

一种求解透平叶栅三维流场的高精度 TVD 格式*

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【摘要】 本文提出了一种应用三阶精度 Chakravarthy-Osher TVD 格式求解环形透平叶栅三维定常流场的隐式近似因子分解方法。控制方程为柱座标速度分量表示的任意曲线座标系下的三维欧拉方程。采用 Beam-Warming 近似分解,对隐式项进行迎风差分,得到了时间精度为一阶、空间精度为 5 点三阶的隐式格式。算例对 5 点三阶和 5 点二阶精度的格式进行了比较。表明空间三阶精度隐格式对计算结果没有明显改进,但收敛残差有较大降低。

关键词: 三维流场 Euler 方程 TVD 格式 透平叶栅

1 前 言

TVD 格式^[1]的出现,使应用时间相关法求解三维欧拉方程成为主要的求解方法,并且已有许多成功的算例^[2,3],其中大部分软件都采用 Yee-Harten^[4]的隐式 TVD 格式,在光滑区域(极值点除外)空间精度为二阶。比较著名的 TVD 格式目前主要有 Harten^[1]和 Osher^[5]的格式,Chakravarthy 和 Osher 又把一维格式^[5]扩展到三维^[6]。对 Harten 和 Osher 的 TVD 格式的比较表明,在一维情况下 Osher 格式的激波分辨率明显高于 Harten 格式,但显式 Osher 格式的 Courant 数必须小于 0.5;在二维情况下 Yee-Harten 格式的分辨率却高于 Chakravarthy-Osher 格式。本文选用了 Chakravarthy-Osher 格式。另一方面,近似因子分解^[7]和 LU 分解技术^[8]在二维流场求解中都有应用。文献[8]提出在三维流场求解中不宜采用近似因子分解技术,原因是如求解状态变量 U^{n+1} ,则三维交替隐式方法对线性方程是无条件稳定的,但稳态解依赖于时间步;如求解状态变化量 ΔU ,则是无条件不稳定的。但文献[8]是针对空间导数采用中心差分格式而言,如果空间差分采用 TVD 格式,那么采用近似因子分解技术的 ADI 方法的稳定性将会发生改变,因此本文仍采用近似因子分解技术求解三维叶轮机机械无粘稳态流场。

本文首先推导适合叶轮机机械的任意曲线座标系下的三维欧拉方程,然后将 Chakravarthy-Osher TVD 格式扩展到三维,采用隐式近似因子分解技术求解方程组。算例求解了一系列环形静叶栅的三维流场,数值试验表明隐式近似因子分解 Chakravarthy-Osher 格式具有良好的收敛性和较高的激波分辨率,且使用 5 点格式空间精度可以达到三阶。

2 控制方程、三维隐式 Chakravarthy-Osher TVD 格式

在任意曲线坐标系 (ξ, η, ζ) 中,以柱座标 (x, r, φ) 速度分量 (u, v, w) 表示三维守恒型

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欧拉方程为:

$$\partial \mathcal{U} / \partial t + \partial \mathcal{E} / \partial \xi + \partial \mathcal{F} / \partial \eta + \partial \mathcal{G} / \partial \zeta = H \quad (1)$$

$$\text{其中} \begin{bmatrix} \mathcal{U} \\ \mathcal{E} \\ \mathcal{F} \\ \mathcal{G} \\ H \end{bmatrix}^T = D \begin{bmatrix} \rho & \rho \bar{u} & \rho \bar{v} & \rho \bar{w} & -\rho v/r \\ \rho u & p \xi_x + \rho u \bar{u} & p \eta_x + \rho u \bar{v} & p \zeta_x + \rho u \bar{w} & -\rho uv/r \\ \rho v & p \xi_r + \rho v \bar{u} & p \eta_r + \rho v \bar{v} & p \zeta_r + \rho v \bar{w} & \rho (w + \omega)^2 - v^2 / r \\ \rho w & p \xi_{\theta} r + \rho w \bar{u} & p \eta_{\theta} r + \rho w \bar{v} & p \zeta_{\theta} r + \rho w \bar{w} & -2\rho v(w + \omega)/r \\ e & (e + p) \bar{u} & (e + p) \bar{v} & (e + p) \bar{w} & \rho v \omega^2 r^2 - (e + p)v/r \end{bmatrix}$$

