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基于有限元技术的大型汽轮机转子寿命评估系统

王 坤[1], 黄树红[1], 黄丕维[2], 张柏林[2]
(1. 华中科技大学 能源与动力工程学院, 湖北 武汉 430074; 2. 湖南电力试验研究所, 湖南 长沙 410007)

摘 要: 结合机械结构寿命评价理论和数值分析方法, 对基于有限元的大型汽轮机转子寿命评估系统进行研究。采用归一化方法对复杂的转子实际换热边界条件进行处理; 依据转子的运行历史数据和结构几何参数自动生成传热学、力学边界条件, 利用 Delaunay 非结构化自动剖分算法对几何模型进行网格剖分, 将载荷谱处理和损伤累积无缝嵌入有限元分析过程。在此基础上, 形成了基于复杂数值方法的转子寿命评价集成化系统, 该系统具备了转子稳态、瞬态温度场、应力场和应变场分析及损伤和寿命评估功能, 能直观显示转子损伤场分布及其演变, 克服了传统方法中一些难以处理的技术障碍。

关 键 词: 汽轮机转子; 有限元; 寿命评估; 疲劳

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前 言

对汽轮机转子进行寿命评估, 是一件系统性工作, 按照美国电力研究院(EPRI)总结的电厂高温部件寿命管理“三级评价法”, 它是一个对不同来源信息的整合和分析的过程。采用何种方式对汽轮机转子进行寿命评估, 最终需要达到怎样的准确程度, 必须依据具体情况制定相应规划[1]。实验手段对转子进行寿命评价, 结果相对直接、可靠, 但是受环境和条件限制较多, 也很难灵敏的反映载荷过程与损伤之间的联系; 以理论分析为特点的评价方法由于涉及到较多的科学和工程问题, 存在一定技术门槛, 但是该方法对载荷过程的仿真及评估具有独特的优势, 所以应用较为普遍。

传统分析式汽轮机转子寿命评价的实施过程一般包括两个主要步骤: 通过计算分析获得关键部位应力及应变载荷分布及其变化, 然后利用疲劳损伤理论对转子服役过程的寿命损耗进行评价, 上述过程也常常被称为部件寿命评价的局部“应力－应变”分析法。由于该方法涉及很多理论和技术性的问题, 如几何拓扑、网格剖分、弹塑性力学、离散传热学、损伤力学、载荷谱处理方法等。使得该方法的应用过程复杂而繁琐, 学术性较强, 从而在一定程度上限制了该方法的工程推广。

目前, 随着计算机硬、软件技术的快速发展, 使用软件技术辅助解决汽轮机转子寿命评价问题已经成为可能。早在 20 世纪 80 年代以来, 不少国内研究者就开始尝试自己编写专用代码进行转子寿命评价, 因为前后处理模块开发等非寿命评价相关的技术性限制因素, 这些程序一般功能受限, 从而没有大规模推广开。

针对上述情况, 本文研究利用目前成熟可靠的寿命评价方法、有限元技术及计算机软件系统开发思想, 研究开发了一套集汽轮机转子温度场、应力场分析、融合传统热力场分析载荷谱处理和损伤场模拟等功能, 具备良好易用性的汽轮机转子寿命(损伤)专业评估系统。

1 大型汽轮机转子寿命评价系统开发与理论

1.1 几何建模方法

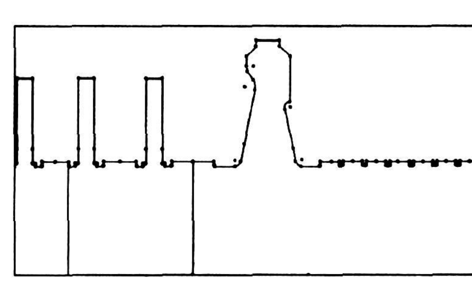

图 1 某 125 MW 汽轮机组高中压转子几何模型

有限元系统几何建模功能应采用由“底层”到“高层”的几何拓扑建模方式。首先建立几何点元素, 由点元素构建几何线元素, 最后以线组成转子模型。线元素上的点元素同时构成模型网格剖分所需

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作者简介: 王 坤(1975－), 男, 湖北洪湖人, 华中科技大学博士研究生.

