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随机参数汽轮机叶片频率的随机有限元分析

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摘 要: 汽轮机叶片的材料特性、结构参数以及汽轮机转速都存在随机性, 从而导致叶片的频率存在分散性, 随机有限元方法可以考虑叶片参数的随机性, 并得到频率的随机特征。将叶片的材料特性和结构参数处理为随机参数, 基于随机变分原理推导了旋转叶片的随机有限元方程, 建立了质量矩阵、线弹性刚度矩阵、几何刚度矩阵、动力刚度矩阵的均值和一阶变异矩阵, 给出了固有频率均值、协方差和变异系数的计算方法。最后对432叶片的静动频率进行了随机有限元分析, 定量给出了叶片参数随机变异导致频率的变异程度, 为高可靠性叶片设计提供了分析工具。

关 键 词: 汽轮机叶片; 随机参数; 随机有限元; 频率

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引 言

叶片是汽轮机的关键部件, 叶片静、动频率分析是汽轮机叶片设计、安装、运行的主要问题。鉴于叶片的重要性, 对叶片的静动特性已经进行了大量研究[1]。影响汽轮机叶片频率的因素主要有材料特性、结构尺寸和转速等参数, 传统分析都是认为叶片的参数是确定性的, 但在叶片设计、加工、安装和工作中, 这些参数本质上都存在一定程度的不确定性, 导致按同一标准设计、加工、安装的叶片在工作中表现出不同的振动特性, 工程中一般用频率分散度表示。为保证叶片的安全运行, 在设计、安装中都对叶片进行频率分析和实验, 并控制叶片的频率分散度在安全范围内。随机有限元方法可以考虑参数的不确定性, 并且具有较高的分析精度。随机有限元方法已经有大量文献进行了综述[2~4], 但应用于汽轮机叶片频率分析的文献不多。文献[5]应用Monte-Carlo法研究了汽轮机泵叶片的随机响应, 文献[6]研究了参数的变化对汽轮机叶片振动特性的影响, 文献[7]研究叶片静态响应的随机分析方法, 文献[8]采用Ritz法研究了根部随机约束叶片的静动频率分析方法。

本文基于摄动法建立叶片频率分析的随机有限元方程, 并建立考虑离心力影响的叶片特征值问题的随机刚度矩阵和随机质量矩阵。最后对432叶片, 考虑其弹性模量、密度、叶片尺寸、转速随机时分析其低阶静、动频率的均值、协方差和变异系数。

1 随机参数叶片的随机变分原理

为了描述方便, 将影响叶片特性的随机参数(如弹性模量、密度、叶片结构尺寸和转速等)称为基本随机变量, 将它们组成一个向量, 称为基本随机向量 $\{b\}$。由于叶片参数属于小变异情况, 基于摄动理论[10], 基本随机向量可以写成一阶摄动格式:

$$\{b\}=\{b^0\}+\varepsilon_p\{b\}' \quad (1)$$

式中: $\{b^0\}$—基本随机变量的均值; $\{b\}'$—基本随机变量的一阶摄动量, 也称一阶变异量; ε_p—小参数。

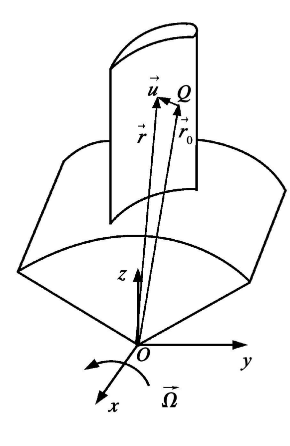

图1 汽轮机叶片运动模型

当叶片在平衡位置附近振动时, 叶片随叶轮以角速度 Ω 绕 x 轴转动, 如图1所示。以叶轮轴线上一点 o 为坐标原点, 则叶片上任意一点 Q 平衡位置

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向量为$\{r_o\}$，弹性变形为$\{u(\{r_o\},t)\}$，它是空间坐标$\{r_o\}^T$、时间 t 和基本随机向量$\{b\}$的函数。在运动中，Q 点的绝对速度为：

$$\{v\}=\Omega[H]\{r_o\}+\Omega[H]\{u\}+\{\dot{u}\} \tag{2}$$

式中：$[H]=\begin{bmatrix}0&0&0\\0&0&-1\\0&1&0\end{bmatrix}$；$\{\dot{u}\}$—$Q$ 点的振动速度。

