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热力涡轮机械

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可控扩散叶型正问题设计方法的研究与应用

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摘 要: 基于正问题设计思路,发展了一种 CDA 叶型的定制叶型几何造型方法,通过采用参数化设计的双圆弧中弧线、多段圆弧厚度分布以及椭圆前缘,来实现控制压气机叶片表面气体流动不产生分离。研究表明:与常规叶型相比,此种方法设计的 CDA 叶型获得了更高的压比和效率;马赫数及极限流线等流场信息显示,该 CDA 叶型能够有效地抑制激波的产生和附面层的分离,改善压气机内部气体的流动状况;此方法能够大量缩短叶片设计时间,有利于工程应用。

关 键 词: 可控扩散叶型; 正问题; 叶片设计

中图分类号: TK474.8 **文献标识码**: A

引 言

可控扩散叶型(Controlled Diffusion Airfoil, CDA)是一种先进叶型设计方法,该法可以成功地使压气机性能得到提升[1-3]。在此基础上发展了考虑端部附面层影响的第二代可控扩散叶型(CDA-II),进一步改善了 CDA 叶片沿整个叶展方向的性能[4]。与其它叶型设计一样,可控扩散叶型的设计方法也有正问题方法、反问题方法和正反问题混合法3种。与其它两种方法相比,正问题方法在工程应用中有着明显优点。它采用已知的叶片几何造型,通过正问题分析得到流场分布情况,如结果不满足要求则重新修改叶型再进行正问题计算,直至获得符合目标的叶型为止。只要已知的叶型能够满足速度和压力分布要求,就可以很快地完成叶片设计工作。因此,正问题设计方法的关键在于给定叶型的几何造型方法。

在 CDA 正问题设计方面,普惠公司(Pratt & Whitney)发展出了一套成熟的 CDA 叶片造型体系[5-6]。本研究结合普惠公司的思路,建立了一种将叶片气动性能与叶型几何形状参数化结合的 CDA 定制叶型造型方法,通过此方法能够很快地获得特定的可控扩散叶型,从而快速完成叶片的工程设计。设计方法主要包括中弧线的确定、叶型厚度分布规律的确定和厚度分布叠加3部分。

1 设计方法

1.1 中弧线设计

中弧线的确定采用双圆弧型中弧线方法,通过两段圆弧在最大挠度点相切而成,如图1所示。

在确定中弧线时,通常已知叶片弦长、进出口几何角及叶栅节距等叶片造型参数。首先给定一个安装角初值,就可以由已知参数确定前段圆弧的弦长及弯角,进一步即可确定前缘点、转接点以及尾缘点的坐标及切线斜率,从而初步确定中弧线及弦线。这时将实际得到的安装角作为初值重新返回进行迭代,直至实际值与初值之间的误差满足最小约束条件,便可以将其作为最终的安装角数值,这样中弧线也随之确定。

1.2 厚度分布规律设计

叶型的厚度分布规律直接决定着叶片吸力面和压力面的几何形状和压力分布,对于叶片的气动性能起着关键性作用。在确定 CDA 叶型厚度分布时,不仅要使其能够较好地控制流动过程中的附面层发展,还要保证厚度分布型线光滑过渡。因此,在确定厚度分布时,采用圆弧相切的方法得到光滑的厚度分布规律型线,并使其表面速度分布具有以下特点[4]:(1) 气流在叶型吸力面从前缘开始,到速度峰值保持连续加速,直到附面层转捩点为止,避免层流附面层过早分离或转捩。(2) 吸力面峰值马赫数控制在1.3以下,以避免出现激波和因激波与附面层相互干扰所引起的附面层分离。(3) 控制气流在吸力面从峰值马赫数点到尾缘区域内的扩散度,以

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保持无激波减速，避免附面层分离，并使表面摩擦最小。(4) 在压力面保持合理均匀的亚声速分布。