的"种子"点,携带网格密度控制信息控制网格单元尺寸,上述方法将使系统建模过程具备直观、简单、易用的特点,如图 1 所示。

1.2 单元系统和网格剖分算法

网格剖分是有限元系统前后处理模块的核心功能之一,也是传统用自编程序进行有限元分析比较困难和繁琐的地方。结构化网格剖分简单,但工作量繁重且总体质量欠佳。文献[2]表明,Delaunay 三角剖分方案具有两种性质:(1)空外接圆性质即任何一个三角形的外接圆均不包含其它数据点;(2)最小内角最大性质即在所有可能形成的三角剖分中,Delaunay 三角剖分中三角形的最小内角之和最大。这两个特性保证了 Delaunay 三角剖分生成的三角形尽可能接近等角或等边,这一性质正是数值计算技术对网格剖分所要求的,因此,对于复杂区域一般使用三角形非结构化网格剖分。

1.3 边界条件

传热学理论中:第一类边界条件(边界上各点的温度值已知):

$$t|_{s_i}=f(x, y, z, \tau), s_i \quad (1)$$

第二类边界条件(边界面上的热流密度值已知):

$$q|_{s_i}=q_w=f(x, y, z, \tau) \quad (2)$$

第三类边界条件(边界面上与接触的流体的温度 t_f 和表面传热系数 h 已知):

$$-\lambda \frac{\partial t}{\partial n}\Big|_s = h(t|_s - t_f) \quad (3)$$

上述 3 类边界条件中,第三类边界条件实质包含了第一类、第二类边界条件,在某些特殊情况下可以将之简化。当流体侧有强烈的流动或其它因此使得物体边界与周围流体之间的对流热阻非常小,则有:

$h\rightarrow\infty$,则 $T_s=T_b$,即第一类边界条件。

当流体侧为绝热保温材料时:

$h\rightarrow 0$,则 $\frac{\partial T}{\partial y}\Big|_s=0$,即第二类边界条件。

对汽轮机转子热分析而言,其边界换热过程比较复杂。蒸汽和转子之间换热可以近似为第三类热边界条件;转子与润滑油之间换热过程由于润滑油比热较大,因此可以近似第一类边界条件;转子与空气之间的换热过程由于空气与转子之间换热系数相对较小,故可以近似为绝热边界等。本文系统中依据上述传热学理论和相关数值技术,将上述转子中不同的换热过程通过第三类边界类型进行了归一化,这样简化了转子的热分析边界条件。不同换热边界中的蒸汽温度和换热系数将通过转子运行数据及换热经验公式获得。

转子的力学边界条件主要是叶片对转子轮盘的拉应力。为简化转子力学边界设置,系统应设计为可以通过输入叶片设计参数和机组运行历史数据,直接完成力学边界条件的生成。

1.4 材料模型

由于转子在运行过程中所经历的温度范围比较宽,对转子进行温度、应力分析时,必须考虑温度对材料力学性能数据和传热性能数据的影响(如弹性模量、比热、泊松比等参数),系统中应构建相关材料参数的数据库,记录在不同温度段内的值,以利于对转子各种物理场进行准确数值分析。

1.5 稳态分析与瞬态分析

稳态温度场的求解在数学上是对椭圆型方程的求解,当稳态导热方程加上时间项 $\rho c\frac{\partial T}{\partial t}$后,就成为瞬态问题的抛物线型方程。此时除了必须知道边界条件外,也要知道初始条件。求解过程就是从初始温度分布开始,每隔一个时间步长,求解下一时刻的温度分布,一步一步地推进分析。抛物线型方程用有限差分法求解时,存在方程组求解的稳定性和收敛速度的问题,这是步进积分所带来的特点。

