An Exponent Decay Model for the Deterministic Correlations in Axial Compressors

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Long Abstract

Introduction

The flow within turbomachinery is inherently unsteady and the unsteady blade row interaction (UBRI) has a large impact on turbomachinery performance. However, unsteady 3D calculation is presently impractical as a design tool in the multistage turbomachinery routine design due to the limitations in computing costs and design schedule. The average-passage equation system (APES), proposed by Adamczyk [1], provides a rigorous mathematical framework for accounting for the UBRI in steady state calculation by introducing deterministic correlations (DC). How to model the DC to close the equation system is the key in the APES.

In recent years, many efforts have been made and some DC models have been proposed [2-8]. These models employed in the APES obviously improve the numerical results in comparison with mixing plane method. However, none of DC models has been widely used in the multistage compressor routine design, because these models are either too complex, too temperamental or still too time consuming. Hence, more research work for modeling the DC should be conducted.

In this paper, the purpose is to propose a DC model that fits compressor routine design. Firstly, a 3D viscous unsteady and time-averaging flow CFD solver is developed to investigate the APES technique. Secondly, steady, unsteady and time-averaging simulations are conducted on the investigation of the UBRI, DC distribution characteristics, and the influence of DC on the time-averaged flow field in axial compressors. Thirdly, the influence of rotor-stator interface treatment is studied and improved. Lastly, an exponent decay DC model is proposed and validated.

1. Methods

A 3D viscous unsteady and time-averaging flow CFD solver is developed based on Denton steady code. The time-averaging flow CFD solver, adopting APES, is developed to account for the unsteady blade row interactions. For unsteady simulation, the dual time stepping approach proposed by Jameson is used. The second order upwind scheme is used for physical time discretization and the SCREE scheme is employed for pseudo temporal discretization. The second order central scheme with addition of second and fourth order artificial dissipation is used for space discretisation. To accelerate the convergence, local time stepping, implicit residual smoothing and multigrid are employed. The mixing plane method is employed in the steady simulation. And the continuous interface plane method in the time-averaging simulation. A dummy cell was used at the rotor-stator interface. The domain scaling method is employed in the unsteady simulation.

Steady, unsteady and time-averaging simulations, employing the developed flow solver, are conducted on the investigation of the deterministic unsteady phenomenon in the first transonic stage of NASA 67 at design condition. Stator blade row is moved upstream to close to the rotor blade, resulting that the axial gap between rotor and stator is 10 mm, in order to highlight the unsteady blade interaction. The unsteady numerical analyses are simplified by modifying the original blade row airfoil counts from 22: 34 to 22: 33. Then the computation domain consists of two rotor blade passages and three stator blade passages. The number of physical time steps is set to 72 for each cycle and the maximum number of inner iterations is set to 150 for each physical time step.

2. Results

The results from steady and unsteady simulations are firstly compared to highlight the importance of the unsteady interactions and to help assess the shortcomings of mixing plane method. The steady simulation with mixing plane method can predict the total performance of the single axial compressor very well in comparison with the unsteady result for design condition. However, the spanwise distribution of total pressure, total temperature, entropy and Mach number predicted by steady mixing plane method has significant discrepancy with the unsteady results.

The DC distribution characteristics are analyzed based on the unsteady results. The DC is not uniform in circumferential direction and the gradients are large in some regions, and DC in general has large magnitudes at the rotor-stator interface and decreases rapidly in flow direction from the interface, especially in the rotor-stator gap. The distribution of spatial correlations along spanwise is in good qualitative agreement with DC, and only has small quantitative discrepancies.

The influence of rotor-stator interface treatment is studied and improved. The new approach greatly decreases the error induced by the interface treatment. Then the APES method with employing DC resulted from the unsteady results, can obtain nearly the same time-averaged flow fields as the unsteady simulation.

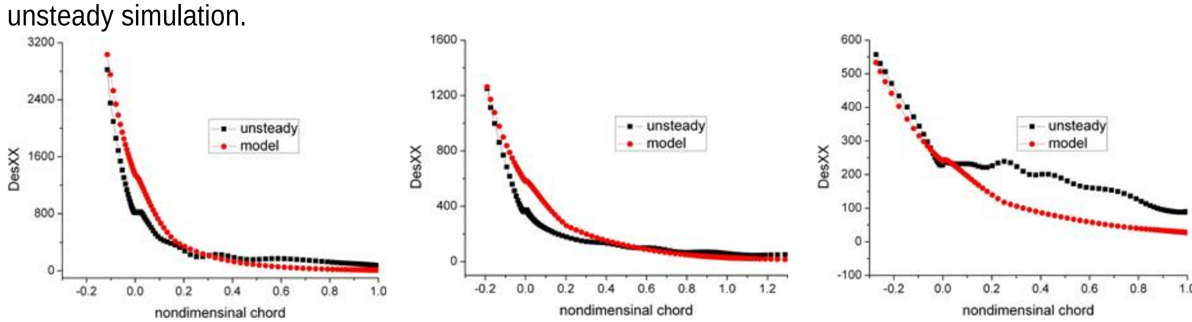

Figure 1. Pitchwise averaged axial-axial velocity correlation along chord in the stator passage (left to right: 10%, 50%, 90% span)

An exponent decay DC model is proposed based on the studies on DC distribution characteristics and the influence of DC on the time-averaged flow field. As shown in Fig. 1, the DC model can predict reasonable DC distribution; whereas in steady simulation with mixing plane method, these DC terms are zero. Then the DC model is added into the developed CFD solver. Numerical results show that the model can take into account the major part of UBRI and provide significant improvements for predicting spanwise distributions of flow properties in axial compressors, compared with the steady mixing plane method. Meanwhile, there is only a little increase (less than 1%) in CPU time owing to the addition of the DC model.

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