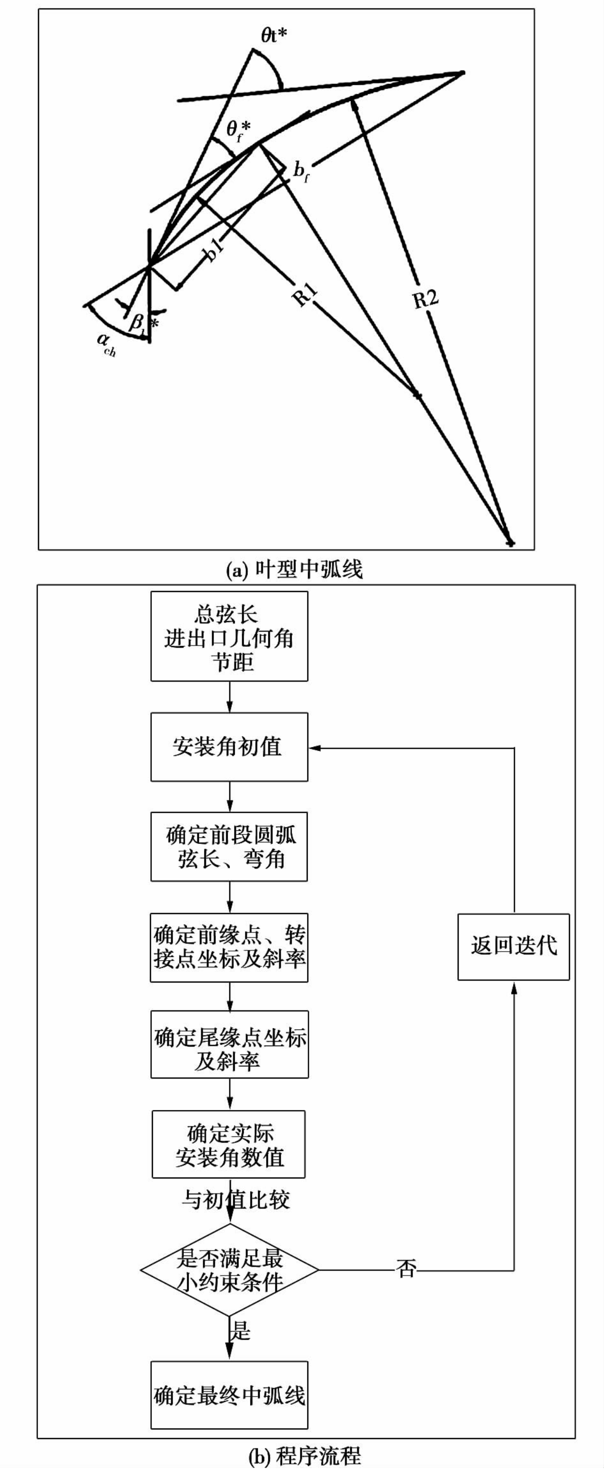


图 1　CDA 叶型中弧线及其设计程序

Fig. 1 Mid-arc line of a CDA airfoil and its design procedure

为进一步抑制前缘表面气流的过度膨胀，减弱吸力峰，在设计叶型前缘时，采用有别于传统叶型的椭圆弧设计。其方法是在以常规方法确定前缘圆弧之后，于距离前缘点 A 一定长度的位置 B 处作与 A、B 两点相切的椭圆弧，如图 3 所示。