将瞬态传热控制方程中的 $\rho c\frac{\partial T}{\partial t}$项差分离散化,是瞬态问题求解的重要一环。在瞬态温度场分析的求解过程中,不同格式的稳定性和收敛快慢差别很大。在比较典型的差分格式中,向前差分格式能得到显式解,不必求解方程组,这种格式是有条件稳定的,使用中要求 Δt 取得很小才能有较好的效果;混合差分格式具有较高的精度,而且稳定性较好,但是需要对时间步长和空间单元尺寸之间的比例进行分析协调,才能达到满意的效果;向后差分格式与向前差分格式具有相同的精度等级,但在瞬态温度场的有限差分法求解中,向后差分得到的是隐式解,它是无条件稳定的,而且在大 Δt 条件下也不振荡,参见式(4):

$$\left|\frac{\partial T}{\partial t}\right|_t=\frac{1}{\Delta t}(|T|_t-|T|_{t-\Delta t})+O(\Delta t) \quad (4)$$

式中:$\left|\frac{\partial T}{\partial t}\right|_t=[\frac{\partial T_1}{\partial t}, \frac{\partial T_2}{\partial t}\cdots\frac{\partial T_n}{\partial t}]^T$,$|T|_t=[T_1, T_2, \cdots T_n]^T$ 是列向量。

系统核心算法采取空间域用有限元和时间域用后向有限差分格式的离散格式,从而充分利用了有限元在空间域对不规则边界的适应性和后差分格式在时间域无条件稳定的优点[3]。

式(5)是有限元方程在 t 时刻的离散格式:

$$[K]\{T\}_t+[N]\left\{\frac{\partial T}{\partial t}\right\}_t=\{P\}_t \qquad (5)$$

整理后可得有限元法计算瞬态温度场的基本方程式:

$$\left([K]+\frac{[N]}{\Delta t}\right)\{T\}_t=\{P\}_t+\frac{[N]}{\Delta t}\{T\}_{t-\Delta t} \qquad (6)$$

式中: Δt—已知时间步长; $\{T\}_{t-\Delta t}$—初始温度场或前一时刻的温度场。

由前述瞬态温度计算方程式(6), 显然, 当 Δt 取足够大时, 原方程可以近似为一个与瞬态矩阵 $[N]$ 无关的方程式, 也就是说等效于一个稳态问题的方程式。因此, 如果将时间步长值取一足够大值时, 分析过程可以等效为稳态换热分析, 从而使得系统可以通过时间参数的选取, 分别模拟转子稳态、瞬态热过程, 同时灵活设置增量步长也可以改变瞬态分析的精确度。

1.6　损伤分析与寿命评价

系统中对各功能模块所需数据采用统一的标准格式进行读取, 并有数据库进行存储, 这样转子各部位材料的损伤分析将无须按照传统模式中通过手工单独提取参考部位的应力谱, 而是完全可以自动按瞬态数据提取载荷谱并进行谱处理, 进而完成对转子模型全域损伤分析, 这一功能使系统可以直观显示转子的定量损伤分布及其演化趋势。

系统采用 ASTM E1049—85 疲劳分析循环计数标准方法中的通用"雨流计数法"以及经典的 Miner 线性累积准则作为损伤评价的技术手段, 并按照变比例原则考虑高温蠕变损伤分量, 参见式(7):

$$\sum_i \frac{n_i}{N_i}+\sum_i \frac{t_i}{T_i}=1 \qquad (7)$$

其中: n_i—转子在给定循环应力作用下循环的周次; N_i—转子在同样条件下破坏时的循环周次; t_i—转子在给定应力和温度下工作时间; T_i—同样条件下的蠕变寿命。

1.7　可视化界面开发

一般有限元分析所需人工耗费中, 90% 为前后处理, 而方程求解过程只占 5% 左右。因此, 系统应采用可视化思想设计开发前后处理模块, 直观显示建模过程及结果信息, 便于操作者使用。

