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近似等反力度涡轮级设计的研究

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等反力度涡轮的概念，五十年代已在苏联提出[1]，六十年代美国提出可控涡设计涡轮[2]时，实际也作了这方面的实践[3]。综合运用导叶前倾 8.5°，以及导叶反扭、即尖部出气角比内部多偏离轴向 6°，达到根尖反力度只差 0.1 的级，效率比常规级高 2%。

一、等及近似等反力度涡轮级设计

按照众所孰知的轴对称径向平衡方程

$$\partial p/\rho\partial r = c_u^2/r + c_m^2\cos\varphi/R_m - c_m(\partial c_m/\partial m)\sin\varphi + F_r$$

式中 p—静压，ρ—密度，c_u—周向分速，c_m—子午分速，r—半径，R_m—曲率半径，φ—流线斜角，F_r—径向力。曾试算过依靠外廓型线先向内收后向外扩，主要以第二离心力 c_m^2/R_m 负值抵消第一离心力 c_u^2/r，以及导叶出气角 α_1 反扭以缓和沿叶高压力差及反力度差，并由反力度不匀度迭代改变沿叶高 c_u 分布的方法，收敛到根尖反力度只差 0.01 以下的等反力度级。但是这个气动布局的叶根出气角 α_2 偏离轴向达约 50°，不利于后续级或尾喷管转接；而且动叶外扩 25°在转子热状态伸长时径向间隙加大而加重漏气损失[4]。

鉴于从构造角度热态间隙要求动叶外廓尽量减小外扩，正式计算改取动叶平顶外廓，主要依靠引入导叶前倾的负值叶片力 F_r 来抵消离心力 C_u^2/r，协同导叶出气角 α_1 反扭，以达到根尖反力度差在 0.1 以内的近似等反力度级的设计。

经过对试算时动量方程仔细订正后的速度径向分布主方程，及所用张力样条流线曲率法（张力系数 10 至 20）[5]，是本文主要依据。

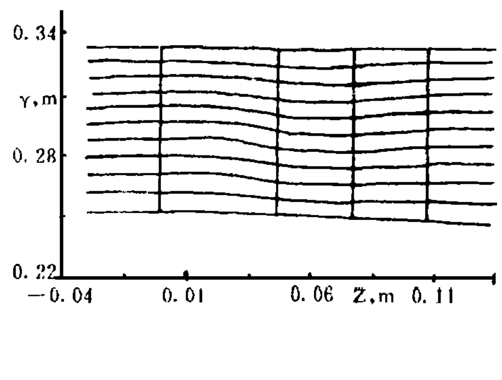

图 1　近似等反力度级通道及通流流线

图 1 示按设定燃气流量 63.2kg/s、初压 p_1^* 为 8.07×10^5Pa、初温 T_1^* 为 1188K、沿叶高等功为 180，693J/kg，算出的近似等反力度级的通道及流线示意图。外廓基本为平顶，只从导叶进口站逐步到间隙中间站最大内凹 1.3mm，然后折回到动叶进口站平顶。根尖反力度只差 0.091，主要靠导叶前缘前倾 15°及其出气角 α_1 反扭 11.6°保证。

损失模型主要取自改进的 $AMDC$ 法[6]，轴向漏气损失取自文献［7］：

$$\Delta L_{漏} = 27.26(\delta^{1.4}/h)(i_1 - i_{2s})$$

冲波损失则根据叶栅数据[8]粗估:

$$\xi_{栅} = 0.0457 + 0.032(Ma_2 - 0.7)$$

$$Y_{冲波} = \{[\pi(\lambda_2)/\pi(\lambda_2/(1-\xi_{栅}) - 1]/[1-\pi(\lambda_2)] - (Y_{栅})_{Ma_2=0.7}\} Y_{AMDC}/(Y_{栅})_{Ma_2=0.7}$$

