

轴流压气机设计点流动损失的预估和分析

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【摘要】 在大量统计数据分析的基础上,采用当量扩散因子 D_{eq} 求得叶片尾缘的动量厚度与弦长比 θ/c 和形状因子 H_{te} ,经修正获得叶型损失值。再应用改进了的端壁损失和激波损失模型,最终算出轴流压气机设计点损失沿叶高的分布规律。验算表明,采用本方法所预估的损失与实测结果十分接近,而且对各种原始叶型均能应用。根据本方法所编制的计算机程序简单实用,可以满足先进轴流压气机气动设计和分析的需要,也可以作为子程序插入 S_2 流面的计算程序中去。

关键词: 轴流压气机 设计点 损失沿叶高分布

1 概述

轴流压气机中的流动损失通常分为4类:叶型损失、端壁损失、激波损失和减振凸肩损失。本文只讨论前3项损失预估。

目前通常用的“叶型损失参数”表达式为:

$$\frac{\bar{\omega} \cos \beta_2}{2\sigma} = \left[\frac{\cos \beta_1}{\cos \beta_2} \right]^2 \left[\frac{\theta}{c} \right] \left\{ \frac{-2H}{3H-1} \left/ \left(1 - \left[\frac{\theta}{c} \right] \frac{\partial H}{\cos \beta_2} \right)^3 \right\} \quad (1)$$

式中, ω 为叶型损失系数; θ 和 H 为叶片尾迹的动量厚度和形状因子; σ 和 c 为叶栅稠度和弦长; β_1 和 β_2 分别为叶栅进、出口气流与轴向的夹角。大量试验表明, 决定叶型损失参数的 θ/c 和 H 值与叶栅的速度扩散程度、进口 Ma 数、雷诺数 Re 以及紊流度有关。如果应用到实际压气机的气动设计和分析中去, 还要考虑三元流动和端壁效应的影响, 因此需要进行大量的经验修正, 才能得到比较符合实际流场的损失沿径分布规律。常见的经验预估方法有以下两种。其一, 是以扩散因子 D 来预估叶型损失参数, 对不同的径向位置提供不同的经验曲线(或公式), 以此来考虑端壁损失。这就是在文献中常见的 $(\bar{\omega} \cos \beta_2 / 2\sigma) = f(D)$ 曲线^[1~4]。应用这些曲线所提供的经验数据, 可以预估出沿整个叶高流动损失的变化。但是, 由于叶型损失参数不仅仅是 D 因子的函数, 不同文献中所提供的经验曲线, 都有很大的局限性, 即便是设计参数很相近的压气机, 在相同的径向位置上, 可提供的经验曲线之间的差别仍是相当大的, 在应用时还需要加以修正^[1~4]。其二, 是以当量扩散因子 D_{eq} 来预估 θ/c 和 H 值, 再由(1)式来求得叶型损失参数值。这种方法定义了当量扩散因子及其经验计算方法。提供了一套对 Ma 数、 Re 、流道收敛比 h_1/h_2 对 θ/c 和 H 值的修正曲线。还考虑到稠度、安装角 γ (叶弦与轴向的夹角)、叶片弯角和相对厚度 (t_{max}/c) 的影响, 基本上可以满足近代压气机和风扇的设计需要。但是这种方法在计算 D_{eq} 值时需要反复迭代而未提供相应的程序, 多达 20 多种修正曲线需要查阅, 实用甚感不便; 而且关键在于只能用修正级平均效率的办法来考虑端壁损失, 因此不能精确预估近端壁处各