$\bar{u}$ 、 $\bar{v}$ 、 $\bar{w}$ 分别为 ξ 、 η 、 ζ 三个方向的速度递变分量: $[\bar{u} \ \bar{v} \ \bar{w}]^T = J^{-1}[u \ v \ w]^T$ 。J 为 Jacobi 转换矩阵 $J = \partial(x, r, \theta) / \partial(\xi, \eta, \zeta)$, D 为 J 的行列式的值, J^{-1} 为 J 的逆阵。求解动叶流场时, 该曲线坐标系随动叶一起旋转。对于定比热流体 $\gamma = \text{const}$, $\mathcal{E}$ 、 $\mathcal{F}$ 、 $\mathcal{G}$ 都为 $\mathcal{U}$ 的线性函数, 方程 (1) 可以线性化写成矩阵形式:

$$\partial \mathcal{U} / \partial t + A \partial \mathcal{U} / \partial \xi + B \partial \mathcal{U} / \partial \eta + C \partial \mathcal{U} / \partial \zeta = H \quad (2)$$

其中 A 、 B 、 C 为雅可比矩阵, $A = \partial \mathcal{E} / \partial \mathcal{U}$, $B = \partial \mathcal{F} / \partial \mathcal{U}$, $C = \partial \mathcal{G} / \partial \mathcal{U}$ 。方程 (1) 的隐式时间差分可写成:

$$\{I + \theta \Delta t [(\partial \mathcal{E} / \partial \mathcal{U}) A + (\partial \mathcal{F} / \partial \mathcal{U}) B + (\partial \mathcal{G} / \partial \mathcal{U}) C]\} \Delta \mathcal{U}^n = -(\partial \mathcal{E} / \partial \mathcal{U} + \partial \mathcal{F} / \partial \mathcal{U} + \partial \mathcal{G} / \partial \mathcal{U} - H)^n \quad (3)$$

θ 是格式为隐式的程度, 取 $\theta = 1$, 故格式为时间一阶精度。采用 Beam-Warming 近似因子分解, 将一个三维问题化为 3 个方向的一维问题:

$$\{I + \theta \Delta t (\partial A / \partial \xi)\} \{I + \theta \Delta t (\partial B / \partial \eta)\} \{I + \theta \Delta t (\partial C / \partial \zeta)\} \Delta \mathcal{U}^n = RHS \quad (4)$$

其中 $RHS = -(\partial \mathcal{E} / \partial \mathcal{U} + \partial \mathcal{F} / \partial \mathcal{U} + \partial \mathcal{G} / \partial \mathcal{U} - H)^n$ 为了减少代数方程求解的工作量, 将方程 (4) 左端对角化, 详细过程参见文献 [4]。记 $\theta \Delta t = \tau$, 则方程 (3) 的迎风半离散格式为:

$$R_A [I + (\tau h_1)(\Delta \Lambda^+ + \nabla \Lambda^-)] R_A^{-1} R_B [I + (\tau h_2)(\Delta \Lambda^+ + \nabla \Lambda^-)] R_B^{-1} \\ \times R_C [I + (\tau h_3)(\Delta \Lambda^+ + \nabla \Lambda^-)] R_C^{-1} \Delta \mathcal{U}^n = RHS \quad (5)$$

其中 h_1 、 h_2 、 h_3 分别为 ξ 、 η 、 ζ 方向的空间步长, R_A 、 R_B 、 R_C 分别为矩阵 A 、 B 、 C 的右特征矩阵, R_A^+ 、 R_B^+ 、 R_C^+ 为相应的逆。 Λ^+ 、 Λ^- 为矩阵 A 、 B 、 C 的特征值组成的对角阵。 Λ^+ 、 Λ^- 分别为由正特征值和负特征值组成的对角阵。