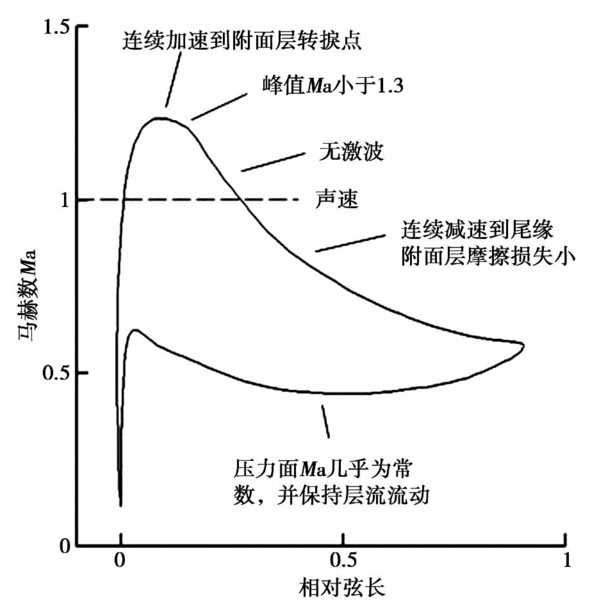


图 2　典型的 CDA 叶型速度分布

Fig. 2 Typical velocity distribution of a CDA airfoil

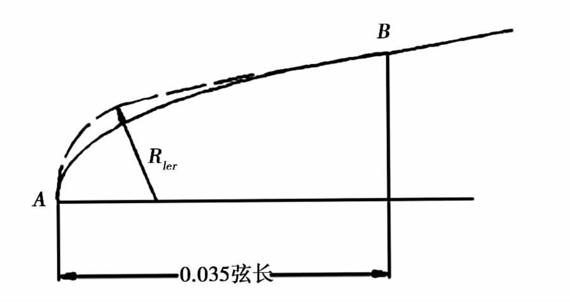


图 3　椭圆前缘

Fig. 3 Elliptical leading edge

1.3　厚度分布叠加

在厚度分布规律确定以后，将厚度分布型线沿弦长进行分割，得到一系列的厚度分布数据；然后按照此分割点在弦上的坐标，对中弧线进行划分；在每个中弧线分点上将其对应的厚度数据相应叠加，最终获得叶片吸力面和压力面的型线。

2　与常规叶型对比分析

为了对此 CDA 叶型的气动性能进行评定，采用

某高压压气机第一级的进出口几何参数,应用此 CDA 叶片造型方法进行了叶型设计。该高压压气机第一级动叶进口马赫数在 0.7 – 0.9 之间,属于高亚声速进口流动范畴。为了便于比较,以同样的进出口参数设计了 NACA 65 – 010 叶型及 C – 4 叶型两套常规叶型方案。图 4 给出了静叶某截面 3 种叶型的几何造型比较。可以看出 CDA 叶型的前尾缘相对较厚,压力面减速区型线更为平缓。

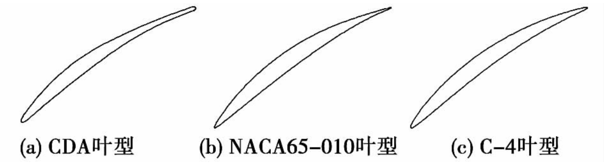


图 4　3 种叶型几何造型对比

Fig. 4 Comparison of the geometrical modeling of three types of airfoil

对 3 种叶型方案采用 NUMECA 的 Fine/Turbo 软件包进行了全三维流场计算。网格质量均满足软件计算精度要求,进口给定总温、总压及速度方向条件,出口给定质量流量,固体壁面采用无滑移绝热边界。3 种方案的计算结果如表 1 所示。

表 1　3 种方案计算结果

Tab. 1 Calculation results of the three schemes

参　数	CDA	NACA 65 – 010	C – 4
转速/r · min^{-1}	9 700	9 700	9 700
质量流量/kg · s^{-1}	99.45	99.45	99.45
总压比	1.310	1.307	1.304
效率/%	90.31	89.86	89.38

由表 1 可以看出,在同样的转速及进口条件下,采用 CDA 叶型的单级方案拥有更强的增压能力和更好的效率。常规标准叶型设计的两套方案中,NACA 65 系列叶型由于其前尾缘较薄、最大挠度位置居中、叶型略微细长而具有较高的临界马赫数,故而更适应高亚声速流动。从表 1 的计算结果也可以看出,NACA 65 – 010 叶型方案性能比 C – 4 叶型方案更佳,但这必须以损失叶片前尾缘强度及可用攻角范围为代价。而 CDA 叶型方案比 NACA 65 – 010 叶型方案性能更有所提升,并且 CDA 叶型比 NACA 65 系列有着更厚的前缘,能够更好地满足强度要求以及适应进口攻角的变化,这也是 CDA 叶型相较于标准叶型稳定工作范围更大的一个主要原因。

图 5 – 图 7 为 3 种方案动叶 10% 、50% 、90% 叶高截面马赫数分布图。从图中可以看出,在进口高亚音马赫数的情况下,动叶栅中的流动成为跨声速流动,此时,常规叶型设计中 C – 4 叶型方案的动叶在中部以上便开始产生激波,叶片顶部激波更为明显; NACA 65 – 010 叶型方案则在 90% 截面出现明显激波; 相比之下,CDA 叶型设计方案则有效抑制了激波的产生。并且从图中可以发现,CDA 叶型在前缘小范围内有一个较大加速,但并没有产生前缘分离,这体现了椭圆形前缘的好处。椭圆形前缘的曲率半径是逐步增大的,能够保持气流在前缘以逐渐减小的法向压力梯度连续加速,抑制前缘表面流动的过度膨胀,从而达到减弱吸力峰,避免层流分离的效果。