径向位置上损失参数,给压气机三元流场的计算和分析带来一定的困难^[5]。

综上所述,本文试图吸收国内外预估流动损失方法的长处,结合自己的经验,提供一种比较实用而精确的预估方法和程序,以满足我国轴流压气机和风扇研制的需要。

2 程序的主要依据

2.1 叶型损失

采用 C. C. Koch 所提供的当量扩散因子 D_{eq} 及 $\theta/c \sim D_{eq}$ 和 $H \sim D_{eq}$ 曲线,分别求出 θ/c 和 H 值,然后修正进口 Ma 数、 Re 数和实际流道收敛比 h_1/h_2 对 θ/c 和 H 的影响。计算中还考虑了叶片厚度对叶栅通道堵塞的影响。所得到的叶型损失系数 $\bar{\omega}$ 是比较符合压气机中实际流动特点的。我们经过大量验算和比较后还发现,对亚音和超、跨音压气机,最终用来计算叶型损失系数 $\bar{\omega}$ 的 θ/c 值,需要加上不同的修正量,而对尾迹形状因子 H 值则无须修正^[5]。

2.2 端壁损失

采用扩散因子 D 对叶型损失参数 $\bar{\omega} \cos \beta_2 / 2\sigma$ 进行加权处理,从而得到近端壁处的叶型损失系数 $\bar{\omega}$ 既避免了因用 D_{eq} 求 θ/c 时需要迭代的麻烦,又克服了只能用级平均效率来修正端壁效应,而难以求得近端壁处实际损失的缺点,比较方便而实用。至于加权修正量的大小,则以 C. C. Koch 修正后的级平均效率为依据,因为这种修正已被大量压气机的实测数据所验证,除个别外,其误差均落在 ± 0.01 之内,这样的精度足以满足工程要求了。

2.3 激波损失

经过分析比较,用以下方法来考虑激波损失增量,非常适合于跨音和低超音压气机。

$$\Delta \bar{\omega} = A \cdot |Ma_{1cr} - Ma_{1cr}| \quad (2)$$

式中, Ma_{1cr} 为临界马赫数, $\Delta \bar{\omega}$ 为激波引起的附加叶型损失系数, A 为经验常数,此处取值为 0.03456。 Ma_{1cr} 值由下式计算

$$Ma_{1cr} = \left\{ \frac{\{ (V_{max}/V_1)^2 / [c_1 + c_2 (V_{max}/V_1)]^2 - c_2 \}^{(k-1)/k} - 2}{k-1} \right\}^{1/2} \quad (3)$$

式中 $c_1 = (k+1)^{k/(1-k)}$, $c_2 = 2^{k/(1-k)}$, $V_{max}/V_1 = A_1 + A_2 (\cos \beta_2 / \sigma) [\lg \beta_1 - (r_2 V_{m2} / r_1 V_{m1}) \lg \beta_2]$, k 为绝热指数, $A_1 = 1.03 + 0.7 (t_{max}/c)$, $A_2 = 0.4 + t_{max}/c$, V_{max} 是叶型吸力面最大速度, V_1 是叶栅上游气流速度, r_1 、 r_2 是叶片进、出口子午流线半径, V_{m1} 、 V_{m2} 是叶片进、出口子午流线速度。

3 主要公式

$$D_{eq} = V_{max}/V_{ate} = (V_p/V_1) \cdot (V_{max}/V_p) \cdot (V_1/V_{ate}) \quad (4)$$

式中, V_p 为叶栅喉部平均流速,该处吸力面速度最大, V_{ate} 为叶栅尾缘自由流速度。

θ/c 和 H 与 D_{eq} 的经验关系式

当 $1.0 < D_{eq} \leq 1.7$ 时

$$\theta/c = 0.002907877 - 0.002353732 D_{eq} + 0.0035701 D_{eq}^2 \quad (5)$$

$$H = 2.005202 - 1.488448 D_{eq} + 0.7643701 D_{eq}^2 \quad (6)$$

当 $1.7 < D_{eq} < 2.25$ 时

$$\theta/c = 0.080782341 - 0.09126548 D_{eq} + 0.02899849 D_{eq}^2 \quad (7)$$

当 $1.7 < D_{eq} \leq 2.0$ 时

$$H = 18.61375 - 21.23994D_{eq} + 6.6433071D_{eq}^2 \quad (8)$$

$$\text{当 } 2.0 < D_{eq} < 2.4 \text{ 时} \quad H = 2.71 \quad (9)$$

根据以下经验式修正流道收敛比 h_1/h_2 对 θ/c 和 H 的影响

$$(\theta/\theta_{h_1/h_2=1}) = 0.4375 + 0.5625(h_1/h_2) \quad (10)$$

$$\text{当 } D_{eq} = 1.7 \text{ 时} \quad (H/H_{h_1/h_2=1}) = 0.841 + 0.159(h_1/h_2) \quad (11)$$