求解方程 (5) 时在 3 个方向分别使用追赶法求解三对角阵, 因此计算量稍大于 LU 分解。

方程 (5) 的右端项 RHS 采用 TVD 格式对通量进行差分, 本文直接将二维 Chakravarthy-Osher TVD 格式扩展到三维:

$$RHS = -[(\hat{E}_{i+1/2} - \hat{E}_{i-1/2})/h_1 + (\hat{F}_{j+1/2} - \hat{F}_{j-1/2})/h_2 + (\hat{G}_{k+1/2} - \hat{G}_{k-1/2})/h_3] \quad (6)$$

式中带有上标 “ $\hat{\cdot}$ ” 的量是对应通量的数值通量。Chakravarthy-Osher 格式的数值通量为 (以通量 $\hat{F}$ 为例):

$$\hat{F}_{j+1/2} = h[(\bar{U}_{j+1}, \bar{U}_j) - [(1 - \Phi)/4] \hat{\tilde{F}}_{j+3/2}^- - [(1 + \Phi)/4] \hat{\tilde{F}}_{j+1/2}^-] \\ + [(1 + \Phi)/4] \hat{\tilde{F}}_{j+1/2}^+ + [(1 - \Phi)/4] \hat{\tilde{F}}_{j+1/2}^+ \quad (7)$$

注意这里下标省去了 i 、 k 。其中 $d\tilde{F}^-$ 、 $d\tilde{F}^+$ 为经过通量限制后的通量差分, h 为 Roe 格式的一阶精度迎风格式的数值通量, 文献 [6] 给出了 3 种等价的表达式:

$$h_{j+1/2} = F(\bar{U}_j) + \sum_{q=1}^m dF_{j+1/2}^{q-} = F(\bar{U}_{j+1}) - \sum_{q=1}^m dF_{j+1/2}^{q+} \\ = \frac{1}{2} [F(\bar{U}_j) + F(\bar{U}_{j+1})] - \frac{1}{2} \left[\sum_{q=1}^m dF_{j+1/2}^{q+} - \sum_{q=1}^m dF_{j+1/2}^{q-} \right]$$

这里 m 为特征值的个数, $m = 5$ 。值得一提的是求解定常解时, 推进过程中这 3 个表达式是不等价的, 只有在流场收敛后才是等价的, dF 为通量 F 经过波面族的变化: $dF = \sum_{q=1}^m dF^q$ 。 dF^q 为通量 F 经过对应特征值为 λ 的波面的变化, dF^q 的计算公式为 $dF_{j+1/2}^q = \lambda_{j+1/2}^q \alpha_{j+1/2}^q$ 。 $\alpha_{j+1/2}^q$ 为特征变量的差分, $\alpha_{j+1/2}^q = l_{j+1/2}^q (U_{j+1} - U_j)$ 。注意在三维情况下由于不满足可积条件, 特征变量不存在, 但特征变量的差分仍有意义^[9]。 $r_{j+1/2}^q$ 为特征值 $\lambda_{j+1/2}^q$ 对应的右特征列向量, $l_{j+1/2}^q$ 为对应的左特征行向量, $\lambda_{j+1/2}^q$ 、 $r_{j+1/2}^q$ 、 $l_{j+1/2}^q$ 均为由气动参数经 Roe 平均计算得到的。

记 $\sigma^q = \lambda^q \alpha^q$, 则 σ^q 为特征通量的差分。以特征变量表示的方程 (7) 具有 TVD 性质, 为使差分格式具有 TVD 性质, 因此对特征通量差分进行限制:

$$\begin{aligned} \tilde{\sigma}_{j+3/2}^- &= \min\text{mod}[\sigma_{j+3/2}^-, \beta \tilde{\sigma}_{j+1/2}^-] \quad , \quad \tilde{\sigma}_{j+1/2}^- = \min\text{mod}[\sigma_{j+1/2}^-, \beta \tilde{\sigma}_{j-1/2}^-] \\ \tilde{\sigma}_{j+1/2}^+ &= \min\text{mod}[\sigma_{j+1/2}^+, \beta \tilde{\sigma}_{j-1/2}^+] \quad , \quad \tilde{\sigma}_{j-1/2}^+ = \min\text{mod}[\sigma_{j-1/2}^+, \beta \tilde{\sigma}_{j-3/2}^+] \end{aligned} \quad (8)$$