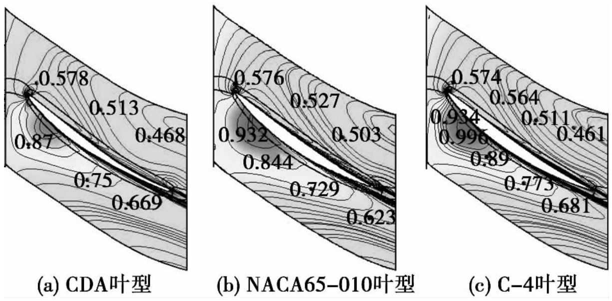


图 5　3 种方案动叶 10% 叶高马赫数分布

Fig. 5 Mach number distribution of the rotating blade at 10% blade height in the three schemes

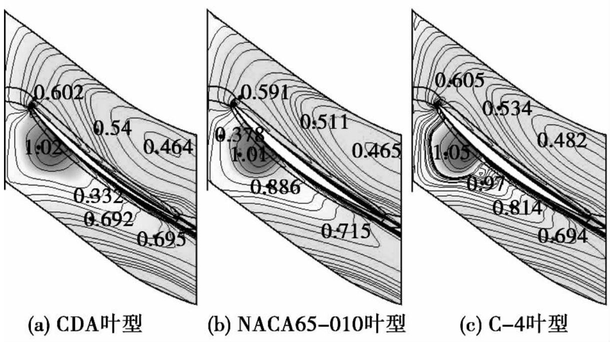
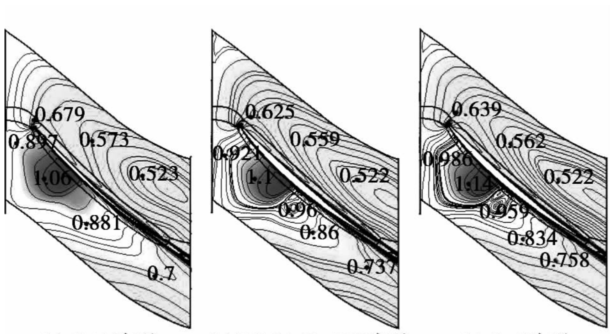


图 6　3 种方案动叶 50% 叶高马赫数分布

Fig. 6 Mach number distribution of the rotating blade at 50% blade height in the three schemes

图 8 和图 9 分别给出了 3 种叶型方案的动、静叶 10% 、50% 、90% 叶高位置处型面压力分布对比。

从图中的静压分布可以看出，从吸力面速度峰值点到叶型尾缘，CDA 叶型方案的逆压梯度程逐渐减小的趋势，而不是像常规叶型一样几乎为直线，这是典型的可控扩散叶型特征。通过叶背型面压力梯度的变化来控制减速区气流的扩散程度，有利于避免附面层发生分离。