式中 Ma_2、λ_2 分别均指叶片出口气流马赫数及速度系数，对导叶及动叶通用。

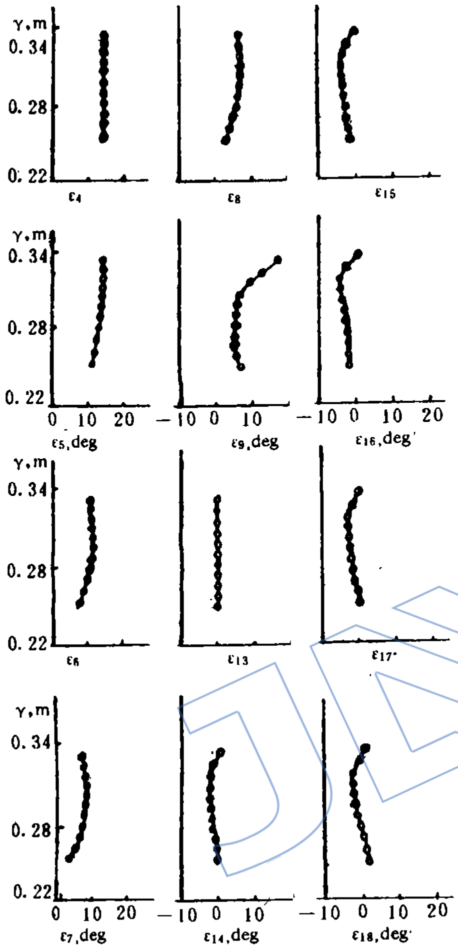

图 2　导叶倾角 ϵ_{4-9} 动叶倾角 ϵ_{13-18}

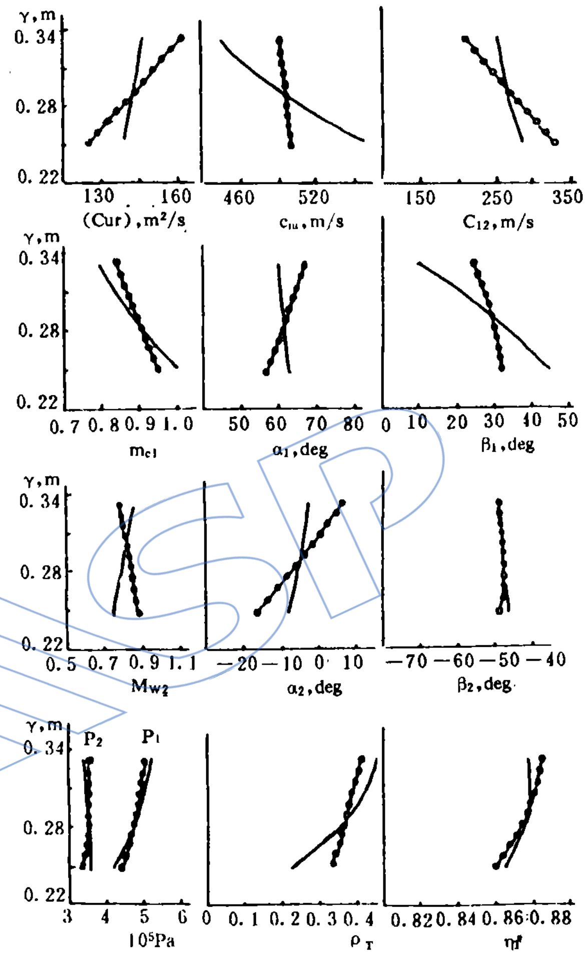

图 3　沿叶高主要参数变化（-0-近似等反力度级，—常规级)

表　1

流线	Y型（其中 Y冲波）		Y尾	Y二次	Y漏	Y= ∑Y 型、尾二次，漏
导叶外环　11	0.0247 (0.0173)	0.0065 (0.0036)	0.0031 (0.0030)	0.0536 (0.0539)	0 (0)	0.0814 (0.0742)
9	0.0224 (0.0185)	0.0070 (0.0047)	0.0035 (0.0034)	0.0537 (0.0539)	0 (0)	0.0796 (0.0757)
6	0.0214 (0.0211)	0.0075 (0.0070)	0.0044 (0.0042)	0.0538 (0.0539)	0 (0)	0.0796 (0.0792)
3	0.0207 (0.0248)	0.0080 (0.0104)	0.0056 (0.0055)	0.0538 (0.0540)	0 (0)	0.0801 (0.0843)