式 (7) 和式 (8) 中的参数 Φ 、 β 为空间差分精度控制参数且需要满足关系式 $\beta_{\max} = (1 + \Phi) / (1 - \Phi)$ 。若取 $\Phi = 1/3$, $\beta = 4$, 则格式为三阶空间精度。式中运算符 minmod 为最小模运算。经过修正的通量差分 (经过波面 q) 为:

$$\begin{aligned} d\tilde{F}_{j+3/2}^- &= \tilde{\sigma}_{j+3/2}^- \cdot r_{j+3/2}^- \quad , \quad d\tilde{F}_{j+1/2}^- = \tilde{\sigma}_{j+1/2}^- \cdot r_{j+1/2}^- \\ d\tilde{F}_{j+1/2}^+ &= \tilde{\sigma}_{j+1/2}^+ \cdot r_{j+1/2}^+ \quad , \quad d\tilde{F}_{j-1/2}^+ = \tilde{\sigma}_{j-1/2}^+ \cdot r_{j-1/2}^+ \end{aligned} \quad (9)$$

经过波面族 ($q = 1, 2, \dots, m$) 的通量差分 (经通量限制后) 为经过各波面的通量差分之和, 即

$$dF^+ = \sum_{q=1}^m dF^{q+} \quad , \quad dF^+ \approx \sum_{q=1}^m d\tilde{F}^{q+} \quad , \quad dF^- = \sum_{q=1}^m dF^{q-} \quad , \quad dF^- \approx \sum_{q=1}^m d\tilde{F}^{q-} \quad (10)$$

将 (9) 式和 (10) 式代入 (7) 得到空间差分为 Chakravarthy - Osher 格式的 TVD 差分格式。

求解方程 (5) 还需给定进出口边界条件。对于进口亚音的涡轮叶栅, 给定的物理边界条件为进口总温 T^* , 进口总压 p^* , 进口气流角 $\alpha(w, u \text{ 间夹角})$, $\beta(v, u \text{ 间夹角})$ 。如出口亚音, 则给定出口静压 p , 其余 4 个参数外插得到。如出口超音, 则不给定任何参数。在固壁边界保证无穿透条件; 在周期性边界保证周期性边界条件。

3 算例与分析

利用本文程序试算了某试验环形透平静叶栅的三维流场。计算网格采用了壁面正交的 H 型网格, 网格数为 $57 \times 11 \times 11$ 。

算例 1 计算了该叶栅实验工况下的流场。实验在低速风洞上进行。图 1 比较了数值计算和吹风实验得到的出口平均 Ma 数。图 1 表明除了叶根叶顶部分因二次流动差别较大外, 其它部分数值计算结果与吹风实验吻合。

算例 2 计算了该叶栅设计工况下的流场。计算过程中分别采用了二阶空间精度 (下称格式 1) 和三阶空间精度 (下称格式 2) 两种格式以比较空间精度对计算的影响。格式 1 使用的 TVD 格式参数为 $\Phi = 1/2$, $\beta_{\max} = 5$, 这是二阶精度格式中三阶截断误差最小的格式。格式 2 的参数为 $\Phi = 1/3$, $\beta_{\max} = 4$ 。图 2、3 分别为三阶精度格式计算得到的根部 Ma 数等值线分布和叶片根部、中部和顶部 Ma 沿型线的分布。图 2、3 及

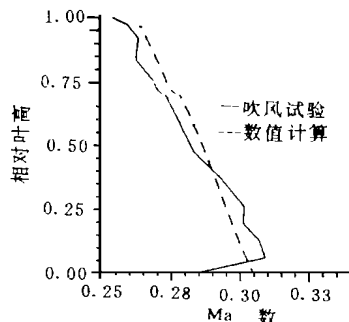


图 1 出口平均 Ma 数比较

二阶精度格式得到的 Ma 数沿型线的分布表明在根部尾缘前方约 $1/5$ 弦长处存在很强的激波, 气流 Ma 数达到 1.4。无论格式 1 还是格式 2 捕捉到的激波宽度只有一个网格, 激波位置相同。由此可见二阶或三阶空间精度隐格式对激波的捕捉能力几乎一样。另外, 两种格式计算的流量差异很小, 格式 1 为 5.59501kg/s , 格式 2 为 5.58820kg/s 。