2　大型汽轮机转子寿命评价系统设计

系统功能设计如图 2 所示, 功能的不同组合可完成对大型汽轮机转子的稳态、瞬态、传热、力学过程分析, 及材料损伤分析和疲劳寿命评价等功能。

温度场分析过程如图 3 所示, 位移分析过程如图 4 所示。

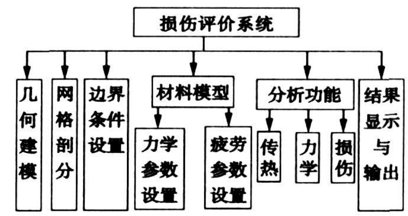

图 2　系统各功能模块

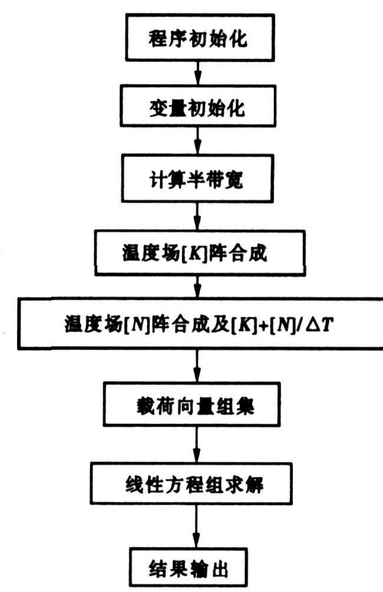

图 3　热分析

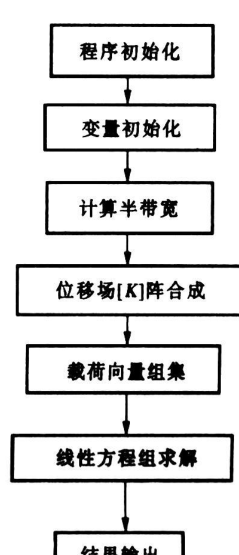

图 4　位移场分析

系统中进行热力耦合情况下的损伤评价分析流程为：热分析→力学分析→谱处理→损伤累积。

3　算例及其验证[4]

对一个简化转子体的冷态启动过程进行寿命损伤评估。该转子几何结构如图 5 所示，数值模型由 7 755 个三节点三角形单元，4 146 个节点构成。

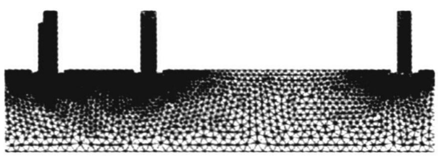

图 5　某转子局部网格图

分析过程分为 51 个瞬态过程，每个时间间隔 600 s。转子材料使用通用转子钢 30Cr2MoV 材料；具有各种换热边界及力边界条件。各边界蒸汽温度变化趋势参见图 6。

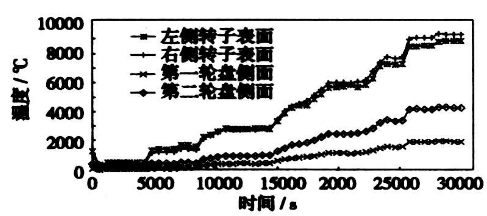

图 6　各边界蒸汽温度变化趋势

图 7 为最大 Von Mises 应力出现时刻 10 200 s 的应力分布图，该时刻最大应力为 605.5 MPa，位于第二轮缘右侧倒角处，针对同样的有限元模型采用国际商用有限元 Msc.MARC 系统计算结果为 602.1 MPa。图 8 为第一轮缘倒角局部损伤分布图。

整个汽轮机转子在该次冷态启动过程中消耗寿命为 9.730×10^{-5}，最大损伤点位于第二轮缘倒角处，如图 7 所示。

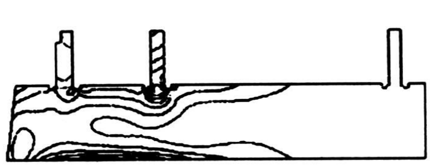

图 7　10 200 s 时 Von Mises 应力分布

图 8　第一轮缘右侧局部损伤分布

4　结　语

（1）研究开发基于复杂数值方法的转子寿命评价集成化系统，该系统具备汽轮机转子的全尺寸建模、转子稳态、瞬态温度场、应力场和应变场分析及定量显示损伤场分布和损伤演变过程等功能，能较好的满足对汽轮机转子的损伤和寿命评估。

