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Aerodynamic analysis and optimization of a transonic axial compressor with casing grooves to improve operating stability

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ABSTRACT

A transonic axial compressor with circumferential casing grooves is optimized to improve operating stability. Numerical analysis is conducted by solving three-dimensional Reynolds-averaged Navier–Stokes equations using the shear stress transport turbulence model. An optimization process based on a weighted-average surrogate model and steady flow analysis are performed with three design variables defining the tip clearance, blade tip angle, and depth of the grooves. The steady stall inception point is identified from the last converged point, and values of the stall margin as the objective function are predicted using steady flow analysis at the design points sampled by Latin hypercube sampling in the design space. The surrogate model is constructed based on these objective function values. Optimization of this model found the optimum design, which yields a considerable increase in the stall margin compared to the smooth casing. To investigate unsteady behavior of the flow in the optimized compressor with casing grooves, an unsteady flow analysis is performed, and the stall inception point is re-predicted using this analysis.

1. Introduction

As a low aspect ratio turbomachine operating at high mass flow rate, an axial compressor is an essential component of gas turbines used in jet engines, marine engines, etc. The compressor may experience severe vibration due to surge and stall when it operates below the designed mass flow rate. This phenomenon simultaneously causes problems of instability and reduced efficiency. Thus, improving the stall margin is an important consideration in the design of an axial compressor.

Tip leakage vortex is well known as one of the primary factors in induced surge and stall in an axial compressor. The trajectory of the tip leakage vortex, which can be affected by the geometry near the tip region, has an important influence on the stability of an axial compressor. To control this flow phenomenon, circumferential casing grooves (CCGs) have been applied as a casing treatment method. This approach has been used in the design of axial compressors for several decades [2]. Using experimental and numerical methods, many researchers have examined techniques to alleviate surge and stall, and to improve the operating stability of axial compressors, using CCGs. Bailey [2] evaluated the effects of depth, location, and the number of CCGs in a single-stage axial compressor through an experimental test. Wenzel et al. [34] experimentally measured the individual stage characteristics and overall performance of a multi-stage axial compressor with CCGs. Shabbir and Adamczyk [32] numerically demonstrated the flow mechanism for stall margin improvement of an axial compressor with CCGs. Numerical and experimental investigations of a high-speed small-scale compressor with CCGs were reported by Wu et al. [36]. Houghton and Day [13] performed experimental and computational studies to investigate the effect of the axial location of a single casing groove on the stability and efficiency of a subsonic axial compressor. Beheshti et al. [4] conducted a parametric study to determine the performance and stability of a transonic axial compressor with CCGs with respect to variations in tip clearance. An evaluation of the stall margin and efficiency of a transonic axial compressor with various CCGs was presented by Kim et al. [20]. Huang et al. [14] studied the effects of the configuration, width, and depth of CCGs on the stall margin and peak efficiency of a compressor using 3-D numerical analysis.

To date, most CCG designs for the enhancement of axial compressor stability have been realized through parametric studies. However, with recent advances in computational fluid dynamics (CFD) and computing power, several researchers [7,18,5] have carried out optimizations of CCGs using systematic optimization techniques. For example, optimization techniques combined with 3-D Reynolds-averaged Navier–Stokes (RANS) analysis were applied to the design of CCGs by Kim et al. [7,18]. Choi et al. [7] used design optimization to improve the stall margin of a transonic axial compressor with two geometric design variables: the depth and

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Nomenclature

CCGs	Circumferential casing grooves
CFD	Computational fluid dynamics
D	Depth of the circumferential casing grooves
DOE	Design-of-experiment
EFFI	Adiabatic efficiency
EXP	Experiment
F	Response
FFT	Fast Fourier transform
GGI	General grid interface
$GSME$	Generalized mean square cross-validation error
KRG	Kriging meta-model
LE	Leading edge
LES	Large eddy simulation
LHS	Latin hypercube sampling
m	Mass flow rate
N_{sm}	Number of basic surrogate models
PBA	PRESS-based averaging surrogate model
PR	Total pressure ratio
PRESS	Predicted error sum of squares
P_t	Total pressure
P_{1-5}	Control points represented by Bezier curve
RANS	Reynolds-averaged Navier–Stokes
RBNN	Radial basis neural network model
RSA	Response surface approximation model
SM	Stall margin
SST	Shear stress transport
T	Tip clearance
TE	Trailing edge
T_t	Total temperature
URANS	Unsteady Reynolds-averaged Navier–Stokes
w	Weight
WTA	Weighted-average surrogate model
X	Design variable
x	Design point
α, κ	Constants of the PBA model
β	Blade tip angle
γ	Specific heat ratio
η	Adiabatic efficiency
τ	Period