为了仔细研究空间精度对计算结果的影响, 图 4 表示了出口平均 Ma 数 (实线) 和平均静压 (虚线) 两种格式相对偏差百分比沿叶高的分布, 即 $(q_2 - q_1) / q_2 \times 100\%$, q_1 、 q_2 分别为格式 1 和格式 2 得到的 Ma 数或静压。由此可见出口平均静压差别很小, 只在根部有较大差异, 这是由于根部超音流动, 出口静压是外插得到的。 Ma 数在根部和顶部有较大差别, 中部差别很小。图 5、6 分别表示根部压力和 Ma 数两种格式相对偏差百分比沿型线的分布。图 5 表明两种格式的静压在喉部有较大差异, 这说明音速点对本文的格式有较大影响。图 6 表明三阶精度格式在激波附近计算的 Ma 数高于二阶精度, 这说明三阶精度较少抹光激波。

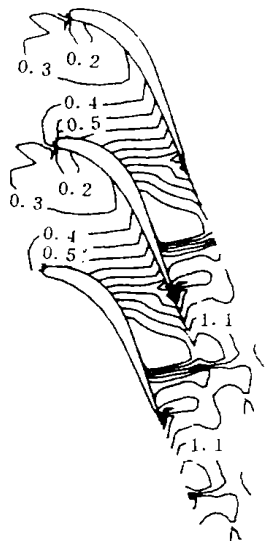


图 2 根部 Ma 数等值线

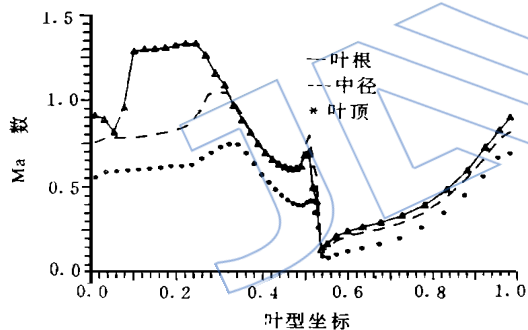


图 3 Ma 数沿型线分布 (三阶精度)

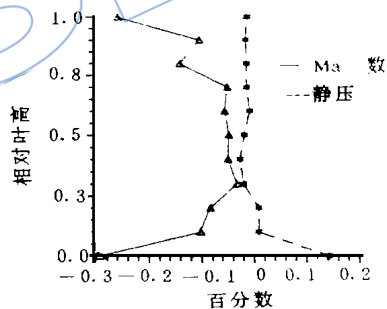


图 4 出口平均参数相对偏差百分数

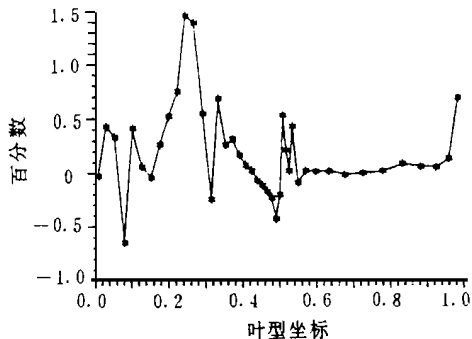


图 5 静压相对偏差沿叶型分布

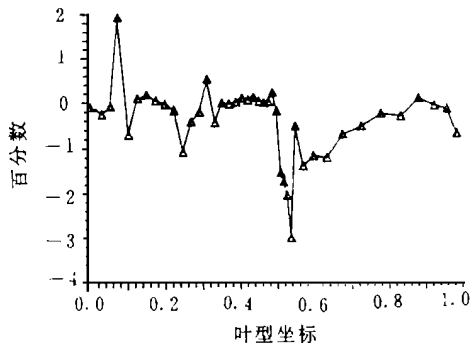


图 6 Ma 数相对偏差沿叶型分布

图 7 表明两种格式的收敛过程有较大差异, 格式 2 优于格式 1。这是因为格式 2 没有三阶频散项, 提高了对间断的分解能力。另外的数值试验表明, 随激波强度的增加, 收敛残差也随之增加。由此可见三阶精度格式在求解含有较强激波的流场时, 优越于二阶精度格式。

