Chinese Journal of Aeronautics, (2016), **29**(6): 1563–1574

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Validation of a novel mixing-plane method for multistage turbomachinery steady flow analysis

Du Pengcheng [a], **Ning Fangfei** [b,*]

[a] *School of Aeronautic Science and Engineering, Beihang University, Beijing 100083, China*
[b] *School of Energy and Power Engineering, Beihang University, Beijing 100083, China*

Received 28 October 2015; revised 23 February 2016; accepted 15 June 2016
Available online 21 October 2016

KEYWORDS

Centrifugal compressor;
Flux conservation;
Mixing-plane method;
Reverse flow;
Turbomachinery

Abstract The steady calculation based on the mixing-plane method is still the most widely-used three-dimensional flow analysis tool for multistage turbomachines. For modern turbomachines, the trend of design is to reach higher aerodynamic loading but with still further compact size. In such a case, the traditional mixing-plane method has to be revised to give a more physically meaningful prediction. In this paper, a novel mixing-plane method was proposed, and three representative test cases including a transonic compressor, a highly-loaded centrifugal compressor and a high-pressure axial turbine were performed for validation purpose. This novel mixing-plane method can satisfy the flux conservation perfectly. Reverse flow across the mixing-plane interface can be resolved naturally, thus making this method numerically robust. Artificial reflection at the mixing-plane interface is almost eliminated, and then its detrimental impact on the flow field is minimized. Generally, this mixing-plane method is suitable to simulate steady flows in highly-loaded multistage turbomachines.

© 2016 Chinese Society of Aeronautics and Astronautics. Production and hosting by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Multistage turbomachinery flow is inherently unsteady due to the relative motion of adjacent rotor and stator blade rows. However, at ordinary operation point, the time-averaged flow field in each blade passage in either rotor or stator blade row is almost the same in the relative frame of reference fixed to the corresponding blade row under consideration. Thus, quasi-steady calculation can be performed based on single blade passage, which can capture the major flow features but with much less computational effort than full unsteady simulation. The simplest way to obtain a steady state solution is the frozen rotor technique. It keeps the relative positions of the rotor and stator fixed, and thus the results are position-dependent. A more reasonable way for quasi-steady calculation is the mixing-plane method which was first proposed by Denton.[1] In this method, spanwise profiles of the circumferentially averaged flow variables are transferred between adjacent blade rows, which means the source of flow unsteadiness in a blade row due to the circumferential nonuniformity propagated from adjacent blade row(s) can be removed so that the steady

---

[*] Corresponding author. Tel.: +86 10 82338270.
E-mail addresses: dupengcheng22@163.com (P. Du), fangfei.ning@buaa.edu.cn (F. Ning).

Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.10.005
1000-9361 © 2016 Chinese Society of Aeronautics and Astronautics. Production and hosting by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

solution can be obtained. Since the mixing-plane method was proposed, it has been the most popular way in the simulations of multistage turbomachinery flows, and it will still be the favorite method for engineers in the next decade.

In general, there are two key steps to realize a mixing-plane method. First, an averaging technique is required to obtain the circumferentially averaged flow state at each side of the interface. Second, the circumferentially averaged flow state must be transferred through the interface. Various detailed treatments of the above procedures are proposed and are still under further improvement in the literature.[2–7]

For the first key step in mixing-plane method, the straight and simplest way is to circumferentially average the flow variables directly. However, first, there is no consensus on what flow variables should be circumferentially averaged.[8] The principal flow variables such as density, velocity and pressure are often selected, while the total pressure, total temperature and flow angles can also be circumferentially averaged to model each successive blade row more like individuals. Second, actually there is no suitable weighted averaging method that can deal with the situation when there exist both forward and inverse flows across the interface. Besides, due to the nonlinear relationship between the flow variables and the flux, the total flux calculated from circumferentially averaged flow variables may be deviated from the total flux of the non-uniform flow. Thus the conservation of mass, momentum and energy would not be strictly satisfied. To solve this problem, the flux-based circumferential averaging technique[2] has been widely used. However, there is a root square operation in solving the mixed-out static pressure from the averaged fluxes, and thus divergence would be encountered during the initial stage of calculations. Another shortcoming of this method is that it cannot allow the reverse flow across the mixing-plane interface directly. Recently, Wang[3] improved this flux-based mixing-plane method. The primitive variable variations are directly determined from the flux difference between the two sides of the interface, and then the numerical stability is enhanced and reverse flow across the interface can be handled. Later on, Ning[4] presented his mixing-plane model which can also ensure the flux conservation but based on a more physical background.