$$\text{当 } D_{eq} = 1.5 \text{ 时} \quad (H/H_{h_1/h_2=1}) = 0.955 + 0.045(h_1/h_2) \quad (12)$$

$$\text{当 } D_{eq} = 1.3 \text{ 时} \quad (H/H_{h_1/h_2=1}) = 1.0075 + 0.0075(h_1/h_2) \quad (13)$$

$$\text{当 } D_{eq} = 1.0 \text{ 时} \quad (H/H_{h_1/h_2=1}) = 1.02875 + 0.02875(h_1/h_2) \quad (14)$$

当 D_{eq} 为其他值时, 利用上述曲线采用内外插法求得。

根据以下公式修正进口 M_{a1} 数对 θ 和 H 的影响

$$\text{当 } D_{eq} = 1.0 \text{ 时} \quad (H/H_{M_{a1}=0}) = 0.9928489 + 0.09481503M_{a1} + 0.3016782M_{a1}^2 \quad (15)$$

$$(\theta/\theta_{M_{a1}=0}) = 1.0 - 0.01131096M_{a1} - 0.047617M_{a1}^2 \quad (16)$$

$$\text{当 } D_{eq} = 1.3 \text{ 时} \quad (H/H_{M_{a1}=0}) = 0.9949702 + 0.08274769M_{a1} + 0.1764078M_{a1}^2 \quad (17)$$

$$(\theta/\theta_{M_{a1}=0}) = 0.997758 - 0.004557785M_{a1} - 0.09767203M_{a1}^2 \quad (18)$$

$$\text{当 } D_{eq} = 1.5 \text{ 时} \quad (H/H_{M_{a1}=0}) = 0.9986671 + 0.04035605M_{a1} + 0.1398818M_{a1}^2 \quad (19)$$

$$(\theta/\theta_{M_{a1}=0}) = 0.998849 - 0.002518556M_{a1} - 0.1149881M_{a1}^2 \quad (20)$$

$$\text{当 } D_{eq} = 1.7 \text{ 时} \quad (H/H_{M_{a1}=0}) = 0.99702 + 0.0364067M_{a1} + 0.08861016M_{a1}^2 \quad (21)$$

$$(\theta/\theta_{M_{a1}=0}) = 0.9973339 - 0.04666825M_{a1} - 0.1249989M_{a1}^2 \quad (22)$$

当 $Re \neq 10^6$ 时, 根据以下公式修正 Re 数对 θ 和 H 的影响

$$\log \left(\frac{\theta}{\theta_{Re=10^6}} \right) = \begin{cases} 1 - 0.166 \log Re & Re \geq 2 \times 10^5 \\ 2.7705 - 0.5 \log Re & Re < 2 \times 10^5 \end{cases}$$

$$\log (H/H_{Re=10^6}) = 0.36 - 0.06 \log Re$$

注意: 叶片表面应有足够的光洁度。根据(1)式可以计算出叶型损失系数 $\bar{\omega}$

端壁损失修正量的经验公式。对压气机转子, 采用扩散因子定义

$$D_R = 1 - (w_2/w_1) + (r_2V_{u2} - r_1V_{u1})/[\sigma(r_1 + r_2)w_1] \quad (23)$$

式中, w_1 、 w_2 分别为动叶进、出口相对气流速度, V_{u1} 、 V_{u2} 分别为进、出口绝对速度的切向分速, σ 为动叶稠度。

当叶高百分比 $\lambda > 70\%$ 时, 修正量为

$$\Delta(\bar{\omega}_r \cos \beta_2 / 2\sigma_r) = 0.4212D_R^{2.326} [\lambda - 0.7] \quad (24)$$

