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Numerical optimization for stator vane settings of multi-stage compressors based on neural networks and genetic algorithms

Bo Li [a,c,*], Chun-wei Gu [a,c], Xiao-tang Li [b], Tai-qiu Liu [b]

[a] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing, China
[b] Shenyang Engine Design and Research Institute, Shenyang, China
[c] Collaborative Innovation Center of Advanced Aero-Engine, Beijing, China

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ABSTRACT

This paper outlines the aerodynamic optimization of stator vane settings for multi-stage compressors via the combination of an artificial neural network (ANN) and a genetic algorithm (GA). The investigation is conducted on a newly developed 5-stage highly loaded axial flow compressor. A three-layer perceptron neural network is employed as surrogate model, replacing an in-house one-dimensional blade stacking computation code. The stagger angles of the four stator vanes serve as the input data of the ANN, and the compressor aerodynamic performances are the outputs of the network. The well-trained ANN is subsequently incorporated into the optimization framework, which is based on an improved real-coded GA. Various advanced strategies, including the elitism operator, blend crossover, non-uniform mutation and self-adaption parameters, are introduced to the GA to promote the searching efficiency and solution globality. The optimization is conducted on the reference operating points under both design- and part-speed conditions to achieve maximum adiabatic efficiency with restrictions on the pressure ratio. The results show that for the design speed, the original stator vane setting is good, and the room for growth in efficiency is limited based on the one-dimensional optimization. However, the optimized stator vane settings improve the adiabatic efficiency by more than 1% under part-speed conditions, and the enhanced efficiency is achieved over the entire operating range. Regardless of the assumption of quasi-one-dimensional flow, the effectiveness of the optimization framework in dealing with the stage-mismatching is demonstrated. Moreover, a new sensitivity analysis method using ANN is proposed to evaluate the relationships between the geometric parameters and aerodynamic performances of the compressor.

0. Introduction

Growing concern over limited energy resources coupled with the ever-rising demand for reliable power supply and efficient aircraft engines is posing significant challenges to turbomachinery engineers. As the core components in gas turbines, modern multi-stage compressors need to meet several requirements such as a wide operating range at preferable high efficiency. A stable and efficient operation of the compressor at all desired operating conditions is of considerable importance especially for aero engines, since instabilities like stall and choke may possibly lead to unsafe operation or even mechanical damage [1]. In a multi-stage environment, the front stages often operate close to choke while the rear stages will tend to stall primarily at high speeds, whereas opposite under part-speed condition. The poor aerodynamic efficiency at lower speeds is also a common problem that we are usually faced with [2]. To reduce the impact of these undesired compressor behaviors, variable geometry systems, such as the variable inlet guide vanes (VIGVs) and variable stator vanes (VSVs), are widely adopted among modern compressors [3,4].

Various numerical analysis methods have been extensively applied to simulate the operating conditions of compressors with the rapid progress of computer science, which reduces the experimental expenses to a large extent. In the framework of a conventional optimization procedure, one-dimensional aerodynamic analysis is a significant tool for conceptual sizing of compressors in the preliminary phase. Based on the mean-line flow modeling methodology, the one-dimensional method can provide a quick and accurate prediction for the influences of variable vanes on the overall performances and aerodynamic configurations. Thus, the axial mismatching between rotor and stator blades can be captured and

* Corresponding author at: Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing, China.
E-mail address: libo12@mails.tsinghua.edu.cn (B. Li).

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Nomenclature

ANN	artificial neural network
GA	genetic algorithm
VIGV	variable inlet guide vanes
VSV	variable stator vanes
MCA	multiple-circular-arc
CDA	controlled-diffusion-airfoil
MLP	multilayer perceptron network
LM	Levenberg–Marquardt
MSE	mean square error
PE	peak efficiency
NS	near stall
IGV	inlet guide vane
S1	Stator 1
S2	Stator 2
S3	Stator 3
SEDRI	Shenyang Engine Design and Research Institute
R_t	tip radius
R_m	mean square radius
R_h	hub radius
$\mathbf{W_i}$, W	weights
$\mathbf{b}$	threshold
$\mathbf{f}$	transfer function
$\mathbf{x_i}$	inputs of ANN
$\mathbf{y}$	outputs of ANN
H	Hessian matrix
E	error function
$\Delta\beta$	variation of stagger angle from design setting (deg)
η	adiabatic efficiency
ε	total pressure ratio
μ	mean of the distribution
σ	standard deviation of the distribution
P_c	crossover rate
P_m	mutation rate
Gen	number of evolution
x	gene in the chromosome
U	boundary of the gene value
f	fitness value
α, r	random numeral
b, λ	control factors