For the second step of a mixing-plane method, i.e., the information exchange across the interface, the most important issue is to prevent wave reflections from the interface. Giles[9] proposed a 1D characteristic-based nonreflective boundary condition (NRBC) in which the circumferential and radial variations are neglected. Then, Saxer and Giles[10] extended this NRBC to quasi-3D flow based on the assumption that the radial variations are small compared to circumferential variations. Anker et al.[11] extended this theory to fully 3D NRBC. The 1D NRBC is most widely used due to its simplicity and robustness.[3–6] However, it does not always work well when the circumferential nonuniformity is strong and/or the adjacent blade rows are closely spaced, and thus the non-physical reflections from the interface would be notable. To remit this problem, Ning[4] proposed a method that a constant-radius buffer layer was added at each side of the interface to damp the outgoing waves.

In this paper, the basic theory of this novel mixing-plane method is first stated and then three typical test cases are given to demonstrate the superiority of this mixing-plane method.

2. Mixing-plane governing equations

From the authors' point of view, the mixing-plane method should not just be a pure numerical procedure to transfer the circumferentially averaged flow variables across the interface. A physical correspondence for this pitchwise mixing can be found, i.e., we can just make the gap between the two adjacent blade rows long enough so as to mix out all the non-uniformities (as shown from Fig. 1(a) and (b)), while the spanwise mixing is assumed to be suspended in the "extended mixing region". Therefore, for a fully converged flow field in the case as shown in Fig. 1(b), we can find such an intermediate position where the flows are pitchwise uniform. At this position, if we cut out an infinitely thin slice as denoted by two lines "ml" and "mr" in Fig. 1(b), the following governing equations expressed in cylindrical coordinate system hold

$$\frac{\partial \overline{\boldsymbol{Q}}}{\partial t} + \boldsymbol{F}_{\mathrm{mr}} - \boldsymbol{F}_{\mathrm{ml}} = 0 \tag{1}$$

where the mixed-out conservative variables $\overline{\boldsymbol{Q}}$ in the slice and the advective flux $\boldsymbol{F}$ are expressed as,

$$\overline{\boldsymbol{Q}} = [\rho, \quad \rho v_x, \quad \rho v_\theta, \quad \rho v_r, \quad \rho e]^{\mathrm{T}},$$

$$\boldsymbol{F} = [\rho U, \quad \rho U v_x + n_x p, \quad \rho U v_\theta + n_\theta p, \quad \rho U v_r + n_r p, \quad \rho U H]^{\mathrm{T}}$$

with t being the pseudo time, ρ the density, (v_x, v_θ, v_r) the absolute velocity components expressed in cylindrical coordinate (x, θ, r), e the total energy, $U = n_x v_x + n_\theta v_\theta + n_r v_r$ the advective velocity normal to the blade row interface, p the static pressure and H the total enthalpy. The unit vector $\boldsymbol{n} = (n_x, n_\theta, n_r)^{\mathrm{T}}$ denotes the normal direction of blade row interface, and n_θ is actually equal to zero because the interface is a revolution surface.

The solution of Eq. (1) is the intermediate mixed-out state. As shown in Fig. 1(b), the advective fluxes from surface "L" to "ml" and from "R" to "mr" are conservative if the flow is inviscid and adiabatic, and we can thus obtain the following equations:

$$\boldsymbol{F}_{\mathrm{ml}} = \frac{1}{S_L} \int_L \boldsymbol{F} \cdot \mathrm{d}S \tag{2}$$

$$\boldsymbol{F}_{\mathrm{mr}} = \frac{1}{S_R} \int_R \boldsymbol{F} \cdot \mathrm{d}S \tag{3}$$

where S is the surface area at the interface, and the subscripts "L" and "R" denote the exit of upstream blade row and the inlet of downstream blade row. Therefore, at each time-marching step for the passage flows, suppose that the boundary conditions at both boundaries "L" and "R" have been defined, and the advective flux across these two boundaries can be evaluated, and thus the flux terms in Eq. (1) are known. Subsequently, the intermediate fully mixed-out state can be updated by solving Eq. (1) through an individual time-marching loop (the time stepping can be synchronized with that for the passage flows). As Eq. (1) converges, the advective flux at the blade row interface is conserved. The solution of Eq.

Download English Version:

https://daneshyari.com/en/article/7154243

Download Persian Version:

https://daneshyari.com/article/7154243

Daneshyari.com