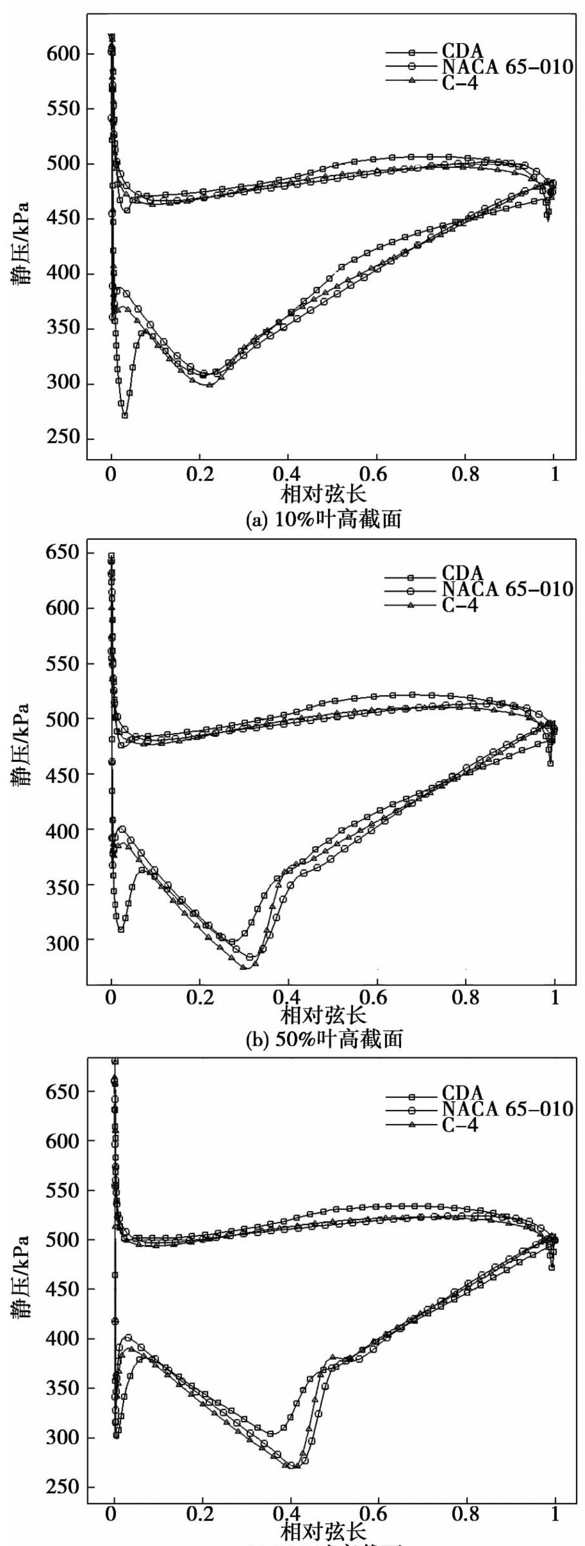


(a) CDA叶型　(b) NACA65-010叶型　(c) C-4叶型

图 7　3 种方案动叶 90% 叶高马赫数分布

Fig. 7 Mach number distribution of the rotating blade at 90% blade height in the three schemes

图 10 和图 11 显示了 3 种叶型方案的动叶、静叶吸力面极限流线情况。从图中可以明显看出，3 种方案的动叶根部、静叶顶部及根部均存在着一定的径向二次流动现象，并且静叶中更为严重，这是由于端壁附面层与主流区相互作用所致。仔细对比 3 种叶型方案的动、静叶吸力面极限流线，可以看到，CDA 叶型动叶吸力面上的角区范围明显比常规叶型方案的小，径向流动程度明显较弱；相比之下，NACA 65 - 010 叶型方案的动叶根部径向流动比较明显，C - 4 叶型方案更为严重，已经发生流动分离。在静叶中，CDA 叶型方案同样有着较小的角区，在上下端壁处的径向二次流情况也比常规叶型方案的弱，而 NACA 65 - 010 方案和 C - 4 方案静叶根部都已经出现严重的回流并产生旋涡，顶部径向流动也比 CDA 方案的明显。这从 3 种方案级出口总压沿展向分布情况图（如图 12 所示）中也可以发现，3 种叶型方案的级总压损失主要集中在上下端壁部分，并且底部端壁情况更为严重，这是由叶片根部流动情况较差所导致的。3 种方案中，CDA 叶型方案的级总压损失要比另外两种常规叶型方案的小，也与极限流线的分析结果一致。



(a) 10%叶高截面
(b) 50%叶高截面
(c) 90%叶高截面

图 8　3 种方案动叶型面压力分布

Fig. 8 Pressure distribution on the surface of the rotating blade in the three schemes