（2）构建的系统将应力应变有限元分析与材料损伤分析和寿命评价进行无缝整合，极大的简化了传统汽轮机转子的寿命评价过程，降低了原方法的使用难度，依托该系统，本文形成了一种较好的汽轮机转子寿命评价方法。

（3）文中算例间接验证了系统核心代码的正确性和可靠性。

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空气分离/烟气再循环技术基础研究进展=**Latest Advances in Fundamental Research on Air-separation/Flue Gas Recycling Technology**[刊,汉]/LI Qing-zhao, ZHAO Chang-sui (Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology, Thermal Energy Engineering Research Institute under the Southeast University, Nanjing, China, Post Code: 210096)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —231~236

The technology for separation and recovery of carbon dioxide produced during fossil fuel combustion is regarded as a comparatively feasible measure to alleviate CO_2 emissions in the near future. Among the numerous CO_2 separation and recovery technologies, air separation/flue gas recycling technology (O_2/CO_2 combustion technology) has an evident edge and a relatively favorable application prospect. The overall situation of CO_2 emissions worldwide is described and the background for proposing the air separation/flue gas recycling technology outlined along with its latest research findings. The emphasis has been put on the exposition of pulverized coal combustion in the environment of O_2/CO_2 and the emission characteristics of various contaminants (SO_2, NO_x and super fine particles). The shortcomings and problems existing in the current research are also pinpointed. The pulverized-coal combustion rate in the environment of O_2/CO_2 is low, featuring a kind of unstable burning and a darkening flame. The formation of pollutants and the desulfuration mechanism of a calcium-based desulfurizing agent clearly differ from those of traditional cases. To study the combustion characteristics of pulverized coal in the environment of O_2/CO_2 and concerted control mechanism of various pollutants will be a main focus for future work. **Key words**: air separation/flue gas recycle technology, O_2/CO_2 combustion, SO_2, NO_x

跨音速压气机叶栅中稠度对弯掠叶栅流场影响的数值分析=**A Numerical Analysis of the Impact of Solidity on Bowed and Swept Cascade Flow Fields in a Transonic Compressor Cascade**[刊,汉]/ZHANG Yong-jun (Engineering Thermophysics Research Institute under the Chinese Academy of Sciences, Beijing, China, Post Code: 100080), FENG Guo-tai (College of Energy Sciences and Engineering under Harbin Institute of Technology, Harbin, China, Post Code: 150001)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —237~240

A comparison of the numerical calculation results of a transonic stationary cascade with test ones shows that the above calculation results are in relatively good agreement with the test ones. To discuss the applicable conditions of bowed and swept blades in a transonic compressor, a numerical analysis was conducted of the flow fields in bowed and swept blades having bending angles ranging from 0 degree to 30 degrees under a 0 degree incidence angle with the solidity being 1.75, 1.50 and 1.25 respectively. The numerical analysis results indicate that the effectiveness of bowed and swept blades with a high solidity is quite evident. The bowed and swept blades can transform the shock waves at the leading edge into oblique ones and meanwhile weaken the intensity of blade passage shock waves, thus diminishing cascade losses caused by shock waves. It can be verified that under transonic conditions, the magnitude of solidity is an important causative factor in determining whether to use bowed blades or not in stationary cascades. **Key words**: diffusion cascade, bowed and swept blade, solidity, transonic

基于有限元技术的大型汽轮机转子寿命评估系统=**A Rotor Service-life Evaluation System for Large-sized Steam Turbines Based on Finite Element Technology**[刊,汉]/WANG Kun, HUANG Shu-hong (College of Energy Source and Power Engineering under Central China University of Science and Technology, Wuhan, China, Post Code: 430074), HUANG Pei-wei, ZHANG Bo-lin (Hunan Electric Power Test and Research Institute, Changsha, China, Post Code: 410007)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —241~244

