

一类关联转子分离尺度与损失的工程模型

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【摘要】 将分离与损失相关联,提出了利用转子进出口参数来确定跨音风扇转子内部分离流动的方法。应用该方法对几个转子流场计算的结果表明,在转子的叶尖区域,由于强的激波与附面层相互作用,使得流动在激波后不久便发生分离。叶尖漏流涡可能对激波与附面层的相互作用诱导流动分离有较大影响。

关键词: 流动分离 损失 转子

分类号: O357.1

风扇/压气机内部分离流动的数值模拟,要求对分离的起始位置、分离的范围及分离的内部流动结构有比较清楚的认识。流动分离产生的损失与跨音风扇转子流动分离尺度的大小密切相关,大尺度流动分离对跨音风扇转子流动产生较大影响。有关分离的实验研究难以深入到转子内部,本文拟通过将分离与流动损失相关联,提出一种利用损失来确定分离大小的分离尺度工程模型。

1 转子叶片表面流动分离与损失的相关性、分离的起始位置与分离尺度

流动分离是转子流动的主要损失源,损失是由源项造成的结果。这里试图将二者进行关联,以进行定量计算。流动发生分离的跨音风扇/压气机叶栅流动结构是在叶栅通道不远,流动发生分离。随着流动向下游发展,分离区愈向叶栅通道中间发展,在尾缘处分离区的尺度为 Δ_{sep} 。跨音风扇/压气机叶栅下游测量平面上所测出的流动总压损失主要包括粘性引起的叶片附面层损失、气流穿越激波所引起的激波损失和激波与附面层相互作用引起的流动分离损失等 3 项损失之和

$$\omega_{ot} = \omega_{ro} + \omega_h + \omega_{ep} \quad (1)$$

根据 Kirchhoff 死水区模型,在分离区之内,流体相对于叶栅的速度为零,因而在分离区内静压为常数,分离区内的压力即为叶片尾缘处的静压值。设尾缘处的静压 P_{ex} 沿栅距方向为均匀分布,尾缘处的平均相对总压 P_{ex}^* 为

$$P_{ex}^* = [P_{ex,main}^*(t - \Delta_{sep}) + P_{ex} \Delta_{sep}] / t \quad (2)$$

式中 $P_{ex,main}^*$ 为在尾缘处主流区的相对总压由激波损失决定。在叶栅的进口近似用一道正激波来代替实际的通道激波系计算激波损失 ω_h 。在尾缘处主流区的相对总压 $P_{ex,main}^*$ 可由下式确定

$$P_{ex,main}^* = P_{in}^* - \omega_h(P_{in}^* - P_{in}) \quad (3)$$

P_{in}^* 、 P_{in} 分别表示叶栅进口处的相对总压和静压。将 (1) 式和 (2) 式代入相对总压损失 ω_{ot} , 考虑到叶栅前缘与尾缘的不同半径的影响, 经过整理可得分离尺度与损失的关系

$$\overline{\Delta}_{sep} = \frac{(\omega_a - \omega_{ro} - \omega_h)(P_{in}^* - P_{in})}{P_{exid}^* - (\omega_{ro} + \omega_h)(P_{in}^* - P_{in}) - P_{ex}}$$

(4)

这里的 P_{exid}^* 为流体从前缘等熵流到尾缘时的相对总压。叶片粘性附面层损失 ω_{ro} 通过与扩压 D 因子相关联的半理论半经验方法确定, 需要指出的是所选的 D 因子与 ω_{ro} 的经验曲线不应包括激波与附面层相互作用所引起的流动分离损失。分离区对主流的作用主要使得主流的流道变小。由连续方程可得

$$\Delta S_{sep(x)} = \Delta S - \frac{(P_{ex}/P_x)^{1/k} V_{ex} \cos \beta_{ex} [\Delta S - \Delta S_{sep(ex)}]}{\cos \beta_x V_{ex}^2 - [2kRT_{ex}/(k-1)][(P_x/P_{ex})^{(k-1)/k} - 1]}$$

(5)

β_x 、 β_{ex} 表示气流方向与 x 轴负方向的夹角。

分离点的起始位置 X_s 表示。 $x = X_s$ 时, $\Delta S_{sep(X_s)} = \delta^{* *}$, $\delta^{* *}$ 为未分离时的附面层动量损失厚度。由文献[2] 可得 X_s 处的气流角 $\beta_{X_s} = \beta_1 + [\theta(1 - X_s/b \cdot \cos \beta_{1k})] \Delta \beta^*$ 。式中 b 为弦长, β_{1k} 为前缘安装角, θ 为叶型弯角, $\Delta \beta^*$ 为无分离存在时的气流转角。即

$$X_s = [1 + \beta_1/(\theta \Delta \beta^*)] b \cos \beta_{1k} - [b \cos \beta_{1k}/(\theta \cdot \Delta \beta^*)] \beta_{(X_s)}$$

(6)