叶片的动能为：

$$T=\frac{1}{2}\int_V\rho(\{\dot{u}\}^T\{\dot{u}\}+2\Omega\{\dot{u}\}^T[H]\{u\}+\Omega^2\{u\}^T[H]^T[H]\{u\}+2\Omega\{r_o\}^T[H]^T\{\dot{u}\}+2\Omega^2\{r_o\}^T[H]^T[H]\{u\}+\Omega^2\{r_o\}^T[H]^T[H]\{r_o\})\mathrm{d}V \tag{3}$$

由无阻尼自由振动线弹性连续体的 Hamilton 变分原理，进行变分计算，并对时间分部积分，则得：

$$\int_V\delta\{u\}^T\rho\{\ddot{u}\}\mathrm{d}V+2\int_V\delta\{u\}^T\rho\Omega[H]\{\dot{u}\}\mathrm{d}V+\int_V\delta\{\varepsilon\}^T[D]\{\varepsilon\}\mathrm{d}V-\int_V\delta\{u\}^T\rho\Omega^2[H]^T[H]\{u\}\mathrm{d}V=\int_V\delta\{u\}^T\rho\Omega^2[H]^T[H]\{r_o\}\mathrm{d}V \tag{4}$$

式中：$[D]$—弹性矩阵；$\{\varepsilon\}$—应变向量。

将影响叶片特性的随机参数在基本随机变量$\{b\}$的均值$\{b^0\}$处作小参数摄动展开，代入式(4)，并比较小参数 ε_p 的同次幂系数，可以得到叶片摄动格式的各阶 Hamilton 随机变分原理，其中零阶和一阶 Hamilton 随机变分原理表达式如下：

零阶 Hamilton 随机变分原理：

$$\int_V\delta\{u\}^T\rho^0\{\ddot{u}^0\}J_v^0\mathrm{d}R+2\int_V\delta\{u\}^T\rho^0\Omega^0[H]\{\dot{u}^0\}J_v^0\mathrm{d}R+\int_V\delta\{\varepsilon\}^T[D^0]\{\varepsilon^0\}J_v^0\mathrm{d}R-\int_V\delta\{u\}^T\rho^0\Omega^{0^2}[H]^T[H]\{u^0\}J_v^0\mathrm{d}R=\int_V\delta\{u\}^T\rho^0\Omega^{0^2}[H]^T[H]\{r_o^0\}J_v^0\mathrm{d}R \tag{5}$$

式(5)与确定性 Hamilton 变分原理形式相同，由此可以看出，确定性有限元分析是考虑参数随机性得到结果的均值部分，按确定性有限元方法不能得到参数随机性导致频率的变异部分。

一阶 Hamilton 随机变分原理：

$$\int_V\delta\{u\}^T(\rho^0\{\ddot{u}\}'_jJ_v^0+\rho'_j\{\ddot{u}^0\}J_v^0+\rho^0\{\ddot{u}^0\}J'_{vj})\mathrm{d}R+\int_V2\delta\{u\}^T(\rho'_j\Omega^0[H]\{\dot{u}^0\}J_v^0+\rho^0\Omega'_j[H]\{\dot{u}^0\}J_v^0+\rho^0\Omega^0[H]\{\dot{u}\}'_jJ_v^0+\rho^0\Omega^0[H]\{\dot{u}^0\}J'_{vj})\mathrm{d}R+\int_V\delta\{\varepsilon\}^T([D]'_j\{\varepsilon^0\}J_v^0+[D^0]\{\varepsilon\}'_jJ_v^0+[D^0]\{\varepsilon^0\}J'_{vj})\mathrm{d}R-\int_V\delta\{u\}^T(\rho'_j\Omega^{0^2}[H]^T[H]\{u^0\}J_v^0+2\rho^0\Omega^0\Omega'_j[H]^T[H]\{u^0\}J_v^0+\rho^0\Omega^{0^2}[H]^T[H]\{u\}'_jJ_v^0+\rho^0\Omega^{0^2}[H]^T[H]\{u^0\}J'_{vj})\mathrm{d}R=\int_V\delta\{u\}^T(\rho'_j\Omega^{0^2}[H]^T[H]\{r_o^0\}J_v^0+2\rho^0\Omega^0\Omega'_j[H]^T[H]\{r_o^0\}J_v^0+\rho^0\Omega^{0^2}[H]^T[H]\{r_o^0\}J'_{vj})\mathrm{d}R \tag{6}$$