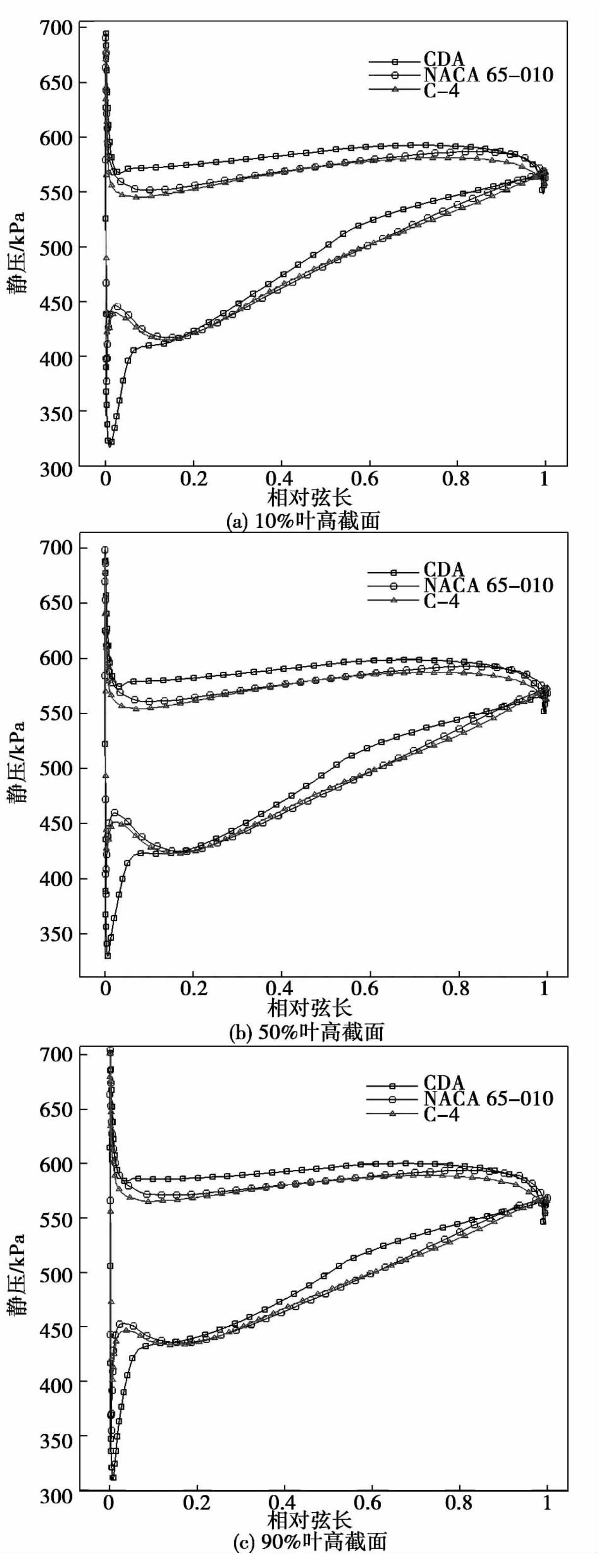


图 9　3 种方案静叶型面压力分布

Fig. 9 Pressure distribution on the surface of the stationary blade in the three schemes

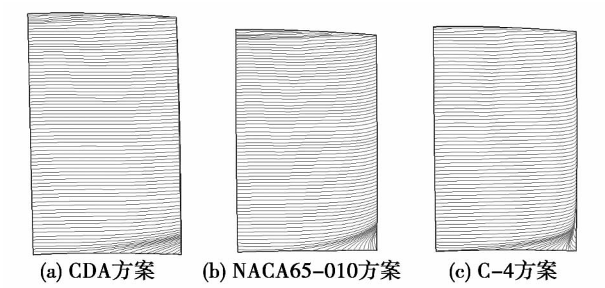


图 10　3 种方案动叶吸力面极限流线

Fig. 10 Limit streamlines on the suction surface of the rotating blade in the three schemes

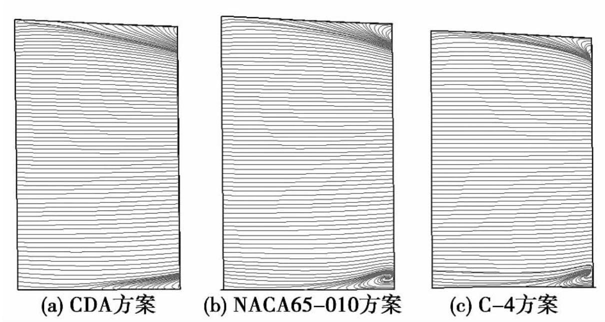


图 11　3 种方案静叶吸力面极限流线

Fig. 11 Limit streamlines on the suction surface of the stationary blade in the three schemes

