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Study on continuous adjoint optimization with turbulence models for aerodynamic performance and heat transfer in turbomachinery cascades

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ABSTRACT

A continuous adjoint method for turbomachinery is presented based on the varied turbulence eddy viscosity (VEV), rather than the constant eddy viscosity (CEV) assumption. Firstly, the grid node coordinates variation and Jacobian Matrices is introduced to deduce the general adjoint system. Then, an objective of entropy generation for aerodynamic and heat transfer is proposed to evaluate the loss of both flow and heat transfer. The VEV adjoint systems with Spalart-Allmaras and SST turbulence models are established for the compressible turbulent flow in turbine cascades with the adiabatic blade wall condition. The aerodynamic optimization cases for turbine cascades show that the VEV adjoint system can achieve higher accuracy, quicker convergence and better optimal result than that of the CEV system in turbomachinery. Furthermore, the improvement of the VEV adjoint method to the mass flow rate constraint is analyzed. Finally, the VEV adjoint system with linearized turbulence model is presented for the isothermal blade wall condition. The optimization results demonstrate the ability of these systems in optimizing the flow and heat transfer performance and reducing the turbine total loss.

1. Introduction

Different from the classic gradient algorithms, the adjoint system carries out the sensitivity analysis independent from the number of design variables, rather than proportional to the design number. For this merit, the adjoint method has been paid much attention. In 1988, Jameson [1] firstly employed the adjoint method in the aerodynamic design optimization for external flow. In the following two decades, with the efforts of Jameson and Reuther, Nadarajah et al. [2,3], and Iollo et al. [4], the adjoint method was developed in both continuous and discrete forms for inverse and direct problems. Subsequently in internal flow, Yang, et al. [5], Giannakoglou and Papadimitriou [6], Feng et al. [7] developed continuous adjoint solvers for 2D/3D turbomachinery inverse and direct optimization design, respectively. Though the development of the optimization system for the complex flow in turbomachinery faces many challenges, significant advances on the adjoint method have been made recently, such as multi-stage optimization [8,9], multipoint optimization [10], unsteady flow optimization [11] and heat transfer design [12].

However, the accurate calculation of the gradient for the complex internal turbulent flow in turbomachinery is still a tough problem. The adjoint systems for the inviscid and laminar flow environments are usually applied to optimize the Euler flow and laminar flow, but not suitable for the internal flow in turbomachinery due to its turbulent features with the Reynolds number up to 10^6. In order to derive the adjoint system for turbulent flow, the constant eddy viscosity assumption was proposed [13,14]. The flow field is solved with turbulence models, but the variation of turbulent eddy viscosity is assumed to be neglected in the adjoint derivation, which means no adjoint equations are corresponding to the turbulence model. The CEV assumption can simplify the derivation and reduce the computational requirement, but this assumption inevitably differs from the varied turbulent eddy viscosity method.

Thus, studies have been conducted on the implementation of the VEV adjoint method since later 1990s. Many works based on the discrete adjoint approach were performed with turbulence models, such as, Anderson and Bonhaus [15], Nielsen, et al. [16], Dwight and Brezillon [17], Giles and Campobasso [18]. Compared with the discrete adjoint method, the continuous method reduces the requirements of memory and CPU greatly, especially for the VEV adjoint optimization. But, limited to the more complex derivation process, a little study on the varied eddy viscosity for the continuous adjoint method has been carried out. Bueno-Orovio, et al.

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Nomenclature

I	objective function
α	design variables
$\boldsymbol{\omega}$	vector of flow variables
$\boldsymbol{\omega}'$	vector of flow variables gradient with respect to Cartesian coordinates
$\boldsymbol{E}$	state equations
$\boldsymbol{\psi}$	vector of adjoint variables
$\boldsymbol{f}_i$	vector of inviscid flux
$\boldsymbol{f}_{vi}$	vector of viscous flux
Q	source term of flow equations
x_i	Cartesian coordinates
J	augmented objective function
M	field integral term of objective function
N	boundary integral term of objective function
dS	element area
dV	element volume
Φ	general quantity
A	matrices about inviscid flux
A_v, B	matrices about viscous flux
C, D	matrices about source term
n_i	component of outward unit normal vectors
p	static pressure
T	temperature
ρ	density
u_i	velocity components
δ	variation operator with respect to design variables
$\hat{v}$	turbulent variable
s	entropy
$\bar{k}$	turbulent kinetic energy
$\bar{\omega}$	turbulent eddy frequency

