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A Double-Passage Shape Correction Method for Predictions of Unsteady Flow and Aeroelasticity in Turbomachinery

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Abstract. In this paper, a double-passage shape correction (DPSC) method is presented for simulation of unsteady flows around vibrating blades and aeroelastic prediction. Based on the idea of phase-lagged boundary conditions, the shape correction method was proposed aimed at efficiently dealing with unsteady flow problems in turbomachinery. However, the original single-passage shape correction (SPSC) may show the disadvantage of slow convergence of unsteady solutions and even produce nonphysical oscillation. The reason is found to be related with the disturbances on the circumferential boundaries that can not be damped by numerical schemes. To overcome these difficulties, the DPSC method is adopted here, in which the Fourier coefficients are computed from flow variables at implicit boundaries instead of circumferential boundaries in the SPSC method. This treatment actually reduces the interaction between the calculation of Fourier coefficients and the update of flow variables. Therefore a faster convergence speed could be achieved and also the solution stability is improved. The present method is developed to be suitable for viscous and turbulent flows. And for real three-dimensional (3D) problems, the rotating effects are also considered. For validation, a 2D oscillating turbine cascade, a 3D oscillating flat plate cascade and a 3D practical transonic fan rotor are investigated. Comparisons with experimental data or other solutions and relevant discussions are presented in detail. Numerical results show that the solution accuracy of DPSC method is favorable and at least comparable to the SPSC method. However, fewer iteration cycles are needed to get a converged and stable unsteady solution, which greatly improves the computational efficiency.

AMS subject classifications: 65Z05

Key words: Double passage, shape correction, Fourier transformation, unsteady flow, aeroelasticity, vibrating blades, turbomachinery.

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1 Introduction

Along with the constant pursuit of the performance and efficiency for turbomachines, the aeroelastic problems are becoming increasingly important as they will impact the engine safety and design cost. Of all blade aeroelasticity phenomenons, flutter stability is extremely critical. It is defined as an unstable and self-excited vibration which is caused by interactions between aerodynamic forces and structural motions. When flutter is encountered during the engine operation, the blade high-cycle fatigue or even damage may occur. In the past few decades, great developments have been made in numerically predicting flutter through the efforts of many scholars. A large number of methods have thus been reported and could mainly fall into three categories: energy method [1–3], eigenvalue method [4, 5] and full time-marching method [6, 7].

The energy method proposed by Carta [1] is currently most widely and successfully used in engineering especially for predicting uncoupled flutter. It is established on the basis of the fact that the regular blade flutter usually manifests as a phenomenon of single-mode vibration and modes uncoupling. It assumes the blade to vibrate at some natural mode and then uses the calculated sum of the work per cycle done by unsteady aerodynamic forces to judge the aeroelastic stability. Therefore, the accurate and efficient simulation of unsteady flows is of great importance to aeroelastic prediction. Based on the energy approach, prediction models for turbomachinery blades have been frequently reported by using CFD solvers with different complexities [3, 8, 9].

With the rapid improvements in the performance of computer, the CFD methods have developed a lot from solving potential to Euler equations and then to RANS equations, from time linearized techniques to nonlinear time-accurate methods. For steady-state flow problems, a single passage (SP) model is always adopted in order to reduce computational efforts. However, in most circumstances involving unsteady flows, this simplified approach may not be appropriate. For example, when studying blade flutter using the energy method, it is generally assumed that all blades vibrate with a constant inter-blade phase angle (IBPA) σ. In this case, a direct idea is to extend the computational domain to multi passages (MP) and the number of required passages now equals to $2\pi/\sigma$. The MP model has such advantages as imposing periodic boundary conditions conveniently, allowing to capture all the time frequencies and easy modification of codes. However, the key point which can not be ignored is the great amount of calculation, especially when σ is small, the needed computational resources may far beyond our limits.

In order to simulate unsteady flows with different IBPAs while avoid modeling multi passages, an effective approach is to use the phase-lagged boundary conditions. Based on it, the direct store method (DSM), first proposed by Erdos and Alzner [10], received a lot of attention as it has fewer assumptions and is easy to implement. However, an important step in DSM is to store all flow variables at circumferential boundaries in a recent vibration cycle and this storage can be very huge especially for 3D computations. To eliminate the drawback of DSM, He [11] proposed a sinusoidal single-passage shape correction method and then extends it to its high-order type so as to be more general