式中：J_v—体积雅可比行列式；J_s—域表面积雅可比行列式。上标 0—该随机变量的均值；下标 j—第 j 个基本随机变量，上标 $'$—随机变量对基本随机变量的一阶导数。

式(6)描述了设计参数(如弹性模量、转速、密度和结构尺寸)的一阶变异引起的变分原理的变化，由该式可以得到叶片的一阶变异有限元方程。

2　叶片固有振动随机有限元方程

文献[11]分析表明，科氏力对高速旋转的汽轮机叶片的轴向振动和扭转振动的固有频率没有影响，对切向振动影响很小，可以忽略不计，因此在本文研究过程中，忽略科氏力对叶片动态特性的影响。转子高速旋转导致叶片产生巨大的离心力，离心力作用会引起叶片附加应变能，从而使叶片的刚度增加，叶片在转动时的固有频率比静止状态时的固有频率高，叶片在转动状态时，考虑刚度增加得到的固有频率称为叶片的动频率。在实际工作时，叶片都随转子高速旋转，因此研究叶片的动频率有重要的实用价值。考虑离心力影响的动力刚度矩阵：

$$[K_\sigma]=\int_V[G]^T[S][G]\mathrm{d}V \tag{7}$$

式中：$[S]$—离心力载荷产生的应力矩阵。$[G]=[\partial][N]$，$[\partial]$—算子矩阵；$[N]$—型函数，表达式见文献[11]。

采用通用的有限元离散方法可以得到单元的有限元方程，通过单元组集可以得到叶片的运动方程，叶片的零阶无阻尼自由振动随机有限元方程如式(8)：

$$[M^0]\{\ddot{a}^0\}+[K_t^0]\{a^0\}=0 \tag{8}$$

式中：$[M^0]$—叶片均值质量矩阵；$[K_t^0]$—叶片均值刚度矩阵，$[K_t^0]=[K^0]-[K_C^0]+[K_\sigma^0]$；$[K^0]$—叶片均值线弹性刚度矩阵；$[K_C^0]$—叶片均值几何刚度矩阵；$[K_\sigma^0]$—单元均值动力刚度矩阵。总刚度矩阵中第二项为考虑旋转与叶片弹性变形的耦合效应导致叶片的刚度的减小，第三项为考虑转动离心力导致

的轴向变形引起的叶片的刚度增加，综合几何刚度矩阵和动力刚度矩阵的影响，叶片的刚度是增加的，因此旋转叶片的动频率要高于静频。

$$[K^0] = \int_V [B]^T [D^0][B] J_v^0 \mathrm{d}R$$
$$[K_C^0] = \int_V \rho^0 \Omega^0 [N]^T [H]^T [H][N] J_v^0 \mathrm{d}R$$
$$[M^0] = \int_V \rho^0 [N]^T [N] J_v^0 \mathrm{d}R \tag{9}$$
$$[K_\sigma^0] = \int_V [G^0]^T [S^0][G^0] J_v^0 \mathrm{d}R$$

式中：$[B^0]$ —均值几何矩阵，$[B^0] = [J_v^0]^{-1}[\partial][N]$；$[G^0]$ —均值$[G]$矩阵；$[S^0]$ —离心力作用下，单元的均值应力矩阵。