当叶高百分比 $\lambda > 10\%$ 时, 修正量为

$$\Delta(\bar{\omega}_r \cos \beta_2 / 2\sigma_r) = 0.1263D_R^{2.326} [0.3 - \lambda], \quad \lambda = (r_2 - r_{2h})/(r_{2t} - r_{2h}) \quad (25)$$

式中 r_{2t} 、 r_{2h} 分别为动叶出口叶尖和叶根半径, $\bar{\omega}_r$ 动叶叶型损失系数。

对压气机静子, 修正方法如下:

当叶高百分比 $\lambda > 80\%$ 时

$$\Delta(\bar{\omega}_r \cos \alpha_3 / 2\alpha_3) = 0.9225(\lambda - 0.8)^{2.09} \quad (26)$$

当叶高百分比 $\lambda < 20\%$ 时

$$\Delta(\bar{\omega}_r \cos \alpha_0 / 2\alpha_s) = 0.9225(0.2 - \lambda_s)^{2.09}, \quad \lambda_s = (r_3 - r_{3t}) / (r_{3h} - r_{3t}) \quad (27)$$

式中, r_{3s} 、 r_{3h} 分别为静叶出口叶尖与叶根半径, $\bar{\omega}_s$ 为静叶叶型损失系数, α_s 为静叶稠度。

激波损失的预估公式参阅本文公式(2)~(8)。

4 预估结果的比较和讨论

应用本程序分别验算了 20 多台轴流压气机转子和静子流动损失沿径分布, 这些压气机中有亚音、跨音和超音的, 结果都令人满意。从图 1 至图 5 不难看出, 本文预估结果与原设计数

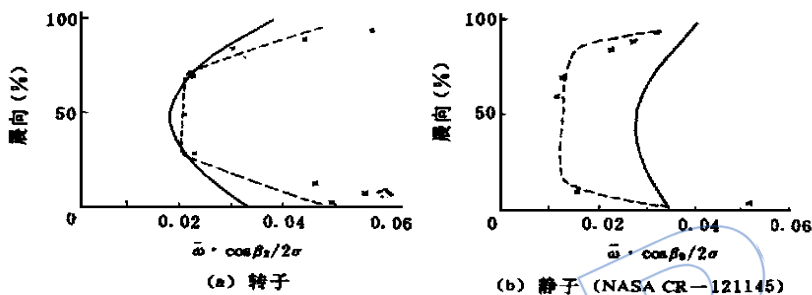


图 1 带串联叶片的单级压气机验算

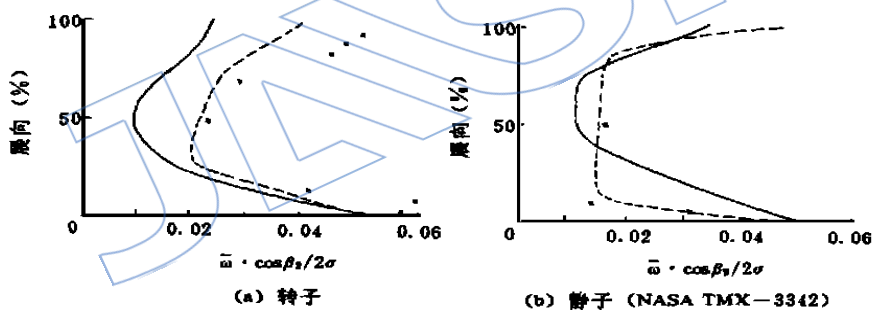


图 2 压比 1.2 的风扇级验算

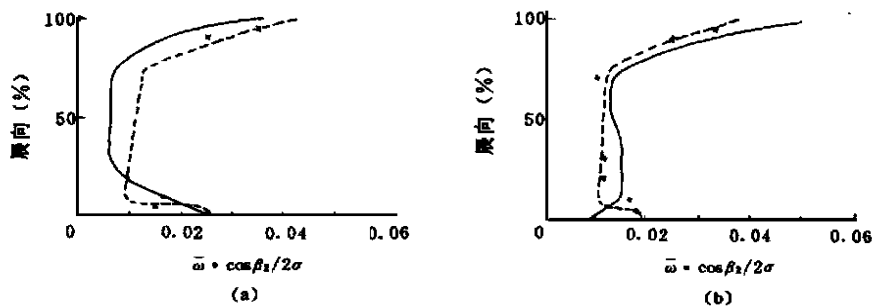


图 3 (a) 跨音单级压气机转子 (NASA TMX-2645) (b) 低稠度跨音压气机转子 (NASA TM-2536)

