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叶栅端壁附面层及叶片力亏损的数值研究*

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本文对轴流压气机叶栅端壁附面层各种计算方法进行了研究，基于理论和实验提出一种将叶片力亏损与端壁附面层主流和横流发展相关联的新的叶片力亏损模型。对三种不同叶栅的计算结果表明，采用本文的力亏损模型和端壁附面层计算方法所预测的端壁附面层发展，尤其是叶片力亏损的发展与实验值的一致性较好，表明本文模型通用性、实用性强。

1. 端壁附面层预测模型　湍流附面层动量积分方程为:

$$d(C_{xe}^2\theta_{xx})/dx + (dC_{xe}/dx)C_{xe}\delta_x^* = D_x + \tau_{ox}/\rho \qquad (1)$$

$$d(C_{xe}^2\theta_{yx})/dx + (dC_{ye}/dx)C_{xe}\delta_x^* = D_y + \tau_{oy}/\rho \qquad (2)$$

$$D_x = \int_o^\delta \frac{f_y - f_{ye}}{\rho}\mathrm{tg}\,\beta dz \quad ; \quad D_y = \int_o^\delta \frac{f_{ye} - f_y}{\rho} dz$$

$$f_y = \Delta p / s \qquad (3)$$

式中f_y 为单位栅距叶片力，D_x 和D_y 分别为叶片力亏损沿x 和y 向的分量，Δp 是相同x 值叶片上下表面压差。附面层动量厚度 θ 和位移厚度 δ^* 为:

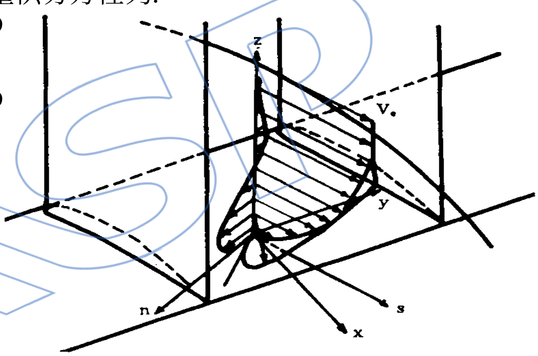

图 1　端壁附面层两种分析坐标系

$$\theta_{xx} = \int_o^b \left(1 - \frac{C_x}{C_{xe}}\right)\frac{C_x}{C_{xe}}dz \quad ; \quad \theta_{yx} = \int_o^b \frac{(C_{ye} - C_y)C_x}{C_{xe}^2}dz$$

$$\delta_x^* = \int_o^b \left(1 - \frac{C_x}{C_{xe}}\right)dz \qquad (4)$$

(1) 和 (2) 式沿图 1 的附面层外缘流线座标 son 可表示为:

$$d\theta_{ss}/dx - \mathrm{tg}\,\alpha_e[d\theta_{sn}/dx + (\theta_{ss} - \theta_{nn})d\alpha_e/dx] + G(2\theta_{ss} + \delta_s^*) - Q(2\theta_{sn} + \delta_n^*)$$
$$= \tau_o\cos\varepsilon_w/\rho C_{se}^2\cos\alpha_e + (D_y\mathrm{tg}\,\alpha_e + D_x)/C_{se}^2 \qquad (5)$$

$$d\theta_{ns}/dx - \mathrm{tg}\,\alpha_e(d\theta_{nn}/dx + 2\theta_{ns}d\alpha_e/dx) + G[2\theta_{ns} - \mathrm{tg}\,\alpha_e(\theta_{ss} + \theta_{nn} + \delta_s^*)] + Q(\theta_{ss} + \delta_s^* - \theta_{nn})$$
$$= \tau_o\sin\varepsilon_w/\rho C_{se}^2\cos\alpha_e + (D_y - D_x\mathrm{tg}\,\alpha_e)/C_{se}^2 \qquad (6)$$

$$G = dC_{se}/dx/C_{se} \quad ; \quad Q = [(dC_{se}/dx)\mathrm{tg}\,\alpha_e + C_{se}d\alpha_e/dx]/C_{se} \qquad (7)$$