同理，可以得到叶片的一阶无阻尼自由振动随机有限元方程：

$$[M^0]\{\ddot{a}\}'_j + [K_t^0]\{a\}'_j = -[M]'_j\{\ddot{a}^0\} - [K_t]'_j\{a^0\} \tag{10}$$

式中：$[M]'_j$—叶片一阶变异质量矩阵；$[K_t]'_j$—叶片一阶变异刚度矩阵，$[K_t]'_j = [K]'_j - [K_C]'_j + [K_\sigma]'_j$；$[K]'_j$—叶片一阶变异线弹性刚度矩阵；$[K_C]'_j$—叶片一阶变异几何刚度矩阵；$[K_\sigma]'_j$—叶片一阶变异动力刚度矩阵。

$$[K]'_j = \int_V ([B^0]^T [D]'_j [B^0] J_v^0 + [B^0]^T [D^0][B^0] J'_{vj} + [B]'^T_j [D^0][B^0] J_v^0 + [B^0]^T [D^0]'[B]'_j J_v^0) \mathrm{d}R$$

$$[K_C]'_j = \int_V (\rho'_j \Omega^{0^2} [N]^T [H]^T [H][N] J_v^0 + 2\rho^0 \Omega^0 \Omega'_j [N]^T [H]^T [H][N] J_v^0 + \rho^0 \Omega^{0^2} [N]^T [H]^T [H][N] J'_{vj}) \mathrm{d}R$$

$$[K_\sigma]'_j = \int_V ([G]'^T_j [S^0][G^0] J_v^0 + [G^0]^T [S]'_j [G^0] J_v^0 + [G^0]^T [S^0][G]'_j J_v^0 + [G^0]^T [S^0][G^0] J'_{vj}) \mathrm{d}R$$

$$[M]'_j = \int_V (\rho'_j [N]^T [N] J_v^0 + \rho^0 [N]^T [N] J'_{vj}) \mathrm{d}R \tag{11}$$

式中：$[B]'_j$—一阶变异几何矩阵，$[B]'_j = -[J_v^0]^{-1}[J_V]'_j [J_v^0]^{-1}[\partial][N]$；$[G]'_j$—一阶变异$[G]$矩阵；$[S]'_j$—离心力作用下，单元一阶变异应力矩阵。

3 叶片频率的统计特性

由式(8)和式(10)可以得到无阻尼叶片的零阶特征值问题和一阶特征值问题：

$$[K_t^0]\{\phi_i^0\} = \omega_i^{0^2}[M^0]\{\phi_i^0\} \tag{12}$$

$$[K_t^0]\{\phi_i\}'_j - \omega_i^{0^2}[M^0]\{\phi_i\}'_j = -[K_t]'_j\{\phi_i^0\} + 2\omega_i^0 \omega'_{ij}[M^0]\{\phi_i^0\} + \omega_i^{0^2}[M]'_j\{\phi_i^0\} \tag{13}$$

求解式(12)可以得到频率的均值，利用振型展开法，按文献[12]方法可以求解式(13)，得到频率对基本随机变量的灵敏度，如式(14)，灵敏度表示该随机变量对叶片频率的影响程度，若频率对该随机变量的灵敏度大，则该随机变量的随机性对频率将产生显著影响，计算中就不能忽略该参数的随机性。

$$\omega'_{ij} = \frac{\{\phi_i^0\}^T ([K_t]'_j - \omega_i^{0^2}[M]'_j)\{\phi_i^0\}}{2\omega_i^0 \{\phi_i^0\}^T [M^0]\{\phi_i^0\}} \tag{14}$$