算例表明本方法能够求解高跨音透平叶栅流场, 计算稳定, 收敛较快。文中还对采用空间二阶精度格式和三阶精度格式进行了对比, 算例表明在隐格式中空间三阶精度计算结果几乎与二阶精度相同, 但三阶精度格式能够明显降低收敛残差, 且比二阶格式稳定。在喉部附近 (音速点) 两种格式有较大差异。

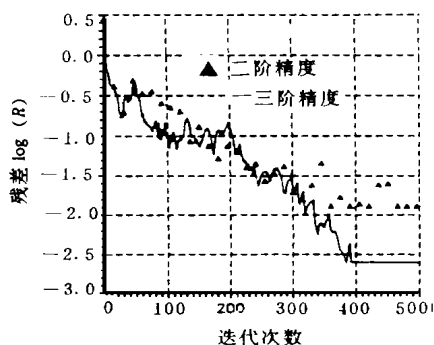


图 7 收敛史

参 考 文 献

- 1 Harten A. High Resolution Schemes for Hyperbolic Conservation Laws. J. of Computational Physics, 1983, 49: 357-393
- 2 Yokota J W, Caughey D A. An L- U Implicit Multigrid Algorithm for the Three- Dimensional Euler Equations. AIAA 87- 0453
- 3 Chakravarthy S R. The Versatility and Reliability of Euler Solvers Based on High Accuracy TVD Formulation. AIAA 86- 0243
- 4 Yee H C, Warming R F, Harten A. Implicit Total Variation Diminishing Schemes for Steady- State Calculations. J. of Computational Physics, 1985, 57: 327- 360
- 5 Osher S, Chakravarthy S R. Very High Order Accurate TVD Schemes Approximating Hyperbolic Conservation Laws. ICASE Report 84- 44
- 6 Chakravarthy S R, Osher S. A New Class of High Accuracy TVD Schemes for Hyperbolic Conservation Laws. AIAA 85- 0363
- 7 Beam R W, Warming R F. An Implicit Finite Difference Algorithm for Hyperbolic Systems in Conversations Forms. J. Computational Physics 1976, 23: 87- 110
- 8 Jameson A, Tukul E. Implicit Schemes and L- U Decompositions. Mathematics of Computation, 1981, 37 (156): 385- 397
- 9 Charles Hirsch. Numerical Computation of Internal and External Flows. Wiley- Interscience Publication, 1990

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FULL- LENGTH PAPERS

A METHOD FOR DETERMINING AIRCRAFT ENGINE GROSS THRUST IN FLIGHT

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ABSTRACT

A method, "gross thrust model", is developed to determine gross thrust of jet engine and afterburning turbofan engine in flight testing. This model is able to determine the gross thrust of modern engines with an acceptable degree of accuracy only by using a few of pressure measurements. The gross thrust model is based on a one-dimensional analysis of flows in mixer, afterburner and nozzle. Some correction coefficients are required to account for three-dimensional effects, the effects of friction and mass transfer, as well as the effects of the simplifying assumptions used in the theory. The correction coefficients in the model are K, C and E. Both K and C are constants, whereas E varies with engine operating conditions. In order to determine the reasonable coefficients K, C and E, it is necessary to acquire engine testing data in the altitude facility at flight conditions as much as possible. A comparison was made between the data determination from the gross thrust model and the gross thrust measured from the altitude facility for engine J85-GE-21 at $H=7620\text{m}$, $M_{a0}=0.90$. It demonstrates that the accuracy of the gross thrust model is about 3.0 percent and depends on the pressure difference between the total pressure of the turbine discharge and the static pressure of the nozzle inlet.