据(预估的)和实测结果三者相比, 本文预估的数据与实测结果十分吻合, 即使在端壁附近, 与

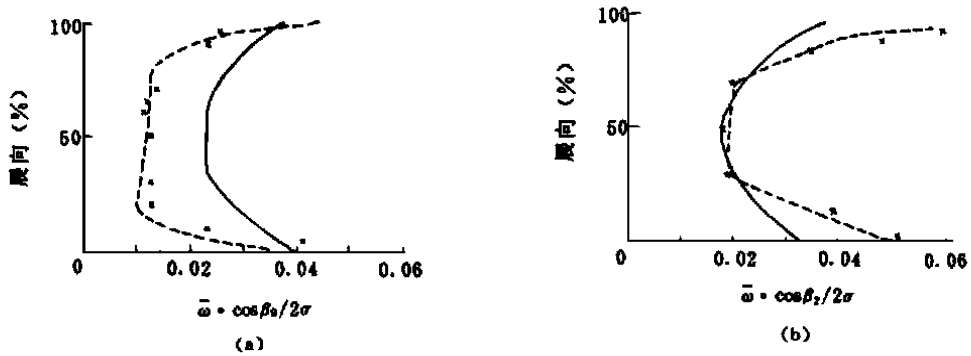


图 4 两级风扇的第一级(a)静子(NASA TP-1314) (b)转子(NASA CR-120859)

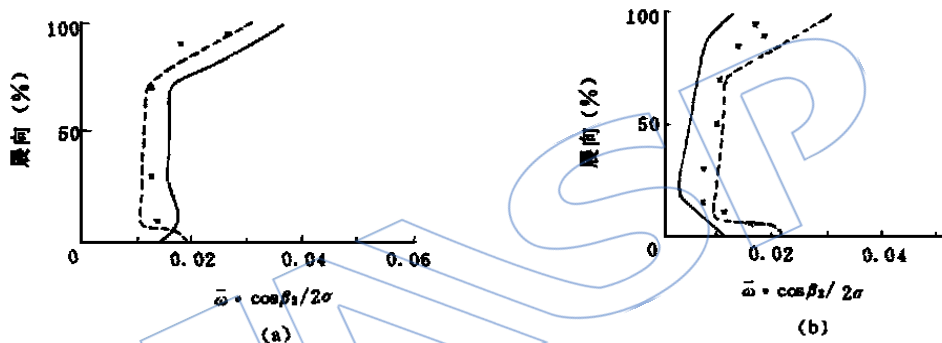


图 5 (a)NASA TMX-2379 转子(b)NASA TP-1338 转子

实测结果的差别也比原设计数据改善较多(--本文预估结果, 一原设计数据, ×实测结果)。本文提供的方法在精度上有很大的改善, 且适应性也好。程序简单实用, 总共只有 200 多条语句, 迭代很快收敛, 可以作为任何一种压气机或风扇的流场计算程序的子程序参加迭代运算。

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INVESTIGATION OF STATIC PRESSURE FIELD IN AN S- SHAPED AIR INTAKE

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ABSTRACT The static pressure fields in an s-shaped diffuser with rectangular cross-section have been measured at different incidences. The results show that the static pressure field at the duct exit is non-uniform. The higher the angle of attack is, the larger the distortion of the static pressure field. The pressure near the boundaries of the model is higher than that near the core, which is mainly caused by both the distorted total pressure field and the distorted flow velocity field. Further investigation on whirling flow field demonstrates that it is necessary to take into serious consideration the deviation between the experimental measurements and the weighted averages by the use of the wall static pressures of the model at high incidence.