式中

$$\theta_{ss} = \int_o^\delta\left(1 - \frac{C_s}{C_{se}}\right)\frac{C_s}{C_{se}}dz \quad ; \quad \theta_{sn} = \int_o^\delta\left(1 - \frac{C_s}{C_{se}}\right)\frac{C_n}{C_{se}}dz \quad ; \quad \theta_{ns} = -\int_o^\delta\frac{C_nC_s}{C_{se}^2}dz$$

$$\theta_{nn} = -\int_o^\delta\left(\frac{C_n}{C_{se}}\right)^2dz \quad ; \quad \delta_s^* = \int_o^\delta\left(1 - \frac{C_s}{C_{se}}\right)dz \quad ; \quad \delta_n^* = -\int_o^\delta\frac{C_n}{C_{se}}dz \qquad (8)$$

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为使方程组封闭采用的补充关系为:

$$d(\delta-\delta_s^*)/dx+\mathrm{tg}\alpha_e d\delta_n^*/dx=E/\cos\alpha_e-[(\delta-\delta_s^*)/C_{xe}]dC_{xe}/dx-Q\delta_n^* \qquad (9)$$

$$E=0.0306[(\delta-\delta_s^*)/\theta_{ss}-3]^{0.653}$$

$$C_s/C_T=\ln(C_Tz/\nu)/0.4+W[1-\cos(\pi z/\delta)]/0.4+5.5$$

$$C_n/C_s=\mathrm{tg}\varepsilon_w(1-z/\delta)^2\ ,\quad C_T=(\tau_{os}/\rho)^{0.5} \qquad (10)$$

令 (10) 式中 $z=\delta$, $C_s=C_{se}$ 可得关系式

$$C_{se}/C_T=\ln(C_T/C_{se})/0.4+\ln(C_{se}\delta/\nu)/0.4+5w+5.5 \qquad (11)$$

本文采用龙格—库塔法求解 (5)、(6)、(9)、(11) 式。

2. 叶片力亏损预测模型 求解上述方程组前, 须给出叶片力亏损预测模型。本文计算结果表明, 对于不同算例, 预测值与实验值差异明显且对于不同的算例相同的力亏损模型得出了相当不同的结果。为此作者从理论上导出了一种新且通用性强的力亏损模型。由 (4) 式和 (8) 式可得:

$$C_{xe}^2\theta_{xx}\mathrm{tg}\alpha_e-C_{xe}^2\theta_{yx}=-C_{se}^2\theta_{ns}+\mathrm{tg}\alpha_eC_{se}^2\theta_{nn} \qquad (12)$$

由文献 [1] 和 [2] 实验结果可知 D_x 和 D_y 远大于壁面摩擦阻力 τ_o, 故略去方程 (1) $\times\mathrm{tg}\alpha_e$ − (2) 式的所得式中的 τ_o 项可得:

$$D_y-D_x\mathrm{tg}\alpha_e=(\delta_x^*+\theta_{xx})C_{xe}^2\sec^2\alpha_e d\alpha_e/dx+d(-C_{se}^2\theta_{nn}\mathrm{tg}\alpha_e+C_{se}^2\theta_{ns})/dx \qquad (13)$$

将 (12) 式代入 (13) 式且引入文献 [3] 的厚度 θ_2 可得:

$$D_y-\mathrm{tg}\alpha_eD_x=(\delta_x^*+\theta_{xx})C_{se}^2d\alpha_e/dx+d(C_{se}^2\theta_2)/dx \qquad (14)$$

式中 $\theta_2=\theta_{ns}-\mathrm{tg}\alpha_e\theta_{nn}$

若出口为平行流, 则 $D_x=-D_y\mathrm{tg}\alpha_e$, $\theta_2=0$, 于是有:

$$D_y=(\delta_x^*+\theta_{xx})C_{se}^2d\alpha_e/dx \qquad (15)$$

上式所表示的力亏损模型与文献 [4] 的力亏损模型完全相同, 且文献 [3] 的力亏损模型也含于 (14) 式的右第二项之中, 这表明作者导出的叶片力亏损方程 (14) 式较目前现有的各种力亏损模型更具一般性, 基于 (14) 式和文献 [1], 作者提出:

$$D_y=k_1[C_{se}^2(\delta_x^*+\theta_{xx})d\alpha_e/dx+C_{se}^2\theta_2/s]\ ,\quad D_x=-k_2D_y\mathrm{tg}\alpha_e \qquad (16)$$