式中：ω'_{ij}—第 i 阶频率对第 j 个基本随机变量的灵敏度。写成矩阵形式，则可以得到频率灵敏度矩阵$[S_\omega]$。通过协方差运算可以得到频率协方差矩阵：

$$[C_\omega] = [S_\omega][C_b][S_\omega]^T \tag{15}$$

式中：$[C_b]$ —随机场离散得到的基本随机变量的协方差矩阵。频率协方差矩阵$[C_\omega]$的对角元素为各阶频率的方差 $Var(\omega_i)$，则各阶频率均方差为 $\sigma = \sqrt{Var(\omega_i)}$。频率均值 $\mu = \omega_i^0$ 和均方差 σ 描述了叶片频率的概率分布特征，如假设叶片的频率为正态随机变量，则叶片频率在$[\mu - 3\sigma, \mu + 3\sigma]$范围内的概率为 99.74%，在$[\mu - 2\sigma, \mu + 2\sigma]$范围内的概率为 95.54%。

根据各阶频率的均方差和均值，可得各阶频率的变异系数，如式(16)所示。频率的变异系数大小反映了频率的分散程度。按概率理论，均方差 σ 可以表示随机变量偏离均值的程度，但是其数值并不能直接地表示该随机变量的分散程度，而采用均方差与均值的比值，称为变异系数，用符号 *COV* 表示，可以准确的表示随机变量的分散程度，消除了随机变量均值不同的影响。如果频率的变异系数为零，说明频率是一个确定性量，如果变异系数较小，说明频率的不确定性或随机性较小。

$$COV = \sigma / \mu \tag{16}$$

4 算 例

某 200 MW 汽轮机次末级叶片为 432 mm 叶片，其主要参数如表 1 所示。432 叶片有限元网格模型如图 2 所示。

表 1　432 叶片参数

	数值
动叶片数/只	94
叶片高度/mm	432
平均直径/mm	1 678
额定工作转速/r·min^{-1}	3 000
材料	2Cr13
蒸汽流量/t·h^{-1}	139
级前/后压力/MPa	0.046/0.015 6
轮周功率/kW	5 210

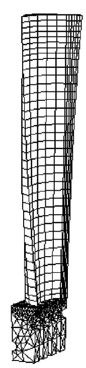

图 2　叶片网格模型

表 2　叶片频率均值

阶次	静频/Hz			动频/Hz		
	本文	文献[13] BDAVA 法	文献[13] VBC 法	本文	文献[13] BDAVA 法	文献[13] VBC 法
1	152.12	156.0	158.27	180.700	177.6	180.23
2	338.29	333.9	349.96	353.577	347.7	364.40
3	697.20	662.8	731.09	721.279	688.3	755.20
4	837.96	848.8	895.75	847.450	854.0	901.58

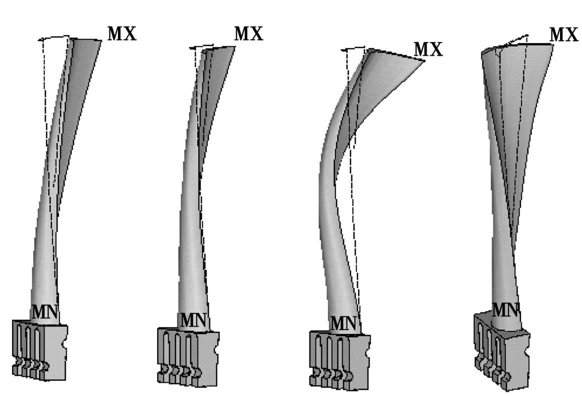

图 3　前四阶均值振型图

表 2 给出了 432 叶片静动频率的均值，从结果中可以看出，本文结果与文献[13] 结果基本吻合，两者差异的主要原因是采用的计算模型有差别。文献[13] 给出单只 432 叶片一阶静频的实验值在 151～161 Hz，本文计算结果与实验值吻合良好。432 叶片的前四阶振型均值如图 3 所示。

图 4 和图 5 为叶片弹性模量、密度取 0.1 的变异系数，转速、结构尺寸取 0.01 的变异系数得到的叶片静动频率的协方差，从图中可以看出，叶片频率方差随叶片振型阶次增加而增加。