由 (5)、(6) 式便可确定分离的起始位置 X_s 。分离点的位置确定以后, 假设从分离点到出口的压力分布为线性分布, 即

$$P_x/P_{ex} = 1 + [P_{(X_s)}/P_{ex} - 1](x/X_s)$$

(7)

进一步假设气流角 β_x 从分离点到出口线性分布

$$\beta_x = \beta_x + [\beta_{(X_s)} - \beta_{ex}](x/X_s)$$

(8)

则从分离起始点到叶栅出口之间的任一位置 x 的分离尺度 $\Delta S_{sep(x)}$ 可由 (5)、(7)、(8) 式共同确定。可见, 分离的尺度由几何参数及叶栅进口气动参数完全确定。

2 算例分析

应用本文提出的分离尺度与损失的关系对文献[3, 4] 的 HTFC 跨音转子在尾缘处的分离尺度大小进行了计算, 其结果如表 1 所示。

表 1 分离尺度与损失的相关性

流线数	10	11	12	13	14	15	16	17	18	19	20	21
Ma_{win}	1.021	1.083	1.147	1.211	1.276	1.340	1.402	1.460	1.514	1.564	1.609	1.653
$P_{in} \times 10^4 \text{ Pa}$	10.97	10.69	10.41	10.14	9.869	9.620	9.407	9.250	9.167	9.160	9.216	9.321
$P_{in}^* \times 10^4 \text{ Pa}$	21.28	22.37	23.59	24.95	26.47	28.15	30.02	32.09	34.38	36.92	39.73	42.86
TW_{in}^*/K	576.6	584.8	593.7	603.3	613.5	624.4	635.9	648.1	660.9	676.5	688.7	703.6
$P_{ex} \times 10^4 \text{ Pa}$	19.40	19.78	20.13	20.47	20.78	21.11	21.44	21.77	22.07	22.32	22.54	22.79
ω_{ot}	0.039	0.033	0.030	0.048	0.067	0.094	0.093	0.100	0.123	0.164	0.213	0.239
$\overline{\Delta}_{sep}(\%)$	0.00	0.00	0.00	0.00	0.25	2.84	0.00	0.00	0.00	0.75	8.43	9.85

由表可见, 在第 14 根流线和第 15 根流线存在有较小尺度的分离。分离主要发生在尖部区域, 和文献[4] 的实验结果相一致。由于较强的激波与附面层的相互作用, 尖部区域的第 21 根

流线(对应于 100% 的相对叶高)在尾缘处的分离尺度达到叶栅通道宽度的 9.85%。第 16 根流线至第 18 根流线的来流马赫数比第 14 根流线和第 15 根流线的高, 激波与附面层的相互作用似应更强, 但却未发生流动分离。产生这种现象的原因可能是由于叶尖漏流涡与激波的相互作用所导致的复杂三维流动效应, 应进一步深入研究叶尖漏流涡对激波的强度、结构及激波与附面层相互作用的影响。

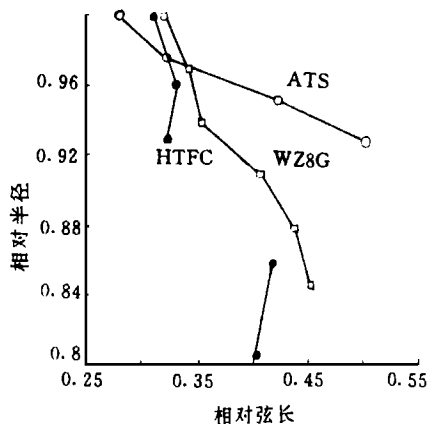


图 1 起始分离点沿展向的分布

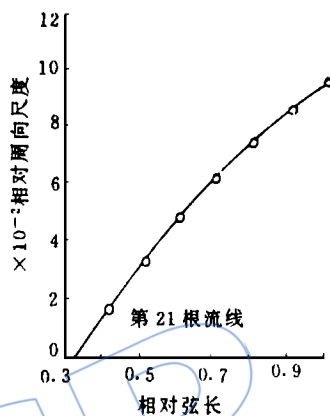


图 2 分离尺度沿通道的变化

图 1 为 HTFC、ATS-1 和 WZ8G 等跨音转子在叶背表面的起始分离点沿展向的分布。由图可见, 在叶尖区域, 流动在激波后不久便发生分离, 起始分离点位置比较靠前。图 2 为 HTFC 转子第 21 根流线的分离尺度沿流向的变化, 流动发生分离以后, 在流向下流的过程中, 分离区不断扩大, 在尾缘处的分离尺度达到叶栅通道宽度的 9.85%。

3 小 结

(1) 通过将分离与流动损失相关联, 提出了利用损失等进出口参数来确定跨音转子内流动分离起始位置和分离尺度的方法。(2) 应用本文提出的分离尺度模型对 HTFC、ATS-1 和 WZ8G 等跨音转子的流场进行了分析, 计算结果表明分离主要发生在尖部区域。流动在激波后不久便发生分离, 起始分离点位置比较靠前。流动发生分离以后, 在流向下流的过程中, 分离区不断扩大。(3) 叶尖漏流涡可能对激波的强度、结构及激波与附面层的相互作用诱导流动分离有较大影响。

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quations are applied to prediction. The experimental and predicted data of the outlet angle due to the secondary flow are presented for three cascades with end – bend blades and one with the corresponding unbended blades. The investigation shows that the change in outlet angle can be accurately predicted by the presented method. Reducing curvature of the blade rear part makes the averaged intensity of the streamline component of the outlet secondary vorticity decrease, but does not change the distance from the center of the vorticity to the end wall.