式中 k_1 和 k_2 为与叶栅及流动条件关联的常数, 计算表明 k_1 取值约为 1.0~1.5, k_2 为 −1.0 ~1.0。该力亏损模型的基本思想为: 由于通道二次横流的影响, 使流动偏离平行流态, 综合考虑附面层发展过程主流和横流流动变化的力亏损模型更趋符合实际。

3. Gregory-Smith 导流叶栅[5] 图 2、3 分别表示计算的机匣上 δ_x^* 和 θ_{xx} 的变化情况, 本

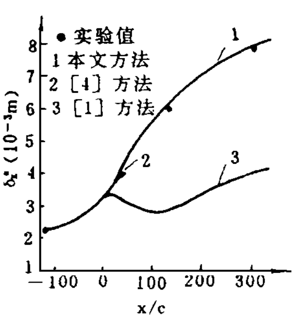

图 2 端壁附面层位移厚度 δ_x^*

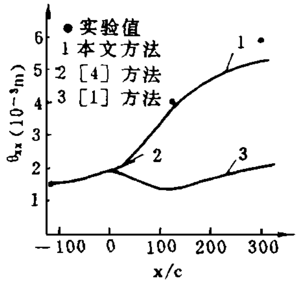

图 3 端壁附面层动量厚度 θ_{xx}^*

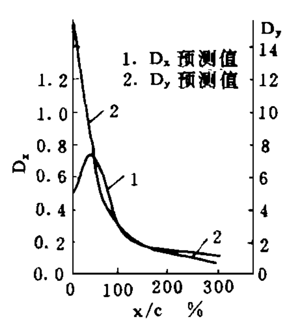

图 4 叶片力亏损弦向变化

文方法明显优于文献［4］的两种模型且与实验结果吻合较好。图 4 中 1、2 线分别表示叶片力亏损 D_x 和 D_y 的变化情况，除 D_x 在前缘略有增加外，D_x 和 D_y 沿弦向迅速减小，在尾缘后虽继续减小但要平缓得多。