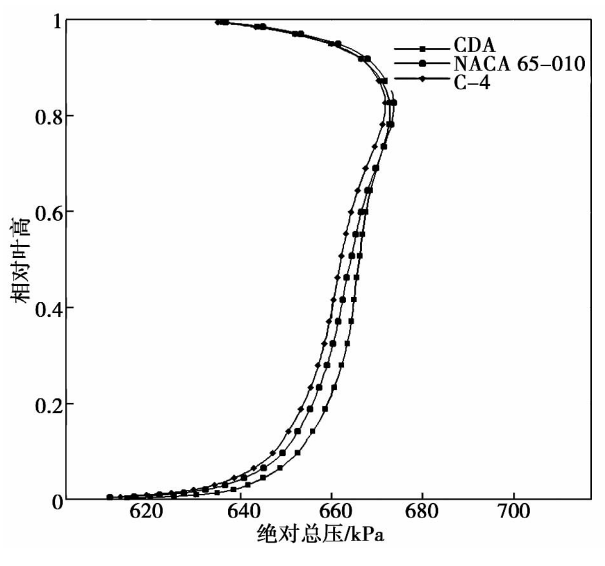


图 12　3 种方案级出口总压沿叶高分布

Fig. 12 Distribution of the total pressure at the outlet of the stage along the blade height in the three schemes

3 结 论

(1) 基于正问题思路建立了一种 CDA 叶型的几何造型方法。通过采用参数化设计的双圆弧中弧线、多段圆弧厚度分布以及椭圆前缘，来实现所期望的叶型表面压力与速度分布，从而控制压气机叶片表面气体流动，防止产生激波及吸力面的附面层分离。通过与常规叶型在单级压气机中的模拟对比，验证了该方法设计的 CDA 叶型对压气机性能提升的积极作用。并且，由于采用定制叶型的参数化设计方法来生成叶片，能够大量缩短叶片设计时间，有利于工程应用。

(2) 对单级压气机的设计流量点进行了全三维流场计算，与 NACA 65 – 010 叶型及 C – 4 叶型相比，此种方法设计的 CDA 叶型在单级环境中获得了更高的压比和效率。该 CDA 叶型能够有效地抑制叶栅通道内激波的产生，使用该 CDA 叶型后压气机叶片表面气体流动的分离状况得到了明显改善，总压损失减小。

(3) 所设计的 CDA 叶型在主流区效果较好，在端部效果明显减弱。这是由端壁区流动强三维性的影响所导致。这也说明在今后展开考虑端部流动影响的 CDA – II 叶型研究是十分必要的。

另外，未来工作中有必要进一步开展该 CDA 叶型在多级大攻角环境下的数值计算与试验工作，以确定其能否有效提高喘振裕度，扩大稳定工作范围。

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(丛 敏 编辑)

新技术、新设计

大功率机组给水系统新一代泵研制

据《Теплоэнергетика》2013 年 2 月刊报道，莫斯科动力学院的专家发布了 100 MW 热电厂动力机组给水系统串联的凝水、增压和给水泵设计和研制的主要成果。

详细介绍了新一代凝水泵、增压泵和给水泵的设计、结构及其特点。

该方案具有优异的性能并更进一步提高了给水泵的效率、可靠性和使用寿命。

(吉桂明 摘译)

燃气热电联产系统余热挖潜方式研究 = Study of the Modes for Tapping the Latent Power in Utilizing the Waste Heat of a Gas Heat and Power Cogeneration System 刊,汉 ZHAO Xi-ling, FU Lin, LI Feng, WANG Xiao (Department of Architectural Technology and Science, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy & Power. -2014, 29(4). -349-354

In the light of the waste heat from the flue gases and steam exhausted from a gas-steam combined cycle heat and power cogeneration unit, described were five technologies for utilizing the waste heat, namely, 3S clutch technology, absorption type heat pump technology, compression type heat pump technology, absorption type heat pump + compression type heat pump technology and heat supply technology based on the Co-ah cycle (absorption type heat exchange heat and power cogeneration centralized heat supply technology) with their enhancement in the capacity to supply heat, energy-saving and cost-effectiveness being quantitatively analyzed. Through the above-mentioned analysis, the authors have come to a conclusion that all the five technologies can be used to enhance the heat supply capacity and the heat supply technology based on the Co-ah cycle, however, can lead to a maximal rise in the heat supply capacity. An analysis of the energy-saving performance leads us to conclude that all the five technologies can achieve their respective energy-saving effectiveness but the heat supply technology based on the Co-ah cycle can accomplish the most outstanding energy-saving effectiveness. An analysis of the cost-effectiveness induces one to conclude that under the condition of increasing the unit heat supply capacity (1 MW), if the absorption type heat pump technology and the heat supply technology based on the Co-ah cycle were adopted, the initial investment would be slightly higher than those of the others and the savings in the operation cost, however, would be relatively more obvious. With the factors in the two aspects, i. e. a rise in the heat supply capacity and cost-effectiveness, being considered in a comprehensive way, the heat supply technology based on the Co-ah cycle is regarded as having more leading edges. **Key Words:** heat and power cogeneration, absorption type heat exchange, waste heat recovery from flue gases, waste heat recovery from the steam exhausted