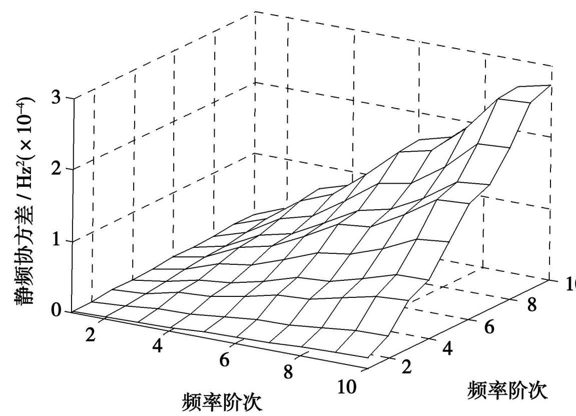

图 4　静频协方差

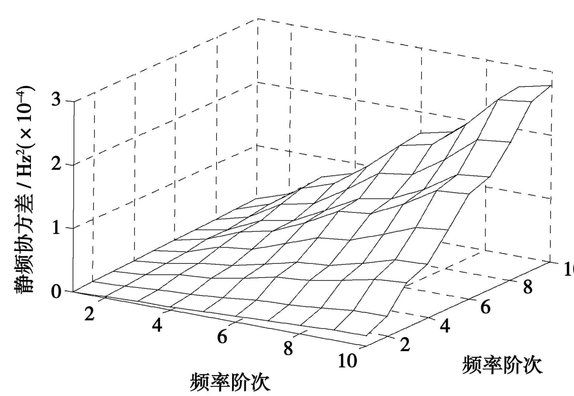

图 5　动频协方差

表 3　频率均值与变异系数

	一阶静频	二阶静频	一阶动频	二阶动频
均值/Hz	152.12	338.29	180.700	353.577
均方差/Hz	10.024 7	21.790 0	10.868 9	22.040 6
变异系数	0.065 9	0.064 4	0.060 1	0.062 3

表 3 为叶片弹性模量、密度取 0.1 的变异系数，转速、结构尺寸取 0.01 的变异系数得到的叶片静动频率的均值和变异系数，从表中可以看出，参数随机

变异导致叶片的静动频率出现变异。

5 结 论

提出了采用随机有限元方法计算叶片静动频率的方法,给出了叶片频率概率统计特征的计算方法。通过对一个 432 mm 叶片的频率进行随机有限元分析,得到的静动频率均值与文献中计算和实验值吻合良好,表明该方法的可靠性。当 432 叶片弹性模量、密度变异系数为 0.1,转速、结构尺寸变异系数为 0.01 时,叶片一阶静频变异系数为 0.065 9,一阶动频变异系数为 0.060 1。算例表明,叶片参数的随机性导致叶片频率的随机性,采用随机有限元方法可以定量给出叶片参数随机性导致叶片频率变异的程度,计算结果对工程应用具有一定的指导意义。

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(编辑 伟)

运行保障

涡轮机组轴内裂纹的振动检查

《Электрические станции》2007 年 10 月号报道,尽管涡轮机组轴内的横向裂纹是极少遇到的故障,但是它不受控制发展的后果可能导致严重的事故,直到机器完全破坏。

公认的防止类似事故的方法之一是在动力机组运行过程中实施并基于具有裂纹的轴的振动特性大量的理论和试验研究结果的振动检查。根据这些研究,裂纹的发展主要影响振动的转动分量级和二元的转动分量级,并且在增加转数的过程中,临界转速最大程度地表现自己。

在技术运行规则和ГОСТ 25364—97 中规定的在 3 昼夜时间间隔内涡轮机组支承振动速度均方根值增加 2 mm/s 的标准不保证对在轴内扩展的裂纹可靠的检查。

为了提高振动检查裂纹的效果,必须规定在表示裂纹发展到临界尺寸的时间间隔内振动的转动分量和二元转动分量向量变化的标准额。

(吉桂明 供稿)