Key Words Blades Secondary flow Flow fields

*) A MODEL TO CORRELATE FLOW SEPARATION WITH FLOW LOSS IN A TRANSONIC ROTOR

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ABSTRACT

A model correlating flow separation with flow loss is proposed for predicting the incipient location and size of the flow separation in a transonic rotor. The flow fields of several rotors have been investigated with the model. The results show that the flow separation mainly occurs in the tip area owing to strong shock boundary interaction, and the incipient separation point is behind the shock location. The tip leakage flow vortex has a strong effect on the interaction between shock wave and boundary layer.

Key Words Flow separation Losses Rotors

A PRELIMINARY INVESTIGATION ON CONTROLLING JET STRUCTURE BY HYDRODYNAMIC EXCITATION

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ABSTRACT

Jets were excited by Karman Vortex Streets under three conditions of Jet Mach Number 0.206, 0.361 and 0.831. Three vortex generators with different geometries were tested. Jet Velocity distributions with and without excitation were measured by stagnation pressure probe. The turbulent characteristics in the jet boundary layer were detected by a single hot wire probe. It is shown that excited jet velocity decay faster than that of unexcited jet, and turbulent energy in jet boundary layer is significantly increased by vortex excitation. Therefore, jet structure can be effectively controlled by hydrodynamic excitations.

Key Words Excitation Jets Boundary layer Karman vortex Control

A STUDY ON SUPERSONIC 6- NOZZLE EJECTOR PERFORMANCE

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ABSTRACT

The supersonic 6- nozzle ejector performance has been investigated experimentally for the given geometric dimensions. The experiment ranges over $1.98 \leq P_p^* / P_s^* \leq 7.46$, $0.971 \leq T_p^* \leq T_s^* \leq 1.02$ and $L_m / D_m = 0.80$. The entrainment ratio α varies from 6.96 to 11.66 for the ejector with a diffuser, and its corrected value $\alpha \frac{T_s^*}{T_p^*}$ varies from 6.88 to 11.62; on the other hand, the entrainment ratio varies from 2.82 to 6.28 for the ejector without the diffuser, and its corrected value varies from 2.78 to 6.24. The experimental results show that the entrainment ratio and its corrected value decrease with the increase

Key Words Dynamic pressure Sensors Calibration

EFFECTS OF REINFORCED TURBULENCE ON SPRAY DISTRIBUTION AND TEMPERATURE PROFILE BEHIND AIRBLAST ATOMIZER

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ABSTRACT

The effects of turbulence intensity on liquid spray distribution and temperature profile behind airblast atomizer have been investigated. Three test model airblast atomizers with different turbulence intensity were experimented: the base line model, the one with lots of small air injection in outer swirler channel and the another with turbulence treatment on the outer swirler wall. The measurements were done by PDA (Particle Dynamic Analyser) to map out the spray and flow characteristic on cold condition, and thermocouple was used to acquire the temperature profile during combustion test. The cold tests show that the secondary atomization, spray and air mixing process can be promoted by the model with reinforced turbulence structure, and more uniform spray distribution can be achieved in the nearer downstream section. The combustion tests show that more even temperature profile and higher combustion efficiency can be obtained. It is because that turbulence fluctuation can effectively promote liquid atomization and spray transportation, and also enhance the burning rate of mixture evidently.

Key Words Air- blast atomizers Temperature distributions Spray combustion

APOLOGY: * This paper was replaced by another paper of same authors in final redaction of JAP Vol. 11 NO. 2 1996, but the substitution of abstracts wasn't carried out. The supplement of the paper is as follows.

PREDICTION OF INCIPIENT SEPARATION INDUCED BY 3- D SHOCK/BOUNDARY LAYER INTERACTION

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ABSTRACT

The flow separation induced by three- dimensional shock/boundary layer interaction has an important effect on performance of a transonic rotor. A method is proposed to predict the incipient separation generated by 3- D shock/boundary layer interaction. The numerical results indicate that the secondary flow generated by the shock/boundary layer interaction is a key factor for the incipient separation. When inlet relative Mach number exceeds 1.5, the strong shock wave/boundary layer interaction may induce the flow separation in tip area of transonic fan.

Key Words Three- dimensional flow Separated flow
Shock wave- boundary layer interference