2018

Optimizing Gas-Turbine Operation using Finite-Element CFD Modeling

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Abstract
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Disciplines
Computer-Aided Engineering and Design | Energy Systems | Mechanical Engineering

Comments

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Optimizing Gas-Turbine Operation using Finite-Element CFD Modeling

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Gas turbine engines are generally optimized to operate at nearly a fixed speed with fixed blade geometries for the design operating condition. The performance of gas turbine reduces when operated at different operating condition. In this work, we present a parametric study to optimize gas-turbine performance under off-design conditions by articulating the rotor blades in both clockwise and counterclockwise directions. 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 certain off-design conditions. To observe the effect of rotor pitching on the performance of the gas turbine, a computational fluid dynamics (CFD) study is performed using the finite element formulation for compressible flows with moving domain. Results obtained from the CFD simulation for different rotor pitch angles are presented in this paper.

I. Nomenclature

\begin{align*}
\eta_d & = \text{adiabatic efficiency} \\
\mathcal{T} & = \text{fluid total temperature} \\
p & = \text{fluid total pressure} \\
\gamma & = \text{specific heat capacity ratio} \\
\text{CFD} & = \text{computational fluid dynamics} \\
\text{ALE} & = \text{arbitrary Lagrangian–Eulerian} \\
\text{SUPG} & = \text{streamline upwind/Petrov Galerkin} \\
\text{SMF} & = \text{surrogate management framework}
\end{align*}

II. Introduction

This work focuses on the parametric study to improve the performance of the gas turbine under off-design conditions via the articulation of rotor blades. Gas turbine blades of conventional rotorcraft turboshaft engines are typically optimized to operate at nearly a fixed speed and a fixed incidence angle. 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. We aim to explore the design space of different rotor pitching angles and to find an optimal angle to increase the efficiency of the gas turbine. To this end, we perform a parametric study by articulating or pitching the blade in both clockwise and counterclockwise directions. The finite-element-based formulation for compressible flows with moving domain [1] is used to solve this problem.

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III. Simulation Framework

A. Gas Turbine Performance

By articulating both stator and rotor blades synchronously, we can establish optimal flow to maximize aerodynamic performance at various stator and rotor flow angle variations under different operating conditions. The 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 0 and 2 denoting quantities at the stator inlet and rotor exit, respectively, the adiabatic efficiency \( \eta_{ad} \) is given by

\[
\eta_{ad} = \frac{1 - \frac{T_2}{T_0}}{1 - \left(\frac{p_2}{p_0}\right)^{\frac{n}{k}}}
\]

Previous studies have shown that turbine blade pitching can help improve gas turbine efficiency under a given off-design conditions [1]. In this work, we extend the work by finding the optimal gas turbine performance under different off-design conditions.

B. Parametric Geometry Design

We propose to vary the pitch angles of the rotor blade 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. [3], we build a parametric design tool based on RHINOCEROS 3D [4] and GRASSHOPPER [5]. The GRASSHOPPER tool is shown in Fig. 1(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. Fig. 1(b) illustrates the result of pitching by changing the input parameters. The stator blades are pitched by 24º and the rotor blades are pitched by 10º. The resulting geometric model is generated automatically and is ready for mesh generation and analysis.

![Parametric geometry design](image)

Fig. 1 Parametric geometry design: (a) The parametric design tool in Grasshopper. (b) Pitching the stator blades by 24º and the rotor blades by 10º.

C. CFD Methodology

In this work, we use the finite-element-based formulation [1] to solve the Navier–Stokes equations of compressible flows. The formulation is stabilized by the streamline upwind/Petrov Galerkin (SUPG) method [6] and yields very good performance for both laminar and turbulent flows. 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 [7] for compressible flow. Furthermore, we separate the computational domain into the rotor and stator subdomains and couple them through the sliding interface [8], a formulation we extended to compressible flow in Ref. [1]. Finally, weakly enforced no-slip conditions [9] are imposed on the blade surfaces in order to alleviate the excessive resolution of the turbulent boundary layers. The validation of the method using a turbulent flow around a cylinder benchmark problem [10] is shown in Fig. 2. For more details of the method, the readers are referred to Ref. [1].
IV. CFD Modeling of Gas Turbine

A. Problem Setup

The fluid domain is modeled by a stationary subdomain containing the stator and a rotational subdomain containing the rotor. The two domains are coupled using the sliding-interface formulation. A uniform axial inflow with velocity of 82.3 m/s, pressure of 2,012,790 Pa and temperature of 1669.78 K is applied at the inlet boundary. The fixed pressure of 1,213,475 Pa is set at the outlet. Both stator and rotor blade are modeled as no-slip condition. The stagnation temperature of 1673.15 K and 1423.15 K are applied weakly on the stator and the rotor blades respectively. On the shaft and the casing surfaces, the zero normal heat flux condition is applied and the no-slip velocity boundary condition is applied strongly. The dynamic viscosity is set to $\mu = 5.551 \times 10^{-5}$ kg/(m s). The gas turbine geometry, dimensions and problem setup are shown in Fig. 3. The fluid domain is meshed using tetrahedral elements with locally refined mesh near the blades as shown in Fig. 4.

Fig. 2 Validation study of finite element formulation for compressible flows.