我国电站锅炉煤粉直接点火技术的发展以及现状＝**Development and Status Quo of Utility-boiler Pulverized-coal Direct-ignition Technologies in China**[刊,汉]/ NIE Xin (College of Mechanical Engineering, Hangzhou University of Electronic Science and Technology, Hangzhou, China, Post Code: 310038), ZHOU Jun-hu, WANG Yang, CEN Ke-fa (National Key Laboratory on Clean Utilization of Energy Sources, Zhejiang University, Hangzhou, China, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(4). —333～337

The working principles and burner structures of various pulverized-coal direct-ignition technologies currently available in China as well as their development and application status are expounded along with the respective merits and demerits being pinpointed. Several omnipresent problems concerning the safety of the burners in question are summarized. To solve the contradiction between the operation safety and oil savings now troubling the power generation industry of China, two approaches were proposed: the first approach involves the adoption of multiple regulating means to reduce the pulverized-coal flow ignition heating, and the second is to integrate the use of direct-ignition technology with traditional ignition oil guns. It should be noted that high-temperature air direct-ignition technology enjoys a relatively high technical advantage due to its flexible regulating means. **Key words**: pulverized coal, oil saving, direct ignition, safe operation, ignition heat

PG9171E 型燃气轮机变工况计算模型的建立＝**Modeling for the Calculation of Off-design Operating Conditions of a Model PG9171E Gas Turbine**[刊,汉]/ XIA Di, WANG Yong-hong (Turbo-machinery Research Institute, Shanghai Jiaotong University, Shanghai, China, Post Code: 200030)// Journal of Engineering for Thermal Energy & Power. — 2008, 23(4). —338～343

To set up a calculation model for the off-design conditions of a PG9171E gas turbine, it is necessary to identify the compressor characteristics of the gas turbine in question on the basis of the original data provided by the power plant. As the current base-line estimation method was established without considering any experimental data of compressors at high-pressure ratios, in general, it can only be used for the estimation of compressor characteristics at a pressure ratio less than 11. However, the pressure ratio of the PG9171E gas turbine compressor has already approximated to 12. To solve this problem, a section-by-section calculation method was for the first time proposed for the calculation of compressor characteristics. The calculation results show that the accuracy of the above method can meet the requirement of practical applications. In respect of the calculation of thermodynamic properties involved in an off-design condition calculation model, a general-purpose relationship for the thermodynamic properties of air, CH_2 gas, C gas and steam was inducted based on thermodynamic properties table No.2. This simplifies the calculation process of wet combustion gas enthalpy and logarithmic pressure ratio values when the combustor operates on heavy fuel oil. A comparison of the calculation results of the off-design condition calculation model with the actually measured parameters of the gas turbine shows that the above-mentioned improved method can meet the requirement for the modeling accuracy in practical applications. **Key words**: compressor characteristics, combustion gas thermodynamic properties, off-design condition calculation model

汽轮机凝汽器喉部流动性能的微型模化试验研究＝**Experimental Study of Micro-modeling of Flow Performances in the Condenser Inlet of a Steam Turbine**[刊,汉]/ ZHANG Lei-lei, CUI Guo-min, GAO Xiao-zhong, et al (Thermodynamic Engineering Research Institute, Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093)// Journal of Engineering for Thermal Energy & Power. — 2008, 23(4). —344～347

Under the precondition of ensuring an identical flow state and by using similarity theory and a method under which a model is subjected to a blowdown in a wind tunnel, established was a set of miniature modeling device for a condenser inlet. An experimental study has been conducted of the flow performances at the condenser inlet under different inlet-flow speeds. The test results show that the modeling test device in question can not only reduce the size of the model and the cost of testing, facilitating the conduct of the test, but also achieve a repeatability of the flow conditions in the condenser inlet. It can be used for the experimental study of the flow friction performance and flow conditions of any condenser inlet. **Key words**: condenser inlet, miniature-modeling device, flow friction, similarity theory

随机参数汽轮机叶片频率的随机有限元分析＝**Stochastic Finite Element Analysis of Turbine Blade Frequencies at Random Parameters**[刊,汉]/ AN Li-qiang, WANG Zhang-qi (Mechanical Engineering Department, North China University of Electric Power, Baoding, China, Post Code: 071003)// Journal of Engineering for Thermal Energy &