AN EXPERIMENTAL STUDY OF AERODYNAMIC PERFORMANCE AND AEROACOUSTIC CHARACTERISTICS OF A SERIES OF PROP- FANS

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ABSTRACT

Aerodynamic performance and aero-acoustic characteristics of straight (un-sweep), forward-sweep and backward-sweep blade with different installed angles have been investigated experimentally under the take-off condition. From their comparative study the following conclusions have been drawn. (1) An optimal prop-fan design should be made by combining both high aerodynamic performance and low aerodynamic noise; (2) Blades with sweep have potentials for noise reduction; (3) Tip-load reduction prop-fan blade design would be benefit to lowering the noise level as well as to the prop-fan efficiency improvement.

A HIGH- ORDER ACCURACY TVD EULER SOLVER FOR 3D FLOWS IN TURBINE CASCADES

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ABSTRACT

A third-order accuracy implicit approximate factorized TVD code is developed using Chakravarthy-Osher scheme to solve the steady flows in annular turbine cascades. The governing equation is the 3D Euler equations in arbitrary curvilinear coordinate systems in terms of cylinder coordinate system velocity components. Beam-Warming factorization and upwind difference are adopted to discretize the implicit term, and the explicit one is discretized by Chakravarthy-Osher TVD numerical fluxes. The boundary condition is ob-

tained from extrapolation. The resulted algebraic equations are tridiagonal block matrix system and solved by sweeping in each direction. So the scheme is a 5 point implicit AF scheme of first-order temporal and third order or second-order spacial accuracy depending on the two TVD factors. Two examples are presented, the first verifies the calculation of third-order scheme with a low speed wind tunnel experiment, the second compares the third-order scheme with the second-order one. The examples indicate that the code results in numerical solutions agree with the experiment, and the third-order scheme has little difference from the second-order one in the solutions, but it decreases the convergent residual greatly. Also it is showed that the two schemes do not agree with each other very well in the throat of the cascade where the flow velocity is equal to the local sound speed.

A METHOD OF USING TVD SCHEME TO CALCULATE INCOMPRESSIBLE FLOWS SEPARATELY

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ABSTRACT

The Total Variation Diminishing (TVD) schemes have been adapted to incompressible flow computations. Considering the characters of the computation in the incompressible flow, a new method is given that the TVD scheme is used with separating the continue equation from momentum equations. The continuum governing equations are discretized on a modified nonstaggered grid. In the momentum equations, the convective terms are discretized by a third-order TVD scheme, and the others are done by central finite difference scheme. The pressures are solved by pressure substitution. Furthermore, a pressure correction procedure and the Gauss-Seidel centrally symmetric iteration algorithm are used to enhance the convergence rate. As a result, the code containing those methods has been applied to computation of two typical flow problems: the channel flow problem and the lid-driven cavity flow problem. A comparison of the present results with the literature data is also given in good agreement. It is shown that the TVD scheme is not only applicable to incompressible flow computation, but also it yields higher accuracy than the non-TVD scheme.

A NEW COMPREHENSION ON STATOR CASCADE UNDER ROTATING STALL

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ABSTRACT

Onset points of rotating stall, time-average performance and flow fields after stall appearing, as well as the unstable behaviors for a single-stage axial-flow compressor and an isolated rotor have been measured successfully with hot-film probes and a three-hole cylindrical pressure probe containing fast response transducers. On the basis of many experimental data, the influences of stator cascade in the single-stage compressor on the whole time-average characteristics and the cessation behavior of rotating stall, as well as the stalled flow field have been elaborated in detail. When a single-stage compressor enters the unstable condition, the roles of the stator cascade, such as postponing the appearance of rotating stall, as well as modifying the stalled flow field and cessation form, have been analysed. There is an obvious difference of the unstable behavior between the single-stage axial-flow compressor and the isolated rotor. At high rotor speed ($\bar{n} > 0.85$), a nonrecoverable stall phenomenon appears for a single stage compressor, but it does not appear for an isolated rotor at any speed.

HEAT TRANSFER FROM SHROUDED ROTATING DISK WITH CENTRIC AIR INFLOW

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ABSTRACT

An air-cooled turbine disk was investigated as the model of a rotating disk.