可控扩散叶型正问题设计方法的研究与应用 = Study and Applications of the Methods for Designing the Positive Problems Relating to the Controllable Diffusion Blade Profile 刊,汉 WANG Qi, MA Yun-xiang, ZHAO Duo, WANG Yu-jing (CSIC No. 703 Research Institute, Harbin, China, Post Code: 150060) //Journal of Engineering for Thermal Energy & Power. -2014, 29(4). -355-360

Based on the ideas for designing the positive problems, developed was a method for geometrically modeling a CDA custom-tailored blade profile. A dual-arc intermediate arc line and multi-section arc thickness distribution parameterizedly designed as well as the elliptical leading edge were adopted to realize an aim to control the air flow on the blade surfaces of a compressor and not produce any separation. It has been found that compared with conventional blade profiles, the CDA blade profile thus designed can obtain an even higher pressure ratio and efficiency. The in-formation about the flow field such as Mach number and limit streamlines etc. indicates that the CDA blade profile can effectively prohibit the production of shock waves and separation of boundary layers, and improve the status of the air flow inside the compressor. The method in question can shorten the design time of the blades in a large amount, thus contributing to applications in engineering projects. **Key Words:** controllable diffusion blade profile, positive problem, blade design

基于 PIV 测试技术的涡轮动叶栅流场可视化研究 = Visualization Study of the Flow Field in a Rotor Cascade of a Turbine Based on the PIV Measurement and Testing Technology [刊，汉] MA Chao, GE Bing, ZANG Shu-sheng (College of Mechanical and Power Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) //Journal of Engineering for Thermal Energy & Power. -2014, 29(4). -361-366

In the light of four operating conditions at four rotating speeds from 780 to 1680 r/min of a rotor blade cascade of a turbine with its design rotating speed being 1 500 r/min, experimentally studied was the PIV (particle image velocimetry) technology in measuring the inner flow field by employing dry ice as the tracer particles and obtained were 2D distribution of the speed field and vorticity field in the middle section and its downstream areas of the flow passages of the rotor blade cascade. It has been found that the transient results measured by using the PIV technology can capture very well the formation and evolution process of the vortices separated from the trailing edge of the rotor blade cascade. Within the operating conditions under the test, the velocity at the outlet and the downstream of the rotor blades continuously increased while the velocity of the gas in the flow passages was characterized by its first increase and then decrease with an increase of the rotating speed of the rotor blades. The output power of the blade wheel had a same variation law governing the air flow speed in the flow passages. In adjacent to the design rotating speed operating condition, the intensity of the vorticity field in the flow passages of the rotor blades was relatively weak and with a decrease of the rotating speed of the blade wheel, the intensity of the vorticity field inside the flow passages of the cascade, especially in the downstream of the suction surface of the rotor blades was obviously enhanced. **Key Words:** rotor blade cascade, PIV testing, laser visualization, flow field analysis

超临界机组参与一次调频对汽轮机寿命影响的研究 = Study of the Influence of the Participation of a Supercritical Unit in the Primary Frequency Modulation on the Service Life of a Steam Turbine [刊，汉] WANG Xu-rong, DAI Yi-ping (College of Energy Source and Power Engineering, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049), LI Fu-shang (Shandong Electric Power Research Institute, Jinan, China, Post Code: 250000), ZHANG Ya-fu (Xi'an Thermodynamics Research Institute Co. Ltd., Xi'an, China, Post Code: 710032) //Journal of Engineering for Thermal Energy & Power. -2014, 29(4). -367-373