Power. — 2008, 23(4). —348 ~352

The material properties and structural parameters of turbine blades as well as turbine speed all feature randomness, resulting in a decentralization of blade frequencies. However, the stochastic finite element method has taken account of the randomness of the blade parameters with the random characteristics of frequencies being obtained. With the material properties and structural parameters of turbine blades being treated as stochastic parameters and based on the stochastic variational principle, a stochastic finite element equation of rotating blades was derived with the establishment of the following: a mass matrix, linear elastic rigidity matrix, geometrical rigidity matrix, the mean value of dynamic rigidity matrixes and a first order variation matrix. In addition, presented was a method for calculating the mean value of natural frequencies, covariance and variation coefficients. Finally, a stochastic finite element analysis was conducted of the static and dynamic frequencies of a 432 mm blade. The frequency variation degree caused by the stochastic variation of blade parameters was quantitatively given, providing an analytic tool for the high reliability design of blades. **Key words**: turbine blade, stochastic parameters, stochastic finite element, frequency

不同进排气管路时涡轮增压机组的热计算方法= **A Method for the Thermodynamic Calculation of a Turbocharger Unit with Different Inlet and Exhaust Ducts**[刊, 汉] / JIN Jia-shan, LIU Long-bo (Marine and Power College, Naval Engineering University, Wuhan, China, Post Code: 430033), JI Guang (Military Representative Office of Chinese Navy Resident at CSIC No. 703 Research Institute, Harbin, China, Post Code: 150036)// Journal of Engineering for Thermal Energy &Power. —2008, 23(4). —353 ~356

On the basis of the off-design condition characteristics data of a turbo-charger unit operating under the condition of designed ducts, established were the curves featuring the variation of the turbo-charger compression ratio, expansion ratio and the efficiencies of various components etc. with the rotating speed of the unit. Then on the basis of the pressure balance equation of the turbo-charger unit with the rotating speed serving as an independent variable, an iterative operation was conducted of the pressure balance points of the unit fitted with various inlet and exhaust ducts, and its operating speed was also determined. The foregoing may avoid the inefficient process of frequently consulting the calculation charts, and result in a simple and convenient method for calculating the off-design thermodynamic performance of the marine turbo-charger unit in question. A specific case calculation shows that if there exists no significant difference between the resistance characteristics of inlet and exhaust ducts on the one side and those of the designed ones on the other, the method under discussion can guarantee the accuracy of the calculation results to be within a range acceptable for engineering design. **Key words**: turbo-charger unit, working parameter, thermodynamic calculation

基于遗传算法的叶型优化设计平台及应用= **A Genetic Algorithm-based Platform for the Optimized Design of Blade Profiles and its Applications**[刊, 汉] / LI Yu, FENG Tao, ZOU Zheng-ping, et al (National Key Laboratory on Aeroengine Aerodynamics and Thermodynamics, College of Energy Source and Power Engineering, Beijing University of Aeronautics and Astronautics, Beijing, China, Post Code: 100083)//Journal of Engineering for Thermal Energy &Power. —2008, 23(4). —357 ~362

In view of the ever growing role played by numerical optimization in turbo-machinery design, a design platform was developed for turbine blade optimization based on a genetic algorithm. By using the platform, an optimization analysis has been conducted of two calculation cases along with the optimization of the bending and sweeping of the stacked generatrix of a fan rotor blade and the optimization of three-dimensional blade thickness distribution for rotating blades in a single-stage turbine. In addition, the optimized results were compared with those of the prototype, and an analysis was also conducted. The comparison results show that the optimization design platform thus developed can be used for the three-dimensional optimization of blades, effectively enhancing the blade performance and improving relevant flow conditions. A single-target optimization can not guarantee that a turbine attains an ideal performance at all the operating conditions. The parameterization description of the blades is of major significance for the optimization and will eventually decide the quality of the final optimized results. **Key words**: turbo-machinery, blade profile, design platform, numerical simulation, genetic algorithm (GA)