RESEARCH OF ONSET OF ROTATING STALL FOR MULTIPLE BLADE ROWS

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ABSTRACT An inception criterion of rotating stall in multistage axial flow compressors is derived for the unsteady, two-dimensional and incompressible flow model according to the small disturbance stability theory. By means of a three-vector equation system, the correlative equations of the undetermined parameters are thus deduced when the small disturbance theory is applied to multiple blade rows. The prediction of the rotating stall onset boundary in the multistage axial flow compressors has been accomplished with the computer program designed by the authors. A theoretical prediction approach is proposed with the aid of the prediction method of stable cascade characteristics. A good agreement between the analytical and experimental results indicates that the theoretical analysis is believable. As compared with the calculation results, the influences of the undetermined parameters, such as stall cells and axial distance between two stages, on the prediction values are discussed.

ESTIMATION OF FLOW LOSS AT DESIGN POINT IN AN AXIAL-FLOW COMPRESSOR

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ABSTRACT On the basis of statistical data and analysis of axial-flow compressors, the ratio of trailing-edge momentum thickness to chord length θ/c and trailing-edge form factor H are determined by the use of equivalent diffusion factor D_{eq} , and then the profile loss of the blade is obtained after appropriate corrections. Finally, the total loss distribution along the blade span of the axial-flow compressor is estimated according to an improved end-wall loss model and a shock loss model. An extensive comparison of the estimated loss data with the original design and test data shows that the loss model presented here is feasible for normal blade profile, double-circular-arc blade profile and multi-circular-arc blade profile of axial-flow compressor, and the accuracy of the estimation is improved greatly. As a part of S_2 flow surface program, a computer subprogram has been worked out.

based on this approach. It gives satisfactory results of the flow field computation and is also very simple and practical. The subprogram can meet all requirements of aerodynamic design and analysis for an advanced axial-flow compressor.

EXPERIMENTAL STUDY ON UNSTABLE BEHAVIOR OF AXIAL COMPRESSION SYSTEM

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Li Zhiwei (Northwestern Polytechnical University)

ABSTRACT Unstable behavior of an axial-flow single-stage compressor has been researched successfully by use of a simple dynamic measuring system. The character and the influence factors of the unstable behavior have been analyzed from systematic view. The experimental results demonstrate that the unstable types of the compressor could convert each other in certain conditions. The compressor rotor speed, the construction and size of the exhaust parts are the main factors influencing the conversion. The surge occurs in the compressor on condition of high rotor speed or large exhaust volume, otherwise the rotating stall appears. The decrease of the exhaust volume leads to increment of the surge frequency. There is an obvious difference of the unstable behavior between the single-stage compressor and the isolated rotor compared. In the condition of high rotor speed ($n > 0.85$), a stall phenomena of nonrecoverable stall appears. Its character is also considered.

EXPERIMENTAL INVESTIGATION ON WHIRL FLUTTER OF PROPELLER ROTOR SYSTEM

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ABSTRACT A whirl flutter of a propeller rotor system has been investigated experimentally in the wind tunnel. The design of whirl flutter experimental equipment and a dynamic stiffness coefficient measurement method for the supporting system are also studied. The experiments show that if the support stiffness of the propeller rotor system is reduced as a result of failure of some elements in the engine frame or mount, the threshold flight velocity of onset whirl flutter will be decreased. The results of its wind tunnel experiments exhibit the same trends as in its theoretical calculation.

STUDY OF A SUBSONIC COMBINED-LEANING TURBINE GUIDE VANE WITH TIP ENDWALL CONTOURING

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ABSTRACT A three-dimensional, multigrid potential flow computation method is developed to analyse subsonic flow in steam turbine nozzle guide vane. In order to reduce the large secondary losses in the first annular nozzle guide vane with very small aspect ratio of 0.26 in a 300MW steam turbine, both tip endwall contouring and combined-lean blades are used in the new design. Experimental investigation shows that the mass-weighted loss coefficient of the new nozzle guide vane is 42 percent less than traditional radial one. The agreement between the measured and calculated results of the pressure distribution on the