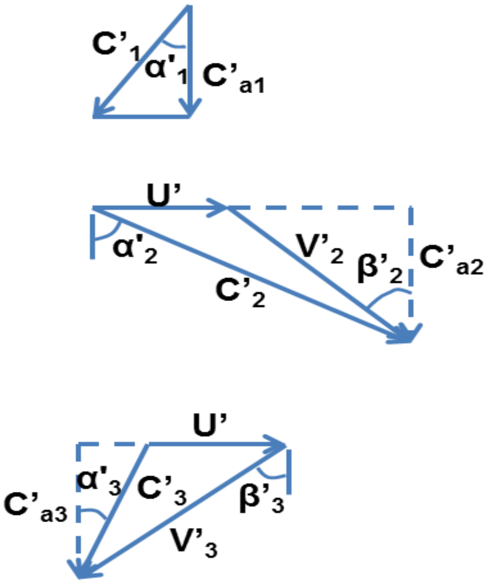

Figure7. Flow velocity triangles through stator and rotor blade passages for axial flow turbine stage (off-design condition)

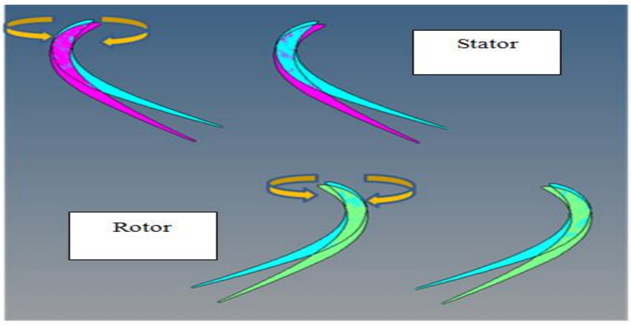

Figure 8. Coordinated articulation of stator and rotor blades for efficient aerodynamic performance (conceptual)

3.1. Smart Materials Based Actuation Systems

Several actuation mechanisms such as piezoelectric, SMA, magnetic, and electrostatic have been used successfully in micro electromechanical systems (MEMS) and may be applicable for micro-turbines. Pneumatic, hydraulic, electromechanical, magnetic and smart materials like SMAs and piezoelectric materials should be considered when trying to determine the best mechanism to use for an articulating blade. One disadvantage to all of these, however, is that none can be used at high temperature and pressure, which is seen in a gas turbine engine. Another issue to consider is that the system will have to be placed in a small package located at the hub and disk of the rotating blade. In order to determine the best mechanism to use for an articulating blade, several factors need to be considered, such as output power density, efficiency, force density, and integration with the system. A good reference comparing some of these actuator categories is found in reference [11].

For this study, it is proposed to articulate the pitch of the rotating turbine blades. One possible design would be to house the actuators inside the turbine disk. 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 shown in Fig. 9. For this design, the smart material based actuators can be housed inside the turbine disk from a packaging design consideration. However the actuator used will have to survive disk temperatures that could reach 700°C and above. The benefit of this design 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 combinedwith Pd, Pt, Au, Hf, or Zr to sustain temperatures in the range of up to ~ 800°C.There has been continued interest in developing high temperature shape memory alloys (SMA) for applications in aerospace, automotive, process and energy industries. However, current commercially available NiTi SMA alloys are limited in their high temperature handling capability. The addition of Pd, Pt, Au, Hf, and Zr to NiTi alloys have shown potential to increase the high temperature sustainability of NiTi alloys up to ~800°C, but their mechanical strength characteristics at high temperature have not been investigated in depth [12]. Reference [7] 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.

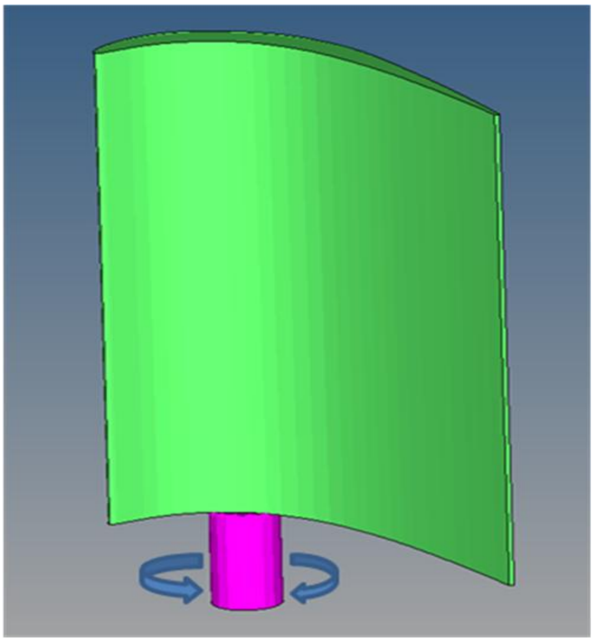

Figure 9. Blade pitch articulation using a high temperature capable SMA

IV. CONCLUDING REMARKS

The paper provides a conceptual assessmentof 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 design and 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 have been reviewed as well. Existing challenges in using NiTi SMAs for high temperature application have been noted.

V. FUTURE WORK

Detailed aerodynamic computational investigations are planned to be carried out to determine the range of angular rotation 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 pzt (piezo-electric) based smart actuators will be investigated in depth for blade articulation application. This adaptive gas turbine blade innovations study includes the following:

1. The CFD modeling to understand the design space for the turbine blade angles.
2. Articulating gas turbine blade mechanism via active and passive actuation.
3. Highly coupled nonlinear fluid structure interaction modeling using isogeometric analysis.

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

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 FVL (Future Vertical Lift) aircraft.
3. More efficient power generation (Power Turbine for a turboshaft engine)

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Nomenclature

α: Absolute flow angle with respect to axial
β: Relative flow angle with respect to axial
C: Absolute flow velocity
C_a: Axial component flow velocity
NiTi: Nickel-Titanium shape memory alloy
Re: Reynolds number
SHP: Shaft horse power
STOL: Short take-off and landing
U: Blade tangential velocity
V: Resultant flow velocity