Fig. 3 Problem setup, geometry and dimensions.
B. CFD Simulation

In the simulation of this problem, the time step size of $\Delta t = 3 \times 10^{-7}$ s is employed, which yields CFL number of around 2. The gas turbine is first simulated for the base design case, i.e., without articulating the stator and rotor blades. The base design case is simulated under the conditions specified in the previous section and the results of the simulation are visualized. The gas turbine stage contains a row of stator blades and a row of rotor blades. The flow accelerates inside the stator blade channels and enters the rotor blade channels. The flow variables are expected to be continuous across the sliding interface between the stator and rotor section. The vorticity contour colored by the velocity magnitude is shown in Fig. 5. To show the continuity at the sliding interface, a cylindrical slice cutting through the fluid domain is generated and the contours of the velocity, pressure, temperature and Mach number are plotted as shown in Fig. 6, and the results appear to be continuous across the sliding interface.
For a gas turbine operating under the off-design or base conditions, flow phenomena such as flow separation may occur. This will increase the flow losses and thus negatively influence the gas-turbine performance. Pitching the blade angle to match flow angle can improve the performance of the gas turbine. In order to know the effect of pitching the blade on the performance of the gas turbine, a brief parametric study of the gas turbine is done by articulating the rotor blade both clockwise and counterclockwise direction. The parametric geometry design which was proposed earlier in this paper is employed to pitch the rotor. Fig. 7 shows the absolute velocity magnitude and Fig. 8 shows the relative velocity magnitude through the rotor passage at different blade angles.

From Fig. 7(a), we can see the absolute velocity magnitude is higher because the inflow to the rotor doesn’t match the rotor blade inlet angle. Also, Fig. 7(c) shows that pitching the rotor in counterclockwise direction doesn’t help which further increases the absolute velocity magnitude. Fig. 7(b) shows the absolute velocity magnitude after pitching the rotor in clockwise direction which shows decrease in the magnitude of absolute velocity. This clearly tells that by pitching the rotor in clockwise, the flow leaves the rotor with small velocity magnitude as a result more flow momentum is converted into the rotor torque which reduces the losses and increases the performance if the turbine.

Before pitching the rotor blades, i.e., at 0º pitch angle, the flow is not fully attached to the surface of the rotor blade, which makes the flow not optimal for the specified inlet condition. By pitching the rotor blade in clockwise direction by 10º, the flow is able to recover a more optimal flow field associated to the gas turbine inlet condition and the flow is fully attached to the blades as shown in Fig. 8(b).

The performance of the gas turbine can be evaluated using the adiabatic efficiency of the turbine stage given in Eq. (1). By evaluating the adiabatic efficiency using the results of the simulation, we find that pitching the rotor blade in clockwise direction gives higher efficiency when compared to pitching in counter-clockwise direction. The efficiency and the corresponding relative velocity results for different configuration can seen in the Table 1. This shows that pitching the rotor blade in clockwise direction increases the relative velocity and also can improve gas turbine performance.

V. Parametric Study

Fig. 6 Contours of flow variables which appears continuous across the sliding interface.

![Flow speed](image1)

![Temperature](image2)

![Pressure](image3)

![Mach number](image4)
Table 1  Comparison of the relative velocity magnitude and the adiabatic efficiency for different rotor pitch angles.

<table>
<thead>
<tr>
<th>Rotor pitch angle</th>
<th>Relative velocity (m/s)</th>
<th>Adiabatic efficiency ($\eta_{ad}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10° counter clockwise</td>
<td>288.21</td>
<td>0.865</td>
</tr>
<tr>
<td>0° (reference design)</td>
<td>215.74</td>
<td>0.889</td>
</tr>
<tr>
<td>10° clockwise</td>
<td>426.94</td>
<td>0.896</td>
</tr>
</tbody>
</table>

Fig. 7 Absolute flow velocity magnitude for different rotor pitch angles.

Fig. 8 Relative velocity magnitude inside the rotor passage with flow stream lines for different rotor pitch angles.

VI. Conclusion

This paper presents the parametric geometry design and study of the gas turbine to obtain the optimal flow through the rotor passage and to improve the performance by articulating the rotor blade in both clockwise and counterclockwise directions. The capability to pitch the rotor blade angle with ease using the parametric geometry design helped in preprocessing the gas turbine geometry effortlessly to do the CFD simulations for different rotor blade angles. The CFD results for gas turbine stage with different rotor angles was investigated using the finite element formulation for compressible flows with moving domain using the ALE approach. The results show that after pitching the rotor blade in clockwise direction, the flow was able to recover a more optimal flow field associated to the gas turbine inlet condition and makes the flow fully attached. The results also shows that clockwise pitching of the rotor increases the relative velocity magnitude which reduces the losses in converting the momentum to rotor torque.
Whereas, pitching in the counterclockwise direction increases the absolute velocity magnitude at the exit of the rotor. The computational results show that pitching the rotor blade in clockwise direction can help in achieving the better performance at the turbine stage.

In the future, we plan to formulate the optimization problem based on the thermodynamic performance measures of the gas turbine subject to constraints. The objective function will consider the gas turbine efficiency and the aerodynamic forces, so as to reach a good balance between aerodynamic and the thermodynamic performance. The Surrogate Management Framework (SMF) technique [11] will be utilized to optimize the performance of a gas turbine under 100%, 75% and 50% design rotor speed. For each of the rotor speed, a combination of stator and rotor pitching angles will be determined to yield optimal performance. The results can potentially be used to guide the control of the gas turbine in real-world engineering applications.

Acknowledgments

This work was supported by the ARO Grant No. W911NF-14-1-0296. The HPC resources that have contributed to the research results reported in this paper were provided by the Texas Advanced Computing Center (TACC) at the University of Texas at Austin. This support is gratefully acknowledged.

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