Subscripts and Superscripts

V	viscous
in	inlet of the passage
out	outlet of the passage
blade	blade wall
i, j, k	indexes
l_c l_a l_t l_e	indexes
t	total parameter
Γ	boundary of turbomachinery cascade
Ω	control volume
$\partial\Omega$	control volume boundary faces

Abbreviation

CEV	constant eddy viscosity
VEV	varied eddy viscosity
FDM	finite difference method

[19] derived the VEV adjoint system coupled with the Spalart-Allmaras model for aerodynamic optimization, but this work is just for the external flow. Zymaris, Papoutsis-Kiachagias and Giannakoglou et al. deduced the VEV adjoint system for the incompressible flow with the Spalart-Allmaras model [20], Launder-Sharma k-ε model [21], and k-ω SST model [22], and applied it to interior flows in duct geometries. In Zymaris, et al. [20], the accuracy of the CEV and VEV adjoint system was analyzed with the Spalart-Allmaras model, but the optimal processes and results were not performed. On the other hand, for the typical turbomachinery, the Reynolds number is up to 10^6, but the Reynolds numbers in the duct flow cases are very low, just as 0.2×10^5 [20], 1.2×10^5 [21], 1.0×10^5 [22]. Due to different Reynolds numbers, the turbulent flow fields and the eddy viscosity variations are very different between turbomachinery and ducts. Meanwhile, the incompressibility is just suitable for low Mach number flow, not for the cases with the Mach number >0.3, and the adjoint equation corresponding to the mass conservation equation must be derived for compressible flow.

With the implementation of the VEV adjoint systems, some researchers compared the differences between the VEV system and the CEV system. In the study of Marta and Shankaran [23], the gradients of CEV approximation differed slightly from that of the VEV system, and proved to be valid for engineering design problems with faster implementation and less resource. However, in the flow with the strong coupling relationship of the mean-flow equations and the turbulence models, the adjoint variables corresponding to the turbulent flow variables couldn't be neglected. Therefore, the CEV assumption would obtain inaccurate gradients, as concluded by a feasibility study on the effects of a usual assumption of CEV for the discrete adjoint method [24]. In the work of Dwight and Brezillon [17], the CEV approximation leads to good gradients in some cases, but exceptionally poor gradients for other cases. Bueno-Orovio, et al. [19] also compared the effect of the CEV assumption. In some cases, the constant viscosity adjoint predicts gradients wrong not only in magnitude but also in direction. In general, the VEV adjoint has better gradient accuracy, and produces better optimized profiles. In flow control optimization of duct [20–22], sensitivity derivatives from the CEV assumption were wrongly signed, which could seriously mislead the designer. However, the flow of turbomachinery is very different and complicated from the duct flow as previously mentioned, and the comparisons of these two adjoint systems in turbomachinery should be analyzed.

In order to analyze the effect of the varied turbulence eddy viscosity in turbomachinery, the present paper develops the general VEV continuous adjoint method. In this method, the techniques of the grid node coordinates variation and Jacobian Matrices are incorporated to the turbulence derivation based on authors' previous work [25,26]. In order to consider the loss from the heat transfer in the non-adiabatic system, a new objective is proposed based on the Second Law of Thermodynamics. The objective consists of the heat entropy generation and mass entropy generation, which can evaluate the overall loss of heat transfer and flow of turbomachinery.

Then, based on the derivation of the VEV adjoint system, the adjoint system coupled with the linearized Spalart-Allmaras turbulence model are established for the internal compressible flow in turbomachinery with adiabatic blade wall condition. The advantages of the VEV adjoint system in turbomachinery over the CEV system are validated through aerodynamic optimization of a 2D and a 3D turbine cascades with Reynolds number of 2×10^6. In addition, an adjoint system for the mass flow rate constraints is established in order to analyze the influence of the varied turbulence eddy viscosity on the mass flow rate constraint. Meanwhile, due to the universality of the VEV adjoint derivation, the adjoint optimization system with linearized SST turbulence model is presented. Finally, to demonstrate the optimal effectiveness of the objective for isothermal blade wall condition, the VEV adjoint system for blade profile design is established with linearized Spalart-Allmaras turbulence model to improve the flow and heat transfer loss evaluation.