Subscripts

in	Inlet
max	Choking mass flow
out	Outlet
peak	Peak adiabatic efficiency point
stall	Near-stall point

width of the CCGs. Kim et al. [18] optimized the design of circumferential casing grooves to maximize the stall margin and peak adiabatic efficiency of a transonic axial compressor by using a hybrid multi-objective evolutionary algorithm. Carnie et al. [5] used optimization to enhance the stall margin of an axial compressor with CCGs by applying a new meshing methodology, the zipper layer meshing approach.

With the aforementioned recent trends, advanced numerical methods such as unsteady RANS (URANS) analysis and large eddy simulation (LES) have been used in the design of axial compressors with CCGs to accurately identify the unsteady stall mechanism. Experimental and numerical investigations of the unsteady interaction of the rotor and circumferential grooves in a single-stage transonic compressor were reported by Muller et al. [26]. Zhao et al. [38] investigated the effects of CCGs on the unsteadiness of tip clearance flow to enhance compressor flow instability. Legras et al. [21] demonstrated the mechanism of unsteady internal flows in a high-pressure multi-stage axial compressor equipped with CCGs using RANS and URANS analyses. Various experimental and numerical studies to understand the steady and unsteady flow phenomena in transonic compressors with CCGs were reviewed by Hah [11].

Among optimization strategies, surrogate modeling has recently become a promising tool for high-performance turbomachinery design [29,33,19,10,30]. Various surrogate modeling techniques, with their intrinsic advantages, have been developed by many researchers. In particular, Goel et al. [9] developed weighted-average surrogate models consisting of a response surface approximation model (RSA) [27], a Kriging meta-model (KRG) [22], and a radial basis neural network (RBNN) model [28]. They concluded that weighted-averaging of surrogate models provides a more reliable prediction method than individual surrogate models. Also, the reliability of one of these models was demonstrated based on the design optimization of turbomachinery by Samad et al. [31] and Kim and Kim [16].

This work presents an optimization procedure for an axial compressor design with CCGs based on a surrogate modeling technique coupled with 3-D steady RANS analysis. The optimization was performed to improve the stall margin of a grooved axial compressor with three design variables defining the tip clearance, blade tip angle, and depth of the CCGs. Moreover, URANS analysis was carried out to investigate unsteady flow phenomena in the optimized compressor with CCGs.

Table 1
Design specifications of the axial compressor with NASA Rotor 37.

Designed mass flow rate, kg/s	20.19
Rotational speed, rpm	17,188.7
Total pressure ratio	2.106
Inlet hub-tip ratio	0.7
Blade aspect ratio	1.19
Tip relative inlet Mach number	1.48
Hub relative inlet Mach number	1.13
Tip solidity	1.29
Number of rotor blades	36

2. Numerical analysis

The compressor model investigated in this work is a transonic axial compressor with NASA Rotor 37 [8]. The compressor rotor operates at a speed of 17188.7 rpm. The total pressure ratio and adiabatic efficiency are 2.106 and 88.9%, respectively, at the designed mass flow rate of 20.19 kg/s. The blade section of NASA Rotor 37 is defined by a multiple circular arc. The tip clearance is 0.356 mm (0.47% span), the choking mass flow is 20.93 kg/s, and the near-stall point is 0.925 of the choke flow. Detailed specifications of the compressor model with NASA Rotor 37 are given in Table 1 from the AGARD report by Dunham [8].

Flow through the axial compressor was analyzed by solving 3-D steady and unsteady RANS equations through a finite volume solver, the commercial code ANSYS-CFX 11.0 [1]. Blade profile creation and computational mesh generation were performed using ANSYS Blade-Gen and Turbo-Grid, respectively. CFX-Pre, CFX-solver, and CFX-Post were used to define boundary conditions, solve the governing equations, and postprocessing the results, respectively. In addition, the creation of circumferential grooves and their