流线	$Y_{型}$（其中 $Y_{冲波}$）		$Y_{尾}$	$Y_{二次}$	$Y_{漏}$	$Y=\sum Y_{型、尾、二次，漏}$
内环 1	0.0200 (0.0282)	0.0088 (0.0140)	0.0067 (0.0070)	0.0539 (0.0540)	0 (0)	0.0806 (0.0892)
动叶外环 11	0.0131 (0.0126)	0.0024 (0.0043)	0.0064 (0.0076)	0.0750 (0.0706)	0.0782 (0.0796)	0.1727 (0.1704)
9	0.0127 (0.0125)	0.0028 (0.0040)	0.0052 (0.0059)	0.0743 (0.0702)	0.0782 (0.0796)	0.1704 (0.1682)
6	0.0159 (0.0154)	0.0046 (0.0044)	0.0053 (0.0053)	0.0736 (0.0697)	0.0782 (0.0796)	0.1730 (0.1701)
3	0.0224 (0.0233)	0.0084 (0.0055)	0.0088 (0.0073)	0.0728 (0.0689)	0.0728 (0.0796)	0.1822 (0.1791)
内环 1	0.0270 (0.0333)	0.0118 (0.0071)	0.0154 (0.0103)	0.0721 (0.0680)	0.0782 (0.0796)	0.1926 (0.1913)

流线	η^*_T，%
11	88.18 (87.65)
9	87.98 (87.43)
6	87.37 (87.59)
3	86.37 (87.04)
1	85.46 (86.25)
平均	87.15 (87.35)

表 1 列出近似等反力度设计各总压损失系数及效率，相应常规级数据引在括号内作比较。

计算结果的导叶动叶倾角变化见图 2，主要参数沿叶高变化见图 3，动叶根出气角 α_2 为 16.6°(级出口为 19.2°)。

按图 1 同样通道内外型线及叶片位置计算常规级的结果，也画入图 3 参考。

由表看出，近似等反力度设计的轴向漏气损失及动叶根部叶型损失，确是低于常规级的；但从总损失系数来看，在导叶是大致相当，而在动叶则明显高于常规级，这就导致级效率还略低于常规级。由于现有损失模型特别是漏气损失及冲波损失的精度很差，效率的计算及对比，只能作为一般参考，需待实验查明。

二、结　束　语

本文首次运用导叶前倾及反扭设计出从构造角度有利的平顶外廓、根尖反力度差小于 0.1 的近似等反力度涡轮级。限于损失模型的精度，其效率及与常规级对比，有待实验验证。

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AN EXPERIMENTAL STUDY OF TIP CLEARANCE EFFECTS ON THE PERFORMANCE OF AN AXIAL TRANSONIC TURBINE

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ABSTRACT In order to investigate the effects of the rotor blade tip clearance on the performance of a highly-loaded axial turbine, a single-stage axial transonic scaled-down turbine with low aspect has been tested with four rotor tip clearances. The reduced revolutions of the turbine vary from 80% to 110% and the turbine total pressure ratios vary from 2.0 to 4.0.

The experimental results are presented and analysed in the paper. The tip clearance effects on the turbine efficency are predicted with five empirical and semiempirical and the results predicted fomulas are compared with the present experimental results. The experimental results show that the effect of tip clearance on the turbine efficiency is significant, but that on the turbine inlet mass flow is small. When tip clearance increases from 1.054% to 2.823%, the turbine efficiency decreases by 5.0% at the design point, but the mass flow increases only by 0.54%.

EFFECT OF VANE AND BLADE NUMBERS ON PERFORMANCE OF TRANSONIC TURBINE STAGE

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ABSTRACT The parameters, such as throat area, trailing edge block ratio and profile turning angle at trailing edge, has been investigated with change of vane and blade number, namely 29, 26 vanes and 47, 52, 42 blades. The results of the effect of the vane and blade numbers on the mass flow, reaction and efficiency of transonic turbine stage are analyzed.

DESIGN OF AN APPROXIMATELY CONSTANT DEGREE OF REACTION TURBINE STAGE

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ABSTRACT This paper is a successful trial of an approximately constant reaction stage designed by through-flow streamline curvature method for the first time tension splines. The tip to root reaction difference within 0.1 is attained mainly by the nozzle vanes with positive lean angle of 15° at leading edge and a reverse to usual exit angle twist of 11.6°. To avoid undesirable tip clearance increase in hot running state which would lead to excessive leakage loss, the shroud diameter is kept essentially constant with only a slight taper from nozzle inlet to axial clearance mid-section and then turning outward to the rotor shroud constant diameter. The variations of main gasdynamic parameters, total pressure loss coefficients and stage efficiency along the blade height are shown in figures together with those for a corresponding conventional stage of same meridional geometry for reference purpose which is seen giving even a little (0.20%) higher efficiency. Nevertheless, owing to lack of accurate loss model, especially in regard to leakage loss and shock loss, the efficiency results including their comparison are subject to experimental verification, although the design of constant reaction in general is credible.