Subscripts

new	the updated
cal	the calculated
ori	the baseline
child, parent	the child and parent generation
max, min, avg	the maximum, minimum and average

updated in a timely manner before computational fluid dynamics simulations and experimental studies, which are not only time-consuming but also expensive. Given that some empirical correlations have taken the influences of the three-dimensional internal flow into consideration, the approach is also referred to as the quasi-one-dimensional method. Howell and Calvert [5] developed a procedure using a stage stacking technique to solve the multi-stage compressor performance problems, and their programs were regarded as a standard for mean-line flow analysis. To date, continuous studies have been carried out by engine manufacturers and researchers to establish the compressor geometry using the empirically based mean-line method [6–10]. Efforts have been made to generate a credible estimate for the performance trends of modern compressors because the performance prediction far from the design point is of great importance during the preliminary design phase. As varying the staggers of several stages is a convenient and economical way to optimize the multi-stage compressor performance, especially under off-design condition, there is, therefore, a demand for a compressor design and optimization system based on one-dimensional aerodynamic analysis coupled with a numerical design optimization method.

Among the many numerical optimization methods, the genetic algorithm (GA), which is classified as a global method, has gained increased popularity in the last couple of decades. Unlike the traditional gradient-based approach, which is prone to fall into a local minimum when the relationship between the geometry parameters and compressor performance is unclear and highly nonlinear, the genetic algorithm is good at handling optimization problems with multimodal design spaces as a consequence of its intrinsic capability [11]. The GA allows for the efficient optimization of complex design spaces and can reach an acceptable optimum solution even when noise and discontinuities exist within the design space. Following the Darwinian principle of the survival of the fittest, the genetic algorithm imitates the natural evolution of biological organisms by starting with a randomly initialized population of individuals. The design variables of each individual are coded as a finite length binary or real-number string, called a chromosome, and the objective function of each candidate solution is evaluated as the fitness. The genetic algorithm computation searches for the true optima according to each individual's fitness by using the simulated evolutionary operators, that is, selection, recombination, and mutation [12]. Offsprings are generated through these unique procedures, which guarantee a monotonic improvement in the fitness value of optimal individuals among each generation, and the continuous generational process stops when the termination criteria or the optimization target is reached. The genetic algorithm is regarded as an attractive heuristic search method due to its availability, ease of use, flexibility, and robustness, as illustrated in [13]. Because of these characteristics, genetic algorithms and numerical prediction methods for compressor aerodynamic performance are often integrated into the optimization framework. Over the last few years, combinations of genetic algorithms and different types of flow solvers have been widely applied for compressor optimization [14–20], and it is worthwhile to conduct further investigations so as to optimize the variable vanes, while there seems to be very little discussion in the literature regarding the use of this population-based method.

As the one-dimensional computation procedure applied in this paper is an in-house code that cannot be made public, for the purpose of universality, usability, and scalability of the newly developed optimization method, the artificial neural network is incorporated into the optimization system acting as a surrogate model. The artificial neural network mimics the behavior of biological neurons through the way that the artificial neurons are connected and formed into a multi-layer network, making it particularly suitable for multi-dimensional interpolation as well as extrapolation applications where the data are not structured [21]. To turbomachinery engineers, the relationship between the design space and the objective function is commonly complex and multidimensional. Previous studies have shown that the neural network approach offers a promising tool for performance representation in compressor design [22–25]. Based on the proper database obtained by the flow solver, the multi-disciplinary optimization system that integrates the genetic algorithm and neural network can always lead to a good result [26–30].

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