In combination with service-life evaluation theories and numerical analysis methods for mechanical structures, a study has been conducted of a finite-element-based service-life evaluation system for rotors of large-sized steam turbines. A normalized method was adopted to process the boundary conditions of complicated actual heat exchange in rotors. The boundary

conditions of heat transfer and mechanics theory have been automatically generated based on the historical operating data and structural geometric parameters. A mesh dissection was conducted of a geometric model by using a Delaunay non-structural automatic dissection algorithm. The load spectrum treatment and damage build-up were seamlessly inserted into a finite-element analysis process. On this basis, formed was an integrated system of rotor service-life evaluation based on a complicated numerical method. The above system can provide such functions as the analysis of rotor steady-state and transient temperature, stress and strain fields as well as the evaluation of rotor damage and service life, thus visually displaying the distribution of rotor damage fields and their evolution, and at the same time overcoming some technically intractable hindrances specific to traditional methods. **Key words**: steam turbine rotor, finite element, service life evaluation, fatigue

汽轮机转子涡动汽流激振力分析与 CFD 数值模拟＝**Analysis and CFD (Computational Fluid Dynamics) Numerical Simulation of Steam Flow Excitation Force Leading to a Whirling of Steam Turbine Rotors** [刊, 汉] /LIU Xiao-feng, LU Song-yuan (College of Energy Source and Environment under Southeast University, Nanjing, China, Post Code: 210096)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —245～249

During the whirling of a steam turbine rotor, its shaft center will deviate from that of the stator, thus producing a Thomas/Alford steam-flow excitation force leading to a loss of stability due to vibrations. In such a case, however, the calculation formula of a traditional blade-tip clearance excitation force can not provide an overall and a correct evaluation of the above force. With the whirling of the rotor and the secondary flow around the blade shroud being comprehensively taken into account in rotating blade passages, the whirling-caused excitation force was analyzed based on the work done by the steam. In the gland seal of the blade tip shroud, CFD values were used to simulate a three-dimensional viscous flow field of the leaking steam, thus determining the magnitude of the steam excitation force. The research results show that under the condition of a small static and dynamic eccentricity, the excitation force in the rotating blade passages induced by the dynamic eccentricity of the rotor whirling is greater than that induced by the static eccentricity, and the pre-swirling velocity of steam flows in the shroud gland has an important influence on the excitation force in the clearance. The non-symmetric steam admission is another important source of the steam excitation force. **Key words**: steam turbine, tip clearance excitation vibration, eddy whirling of rotor, computational fluid dynamics (CFD)

刷式密封泄漏流动特性影响因素的研究＝**A Study of the Influence of Brush-type Seals on Leaking Steam Flow Characteristics** [刊, 汉] /LI Jun, YAN Xin, FENG Zhen-ping (Research Institute of Turbo-machinery under Xi'an Jiaotong University, Xi'an, China, Post Code: 710049)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —250～254

By employing techniques for seeking a solution to Reynolds-Averaged Navier-Stokes equation based on an improved Darcian porous medium model, a numerical analysis and study has been conducted of the law governing the influence of pressure ratio and bristle pack thickness on the leaking steam flow characteristics of brush-type seals under the condition of a given radial clearance. Based on the test data published for leaking steam flow rates of brush type seals, determined was the permeability coefficient of the porous medium of the bristle pack. By using the permeability coefficient of the bristle-pack porous medium thus obtained, calculated respectively were the leaking steam flow rates and flow patterns of brush type seals at the ends of a shaft under the condition of 7 pressure ratios and 5 kinds of bristle pack thickness at a given radial clearance. The calculation results indicate that both the pressure ratio and bristle pack thickness can influence the leaking steam flow rate of a brush type seal. Under the condition of a given pressure ratio, the leaking steam flow rate will decrease with an increase of bristle pack thickness. At a given bristle pack thickness, the leaking steam flow rate will increase with an increase of pressure ratio. As the leaking steam flow rate of a brush type seal assumes approximately a linear variation relationship with the pressure ratio and bristle pack thickness, the impact of the latter two items on the