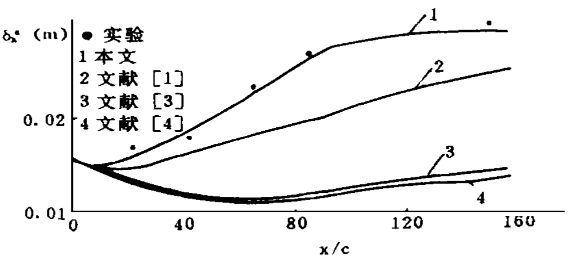

图 5　δ_x^* 沿弦向发展

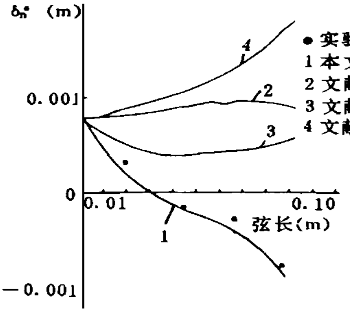

图 6　δ_n^* 沿弦向发展

4. 文献［1］和［6］的实验压气机叶栅　图 5、6 分别表示 δ_x^* 和 δ_n^* 沿弦向变化，本模型的预测值与实验值吻合较好，与现有力亏损模型计算结果比较，进一步表明了本文模型的优越性和通用性。图 7、8 表示 D_x 和 D_y 的弦向变化，本模型的 D_x 和 D_y 预测值和实验值一致性较好。实验和预测均显示 D_x 和 D_y 的绝对值从叶栅前缘始迅速减小，这一点与图 4 相类似。从图 7 看出本模型再次显示出优越性。图 8 仅表示诸模型的预测结果，它们均显示 D_x 和 D_y 沿叶弦变化剧烈，这与图 7 差异较大，这可能与该端壁附面层为进口高度偏转高负荷叶栅轮毂附面层特性有关。计算结果还表明 Gregory-Smith 叶栅 D_x 和 D_y 为正值且 D_x 接近零，这与文献［4］结论相一致。两种高负荷的压气机叶栅 D_x 为正值，D_y 为负值且 D_x 和 D_y 均比端壁摩擦阻力大得多，这与文献［1］实验结果相一致。

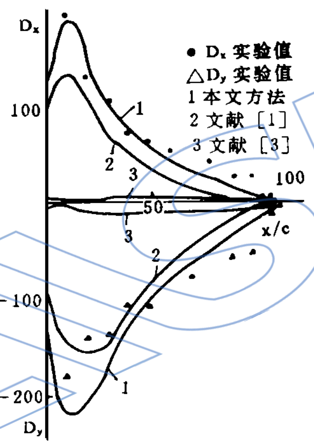

图 7　叶片力亏损沿弦向变化

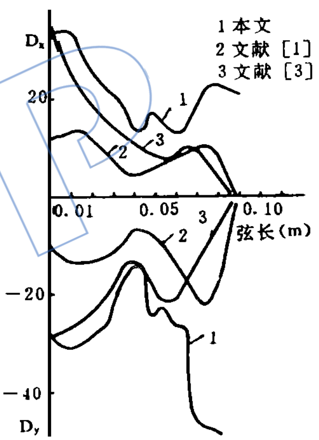

图 8　叶片力亏损预测值

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DIGITAL REAL-TIME SIMULATION OF A TWIN- SPOOL TURBOJET

Liu Shangming, Wang Xueyu, Zhu Xingjian
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ABSTRACT A digital real-time simulation by means of single micro-computer has been developed for an actual two-spool afferburning turbojet engine. In order to overcome the contradiction between the computation precision and the speed necessary to digital real-time simulation technique, the characteristics of engine components have been reasonably simplified and modified and 80286 macro-assembly, 80287 float arithmetic parallel processing method and some programing techniques have been adopted. A non-linear, large-deviation digital real-time simulation has been obtained. The results of this simulation are comparaed with the measured data. It is shown that its calculation accuracy and speed are suitable for the real-time simulation.

TECHNICAL NOTES

EXPERIMEATAL INVESTIGATION OF A SMALL TWO- STAGE TRANSONIC AXIAL COMPRESSOR

Li Liangming *(Nanhua Powerplant Institute)*

ABSTRACT A small-dimension two-stage transonic axial compressor has been designed with blade tip veloicty 436m/s and design revolution 45000r/min. Its tests has been carried out to investigate the performance of this compressor. It is shown that its performance attains or exceeds its design specifications. This paper also considers the effects of radial and axial clearances, probe blockage, step matching and measuring techniques on the performance of the compressor.

NUMERICAL STUDY OF END- WALL BOUNDARY LAYER AND BLADE FORCE DEFECT IN CASCADES

Wu Hu, Liu Songling, Chen Fuqun *(Northwestern Polytechnic University)*

ABSTRACT A detail research has been completed for calculation of end-wall boundary layers within an axial compressor cascade. A new calculation model for blade force defect is proposed, which is associated with development of primary flow and transverse flow. A unique feature of this method lies not only in capability to calculate the development of end-wall boundary layers inside the cascade passage without any assumption about the exit of cascade, but also in ability to take into account the influecnce of its tip clearance. The calculational results of three heavily loaded cascades show that this model is superior to other existing models.

IMPROVEMENT IN SOLUTION OF EIGENVALUES WITH TRANSFER MATRIX METHOD ON COMPUTER

Li Yan *(Nanhua Powerplant Research Institute)*

ABSTRACT A measure is taken based on secant method and tangent method to improve the computational method of eigenvalues with transfer matrix method on computer. In the new measure